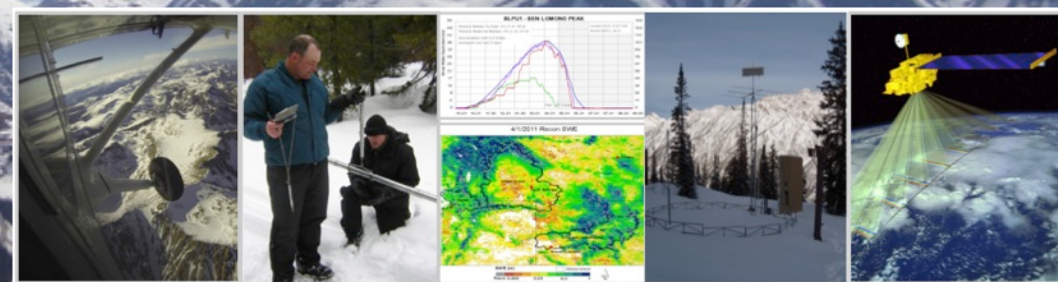
Measuring and modeling our snow water resource



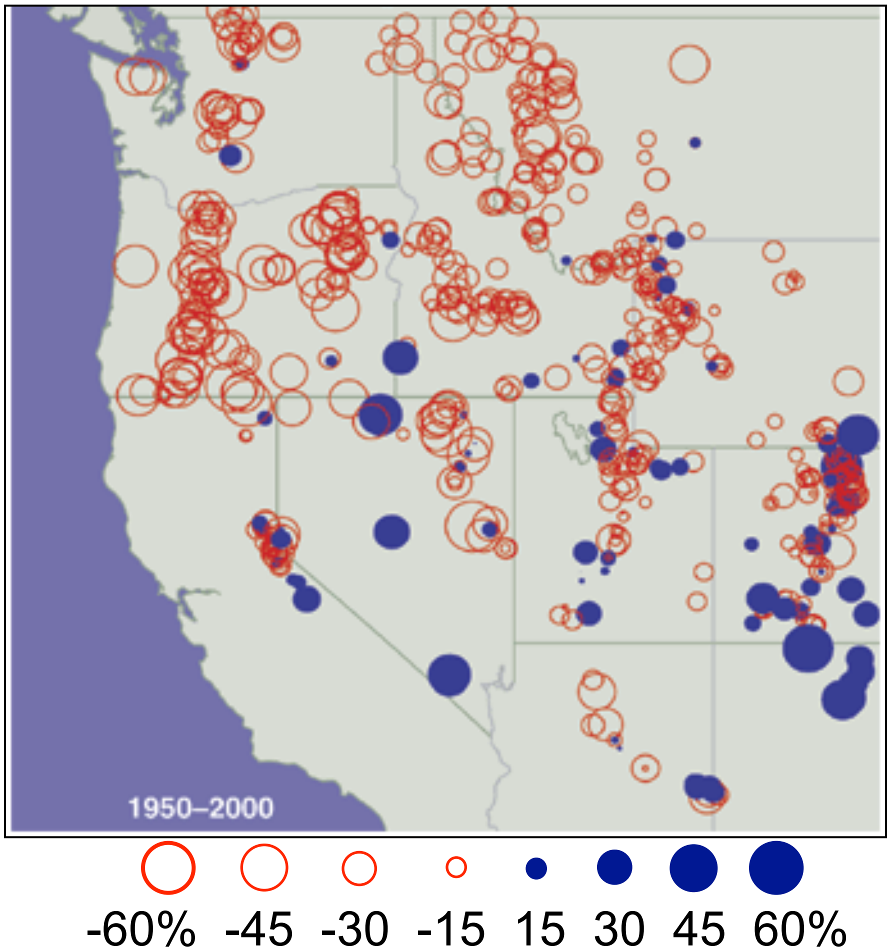
Broomfield, CO
September 9, 2015

Photo: Jim Steenburgh

NIDIS · Colorado Basin River Forecast Center CBRFC · Colorado Water Conservation Board, Department of Natural Resources · NRCS Natural Resources Conservation Service Snow Survey

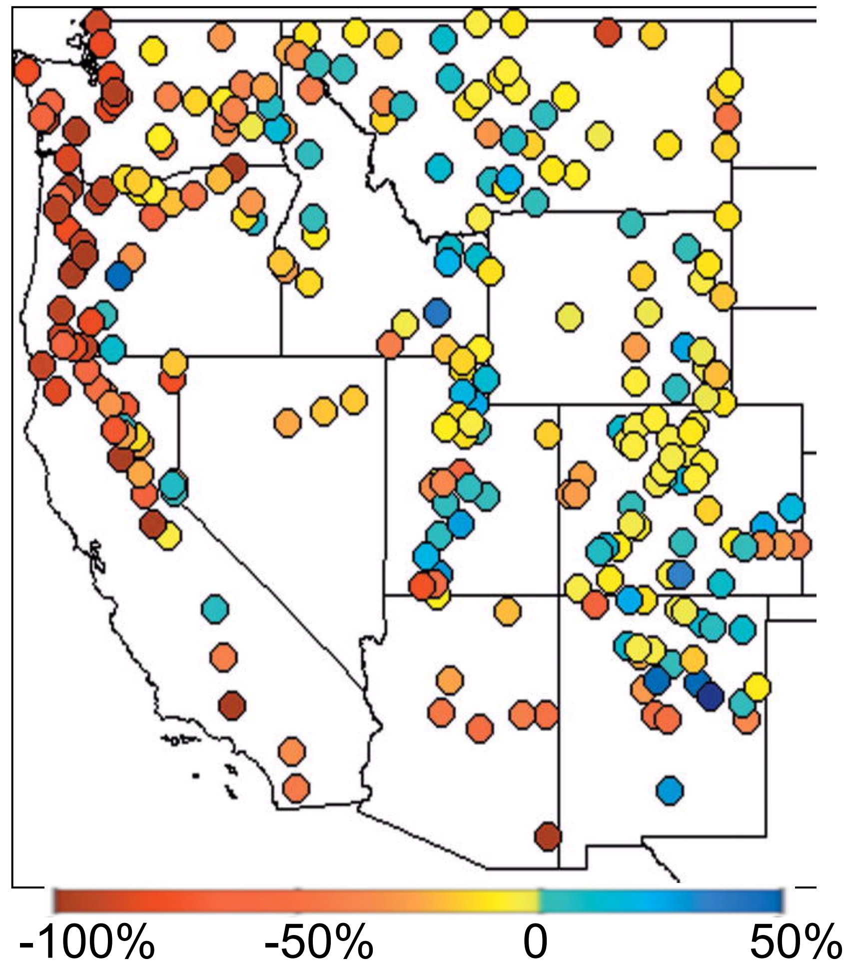
Westwide Snowpack Trends: 1950 - 2000

Percent change in April 1 snow water equivalent



Service, 2004

% change in snowfall to rainfall

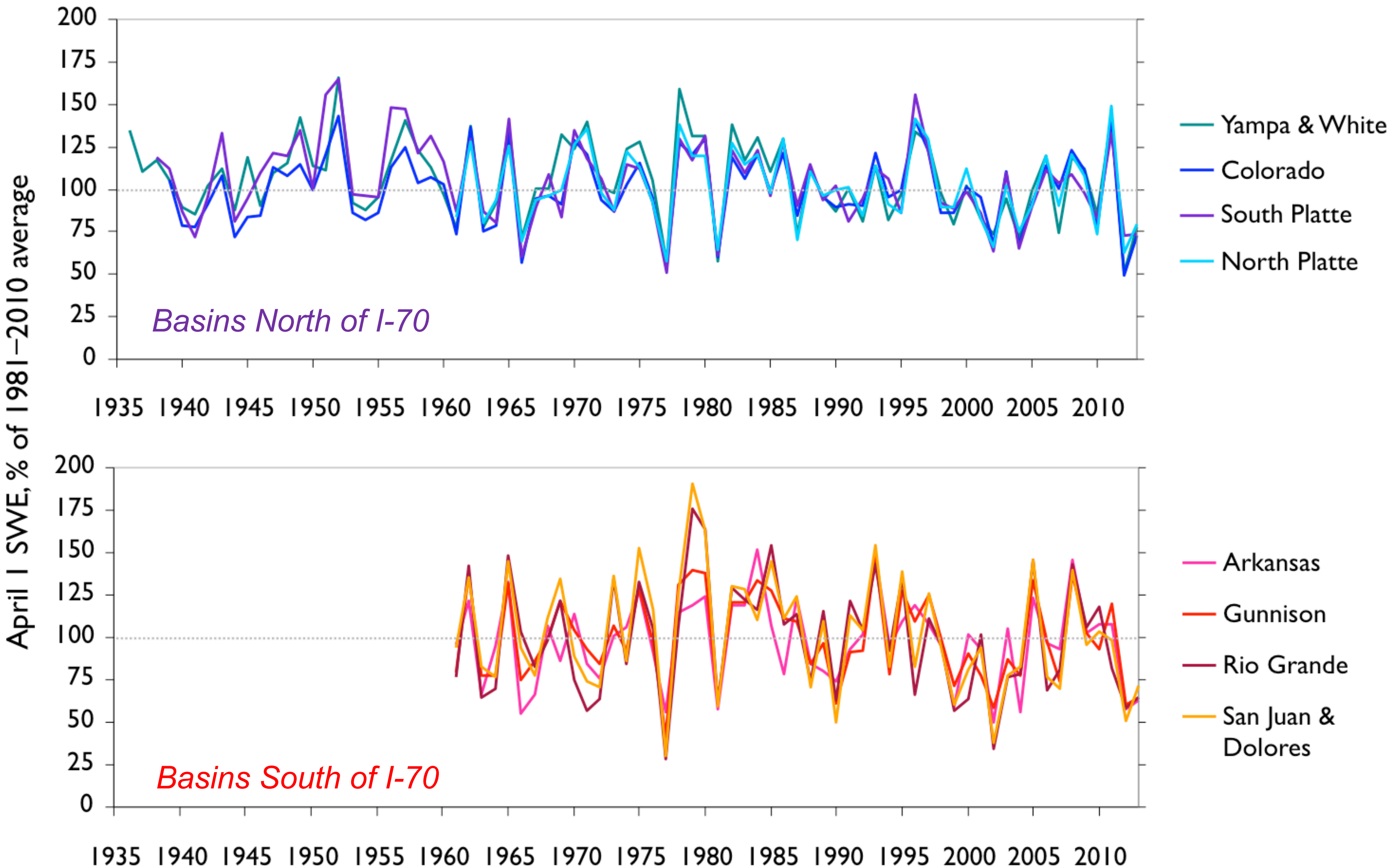


Knowles et al., 2006

Colorado April 1 SWE:

generally low since 2000

no significant basinwide trends over past 30 & 50 years

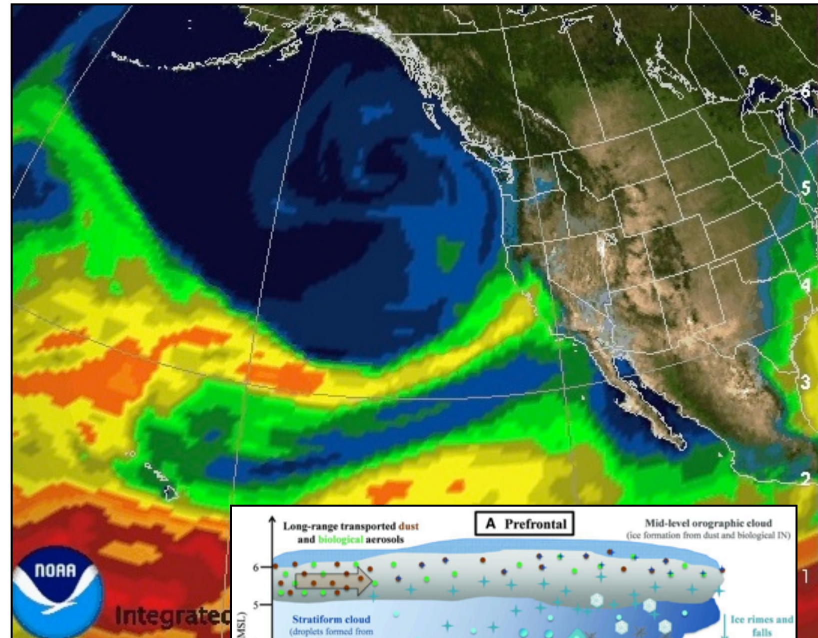


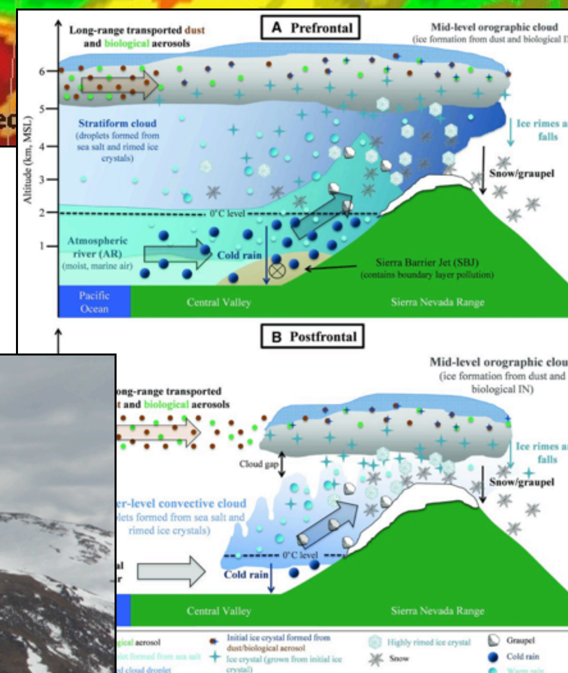
Climate Change in Colorado (2014); Figure 2-9

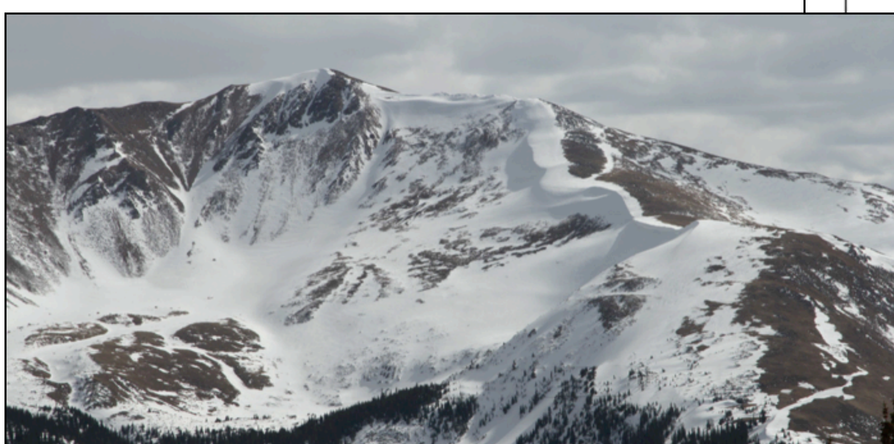
Snow accumulation

depends on complex processes at multiple scales:

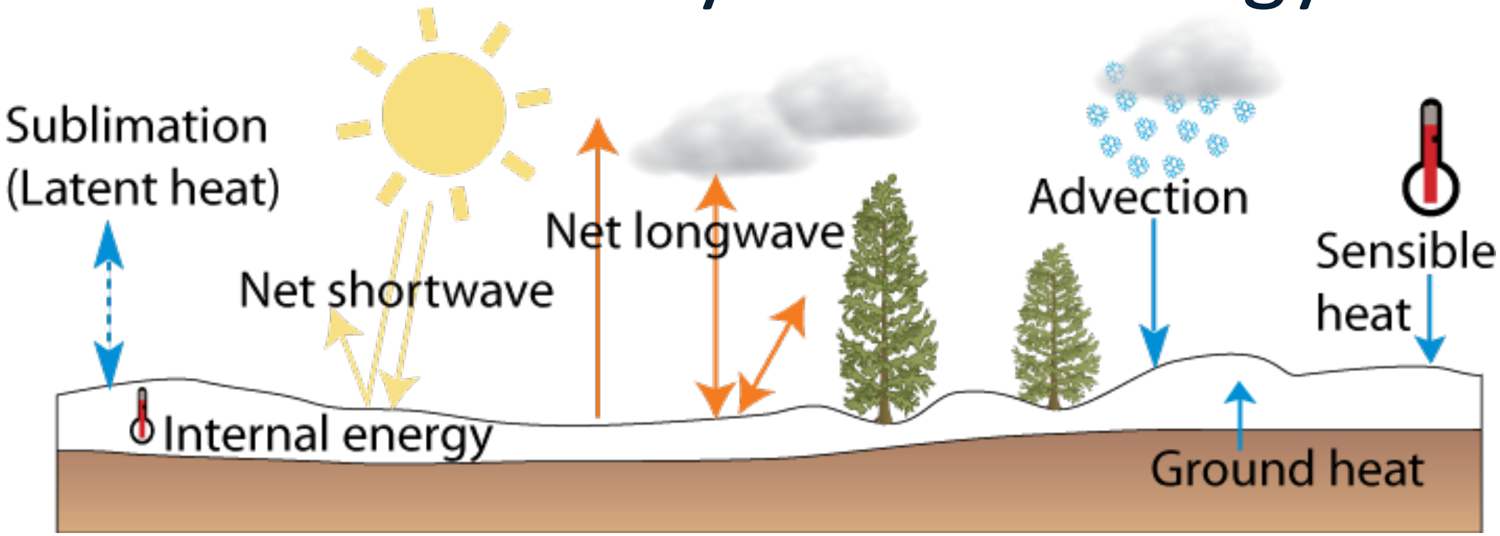
- Storm track
- Storm synoptics
- Air temperature & moisture
- Orientation of moisture flux relative to topography
- Orographic enhancement
- Wind redistribution
- …







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 → $\frac{dU}{dT}$

Melt energy → Q_m

Albedo → α

Shortwave radiation → S

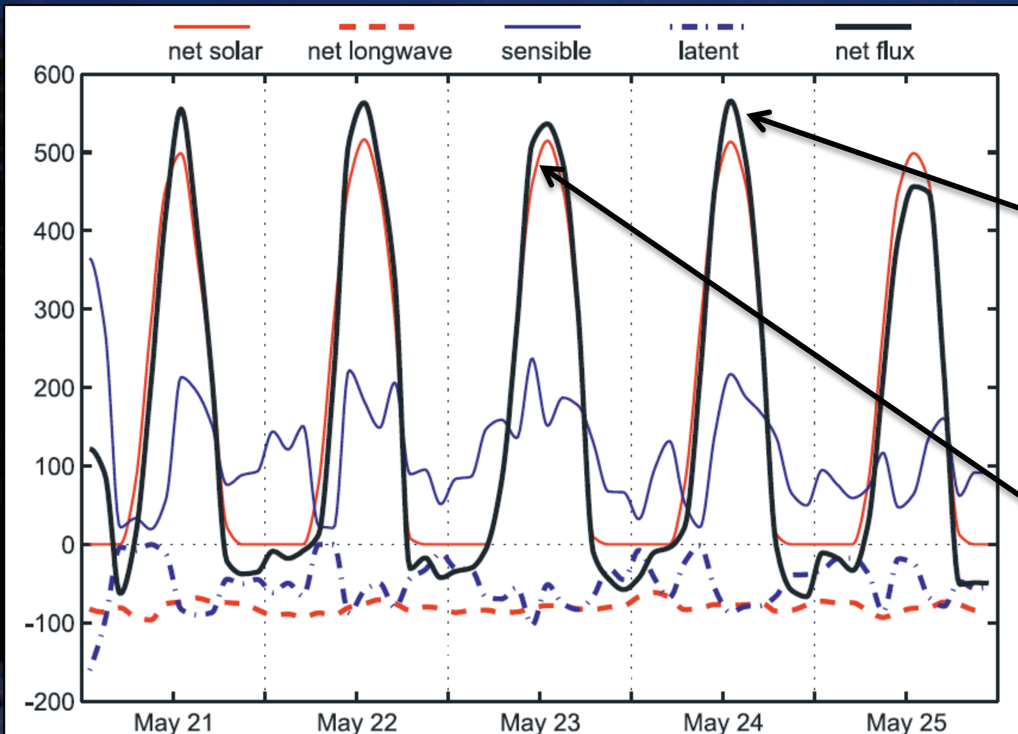
Net Longwave radiation → L^*

Sensible heat/advection → Q_s

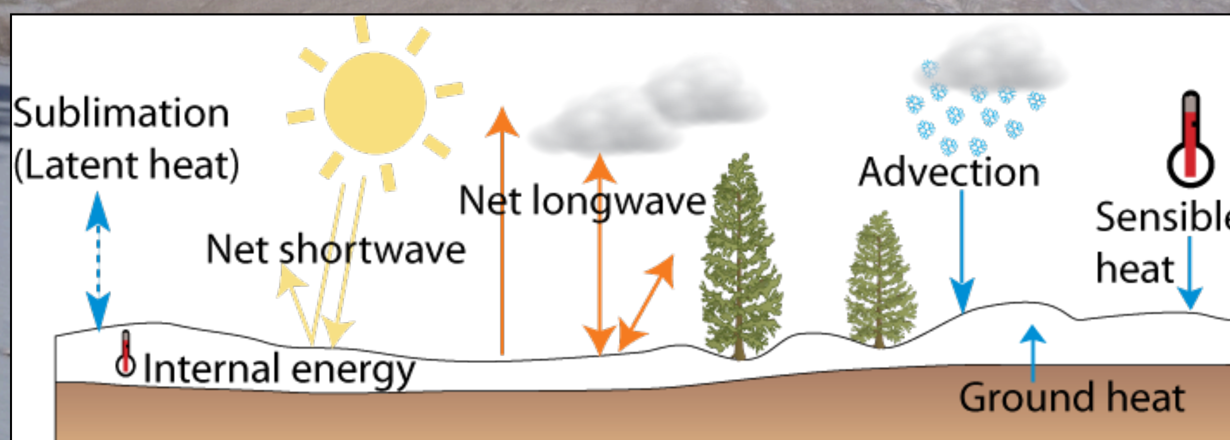
Latent heat → Q_v

Ground heat → Q_g

Solar radiation controls snowmelt



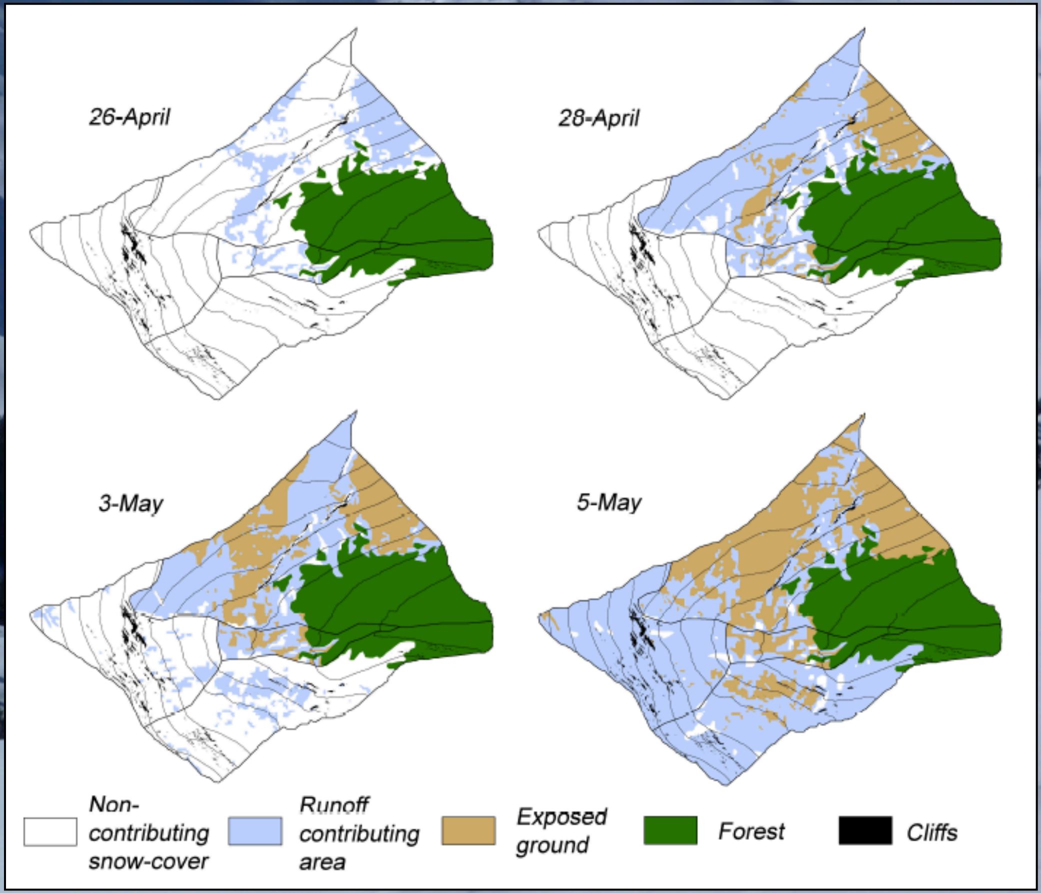
Bales et al. (2006)



April 2010
Senator Beck Basin, San Juan Mountains

Snow accumulation patterns control melt volume & timing

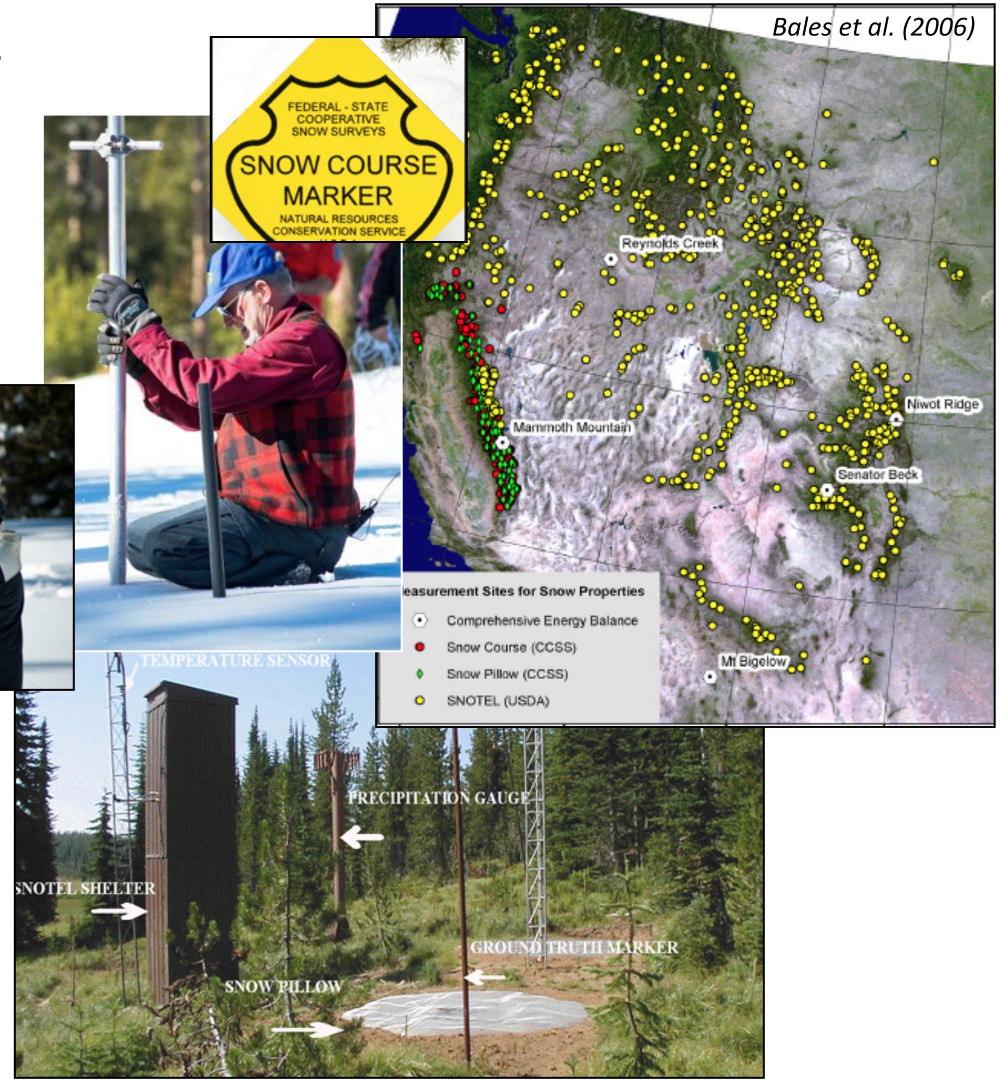
- different spatial patterns can produce the same values at point locations
- distribution of SWE + terrain drivers of energy balance determine melt & runoff patterns



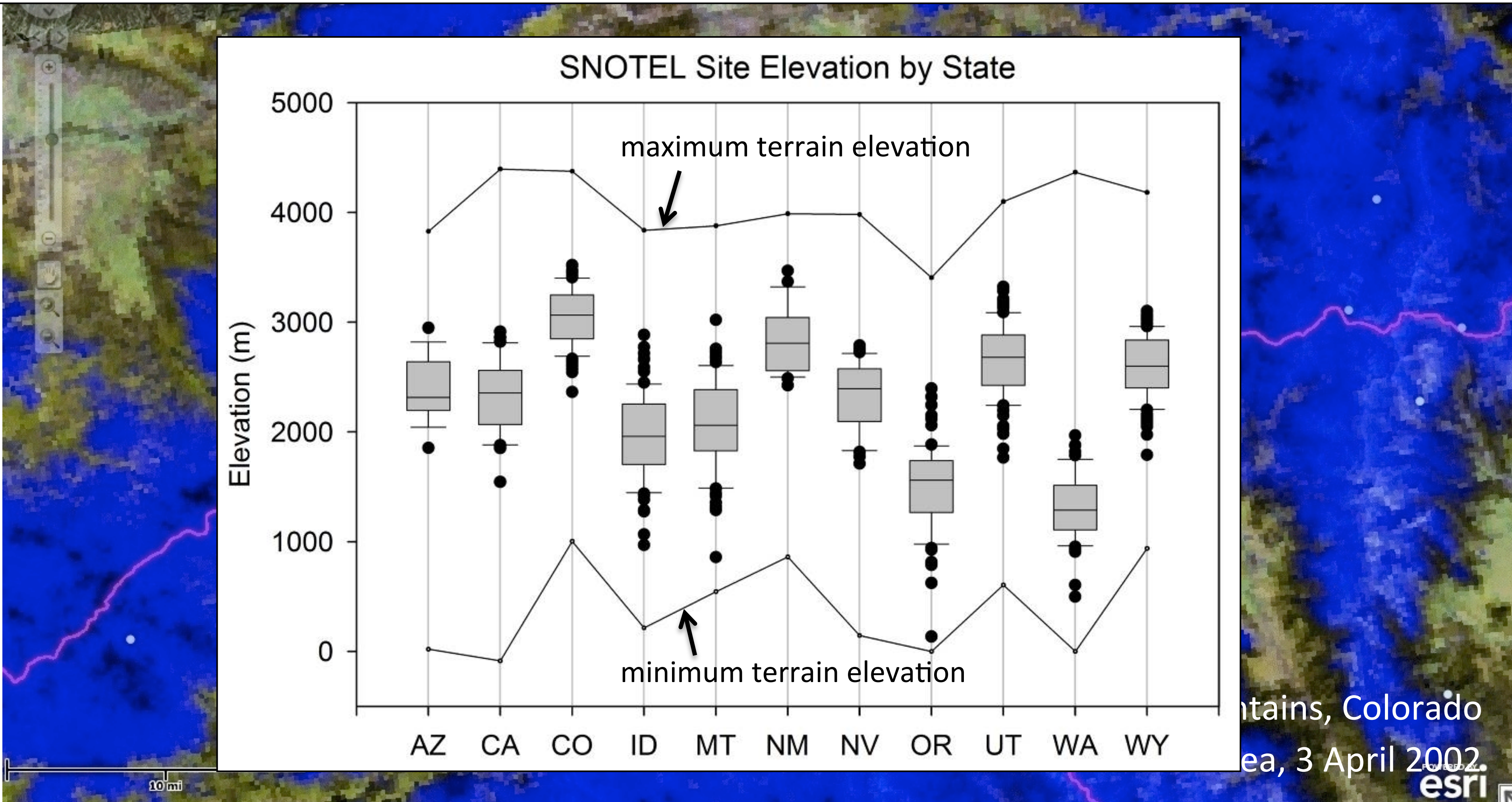
DeBeer & Pomeroy, 2010 HESS

Operational Snow Monitoring

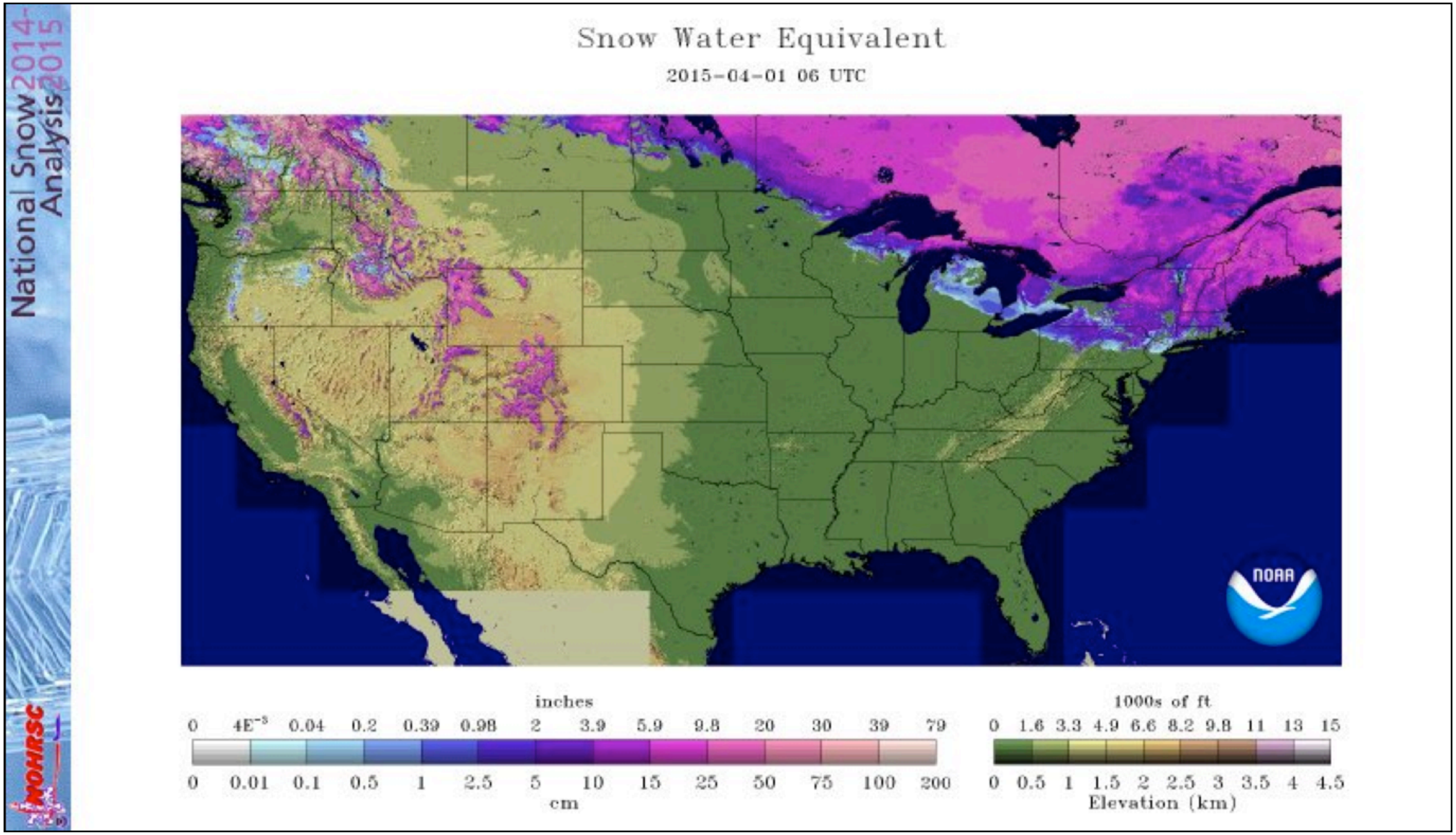
- Snowmelt provides 75-80% of water supply in western US
- Snow Water Equivalent (SWE) is measured at manual snow courses & automatic SNOTEL snow pillows
- Manual & automated measurements are used for statistical & index forecasts
- Measurements



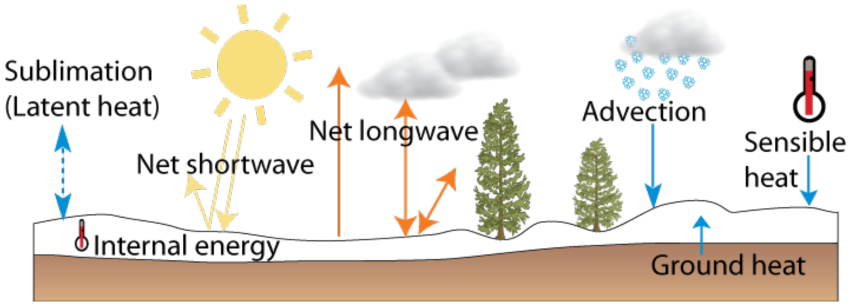
Operational Snow Monitoring



National Weather Service: SNODAS



Snowmelt & runoff simulation & forecasting



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
- *$Q = f(T_{air}$*melt factor)*
- Calibrated to observations

Physically-based hydrology model

- e.g. PRMS

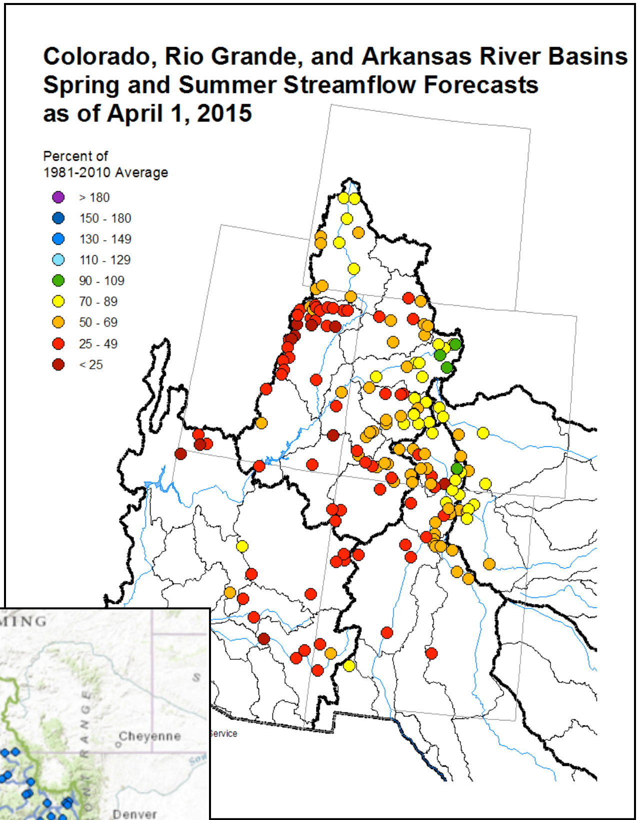
$$Q_m + \frac{dU}{dT} = (1-\alpha)S + L^* + Q_s + Q_v + Q_g$$

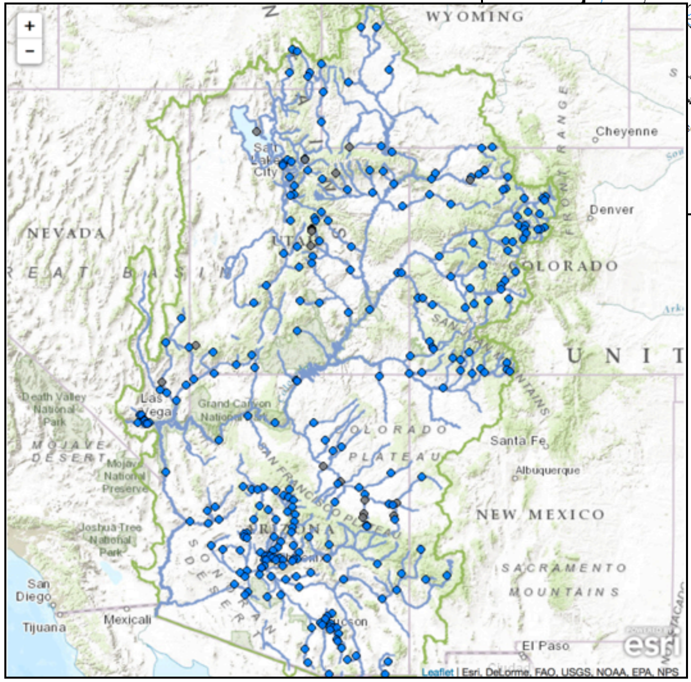
- Common research tool

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

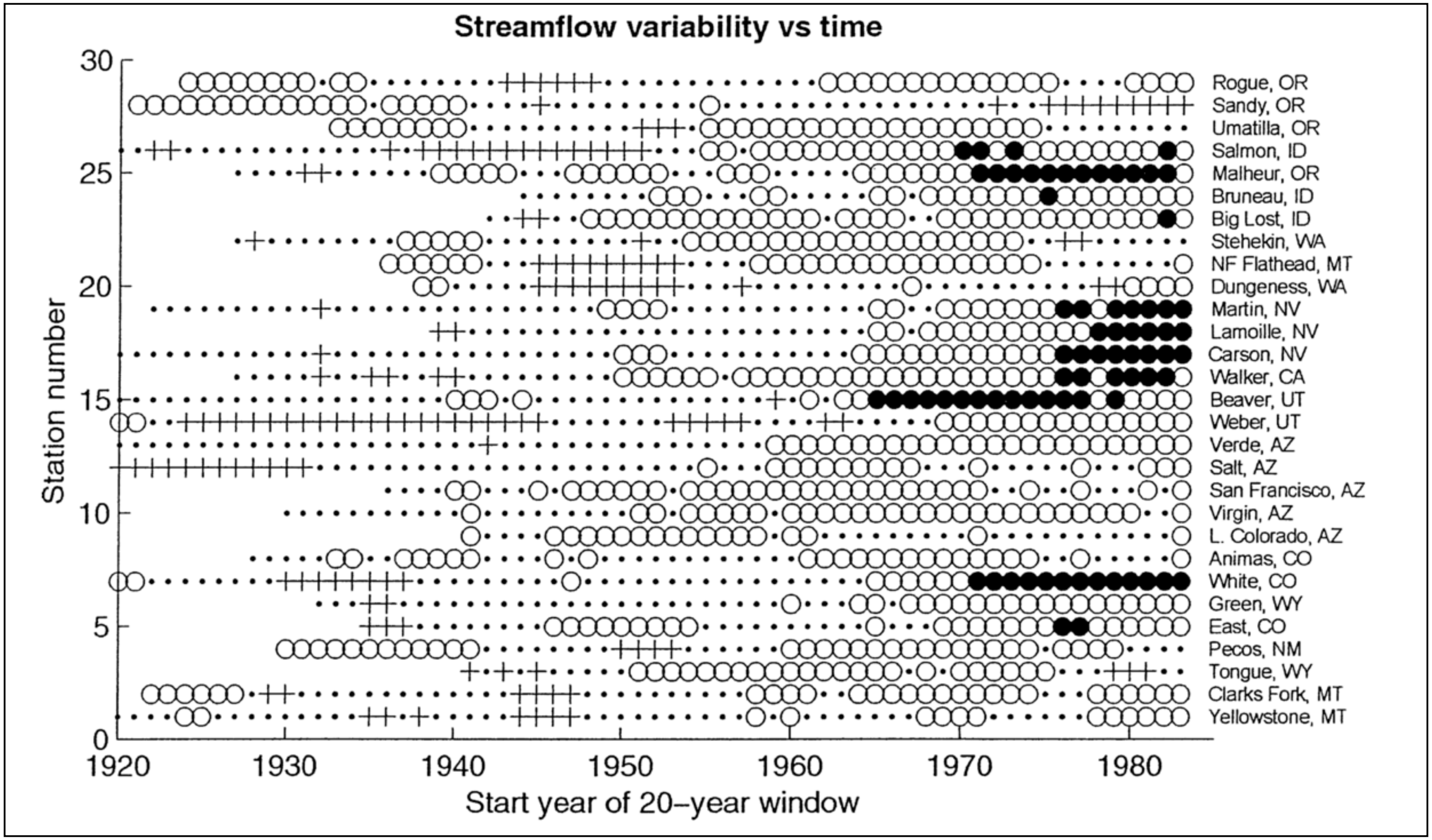
** Both methods assume calibrations apply to current conditions*





Forecast error sources

Streamflow variance is increasing

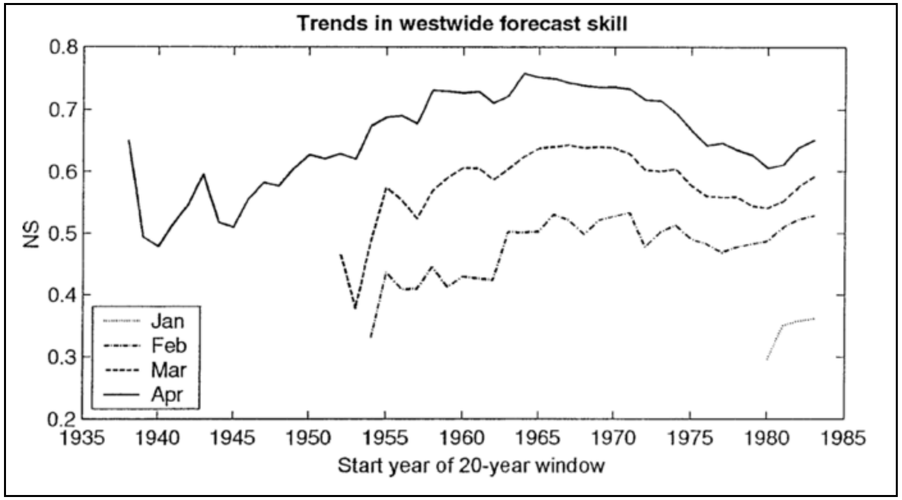


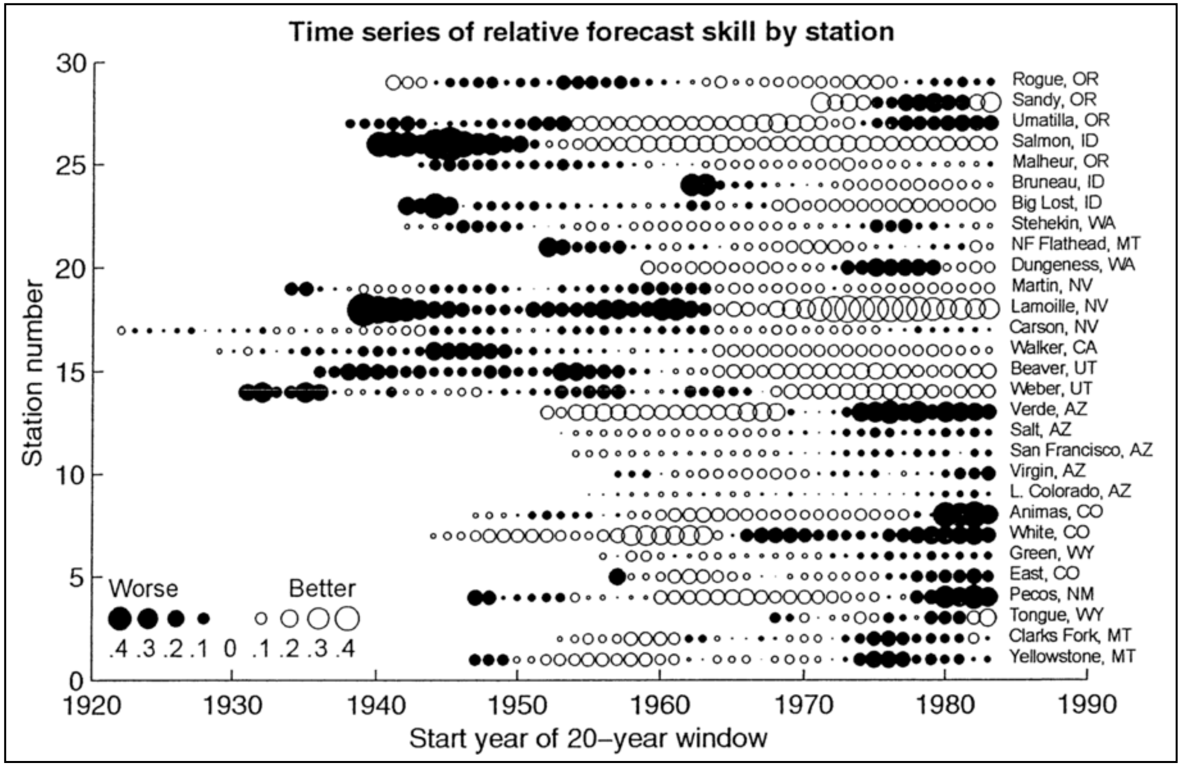
Pagano et al., 2004 – J. of Hydrometeorology

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



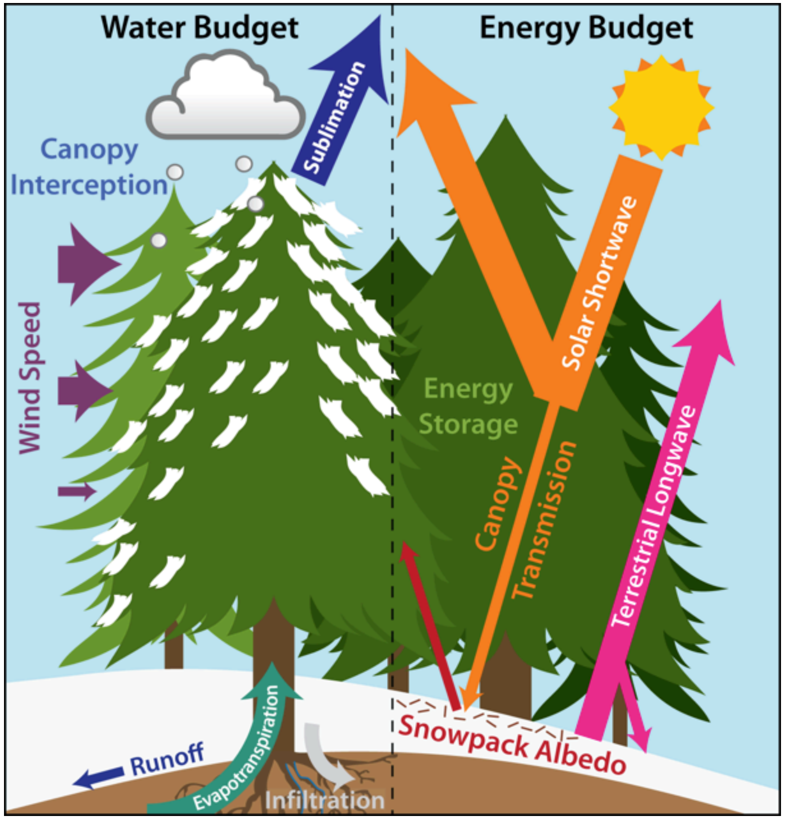


Pagano et al., 2004 – J. of Hydrometeorology

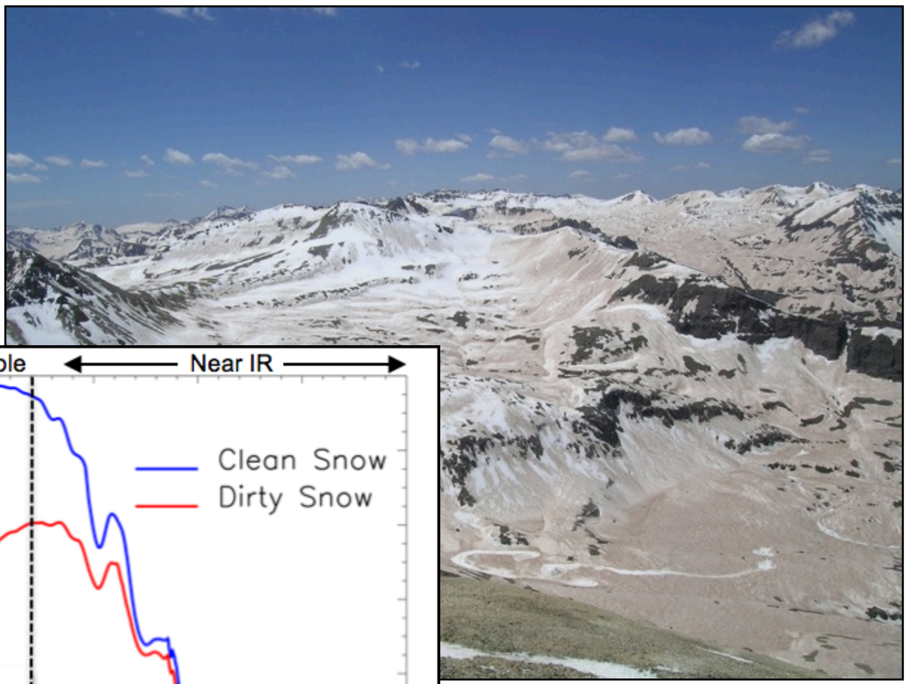
Forecast error sources

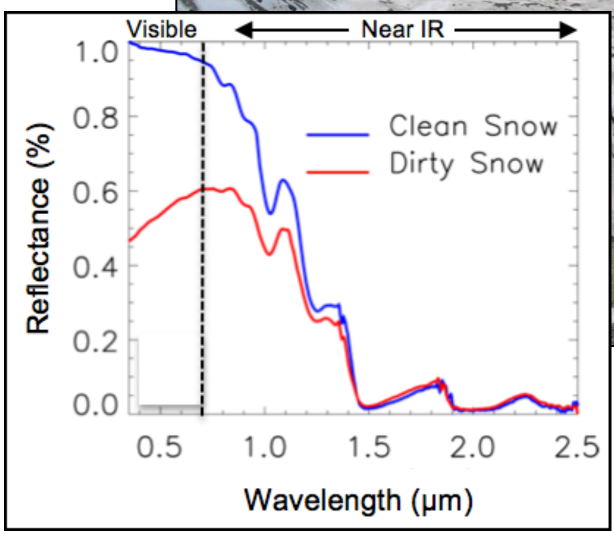
Land cover change/bark beetle

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



Pugh and Gordon, *Hydrological Processes*



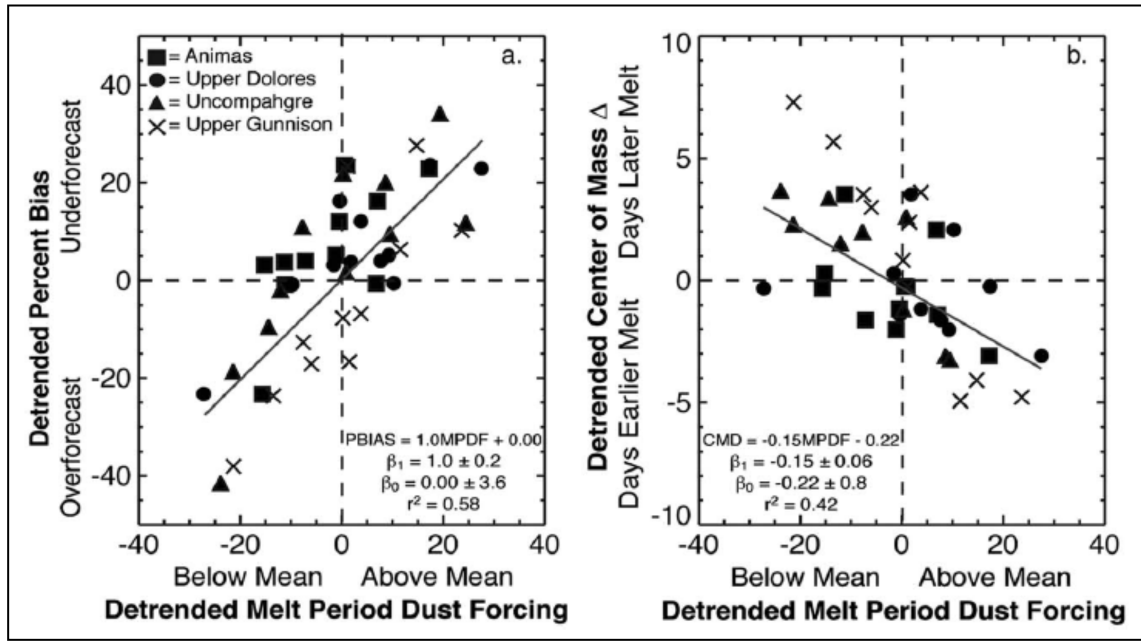


Dust on snow

- 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



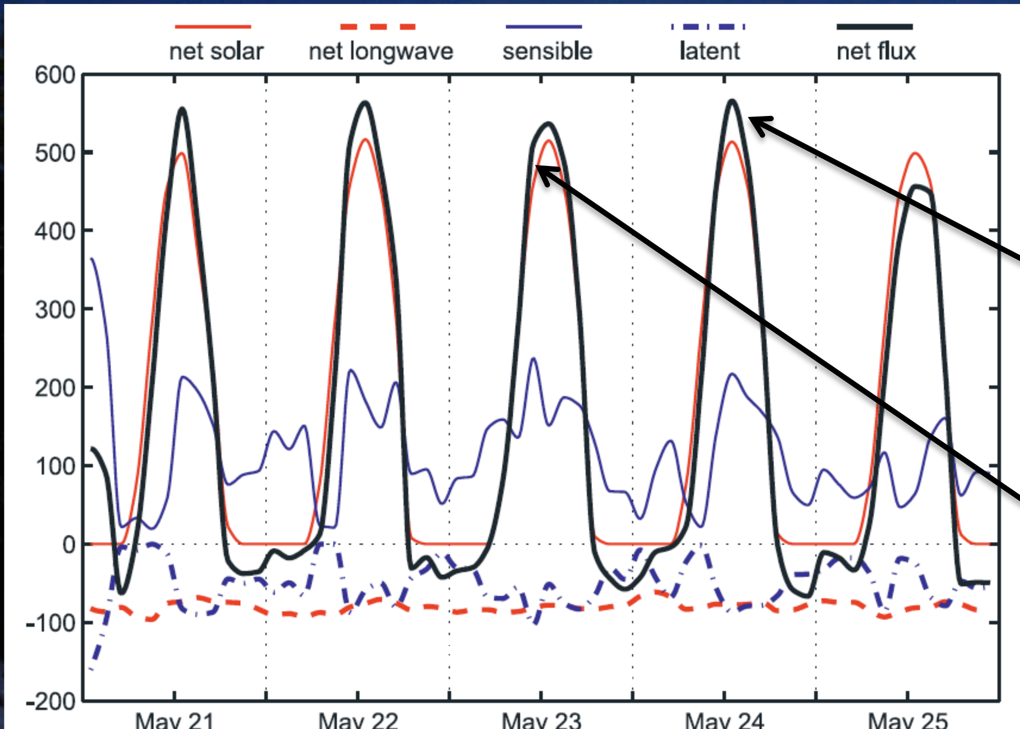
Impact of dust radiative forcing in snow on accuracy of operational runoff prediction in the Upper Colorado River Basin

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

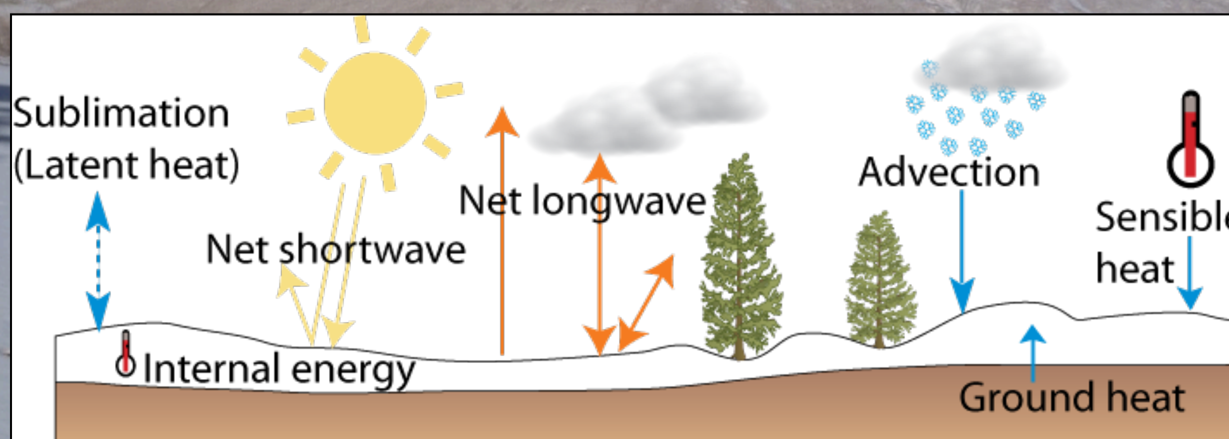
- need dynamic melt factor adjustment or energy balance model

Solar radiation controls snowmelt



Bales et al. (2006)

repeat, spatially explicit maps of snow albedo are needed



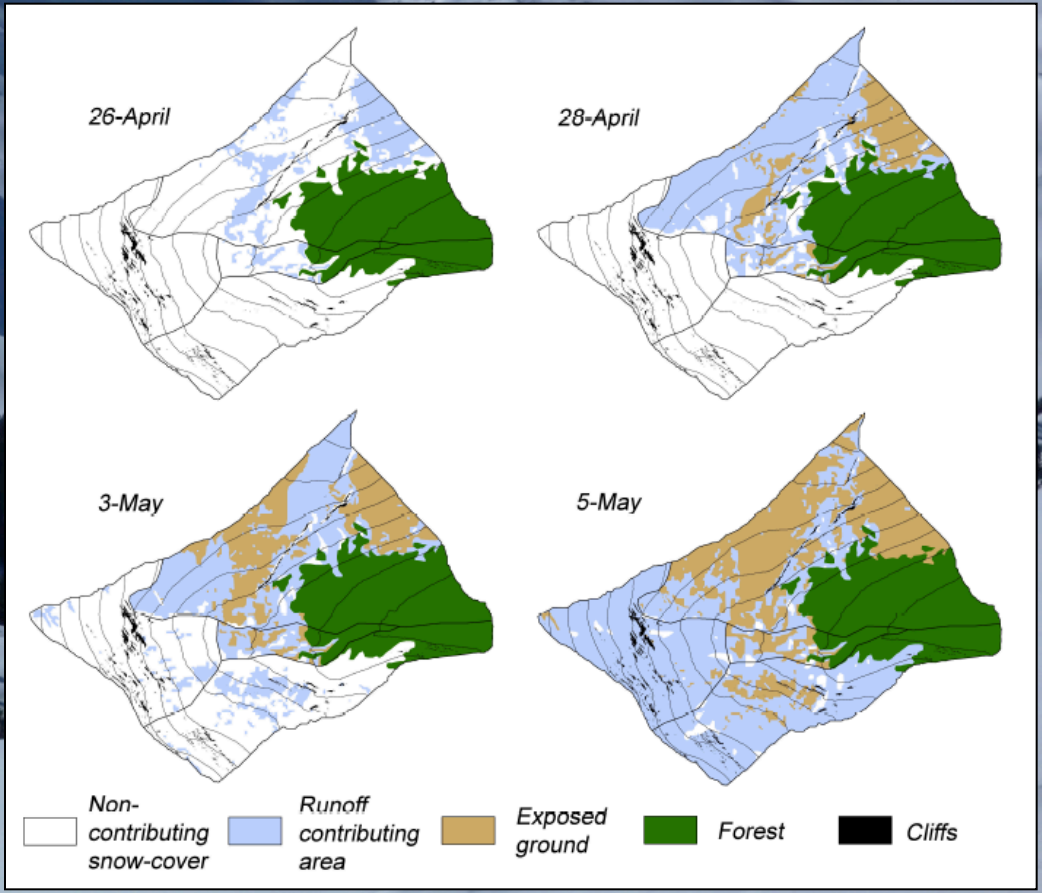
April 2010

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

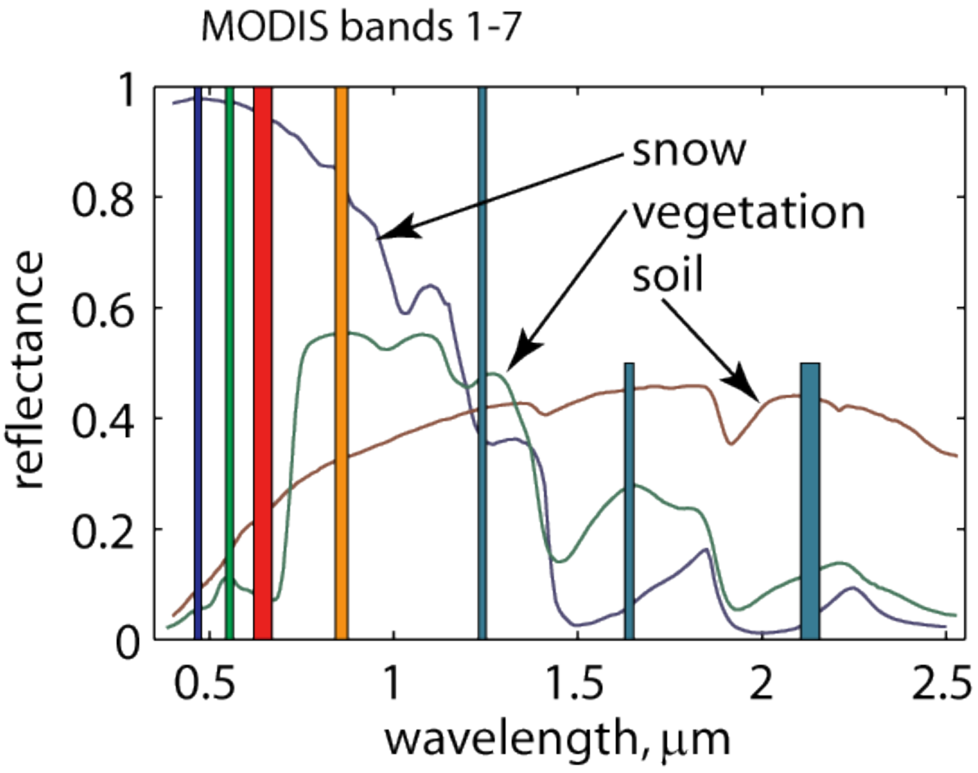
repeat, spatially explicit maps of snow depth/SWE are needed

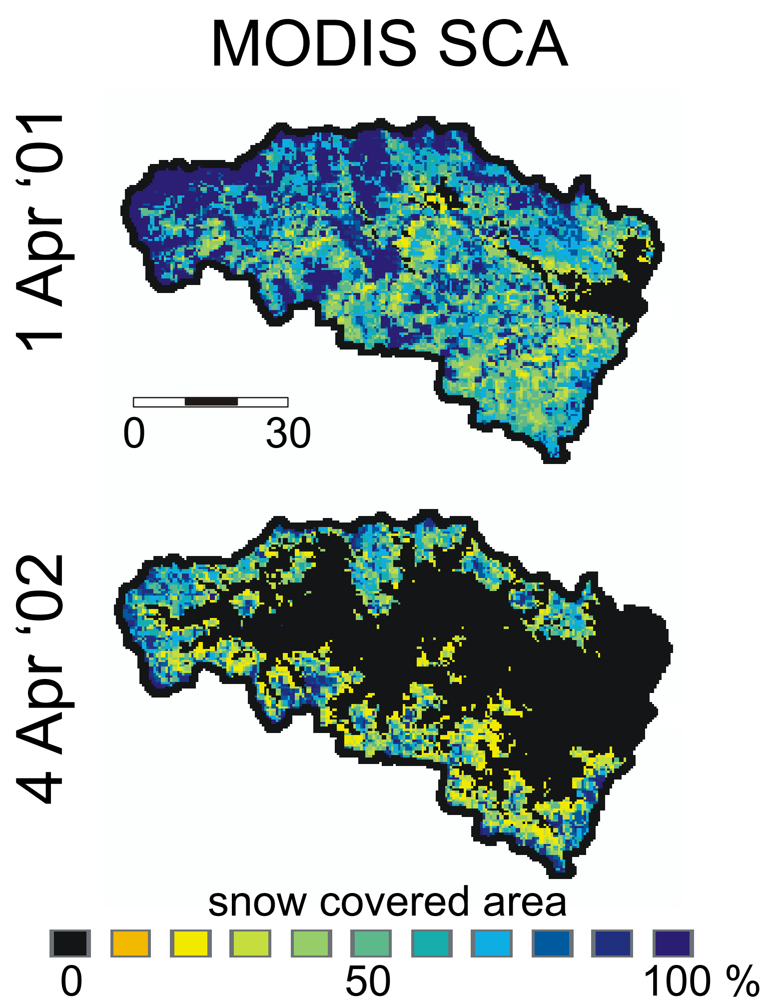


DeBeer & Pomeroy, 2010 HESS

Optical remote sensing

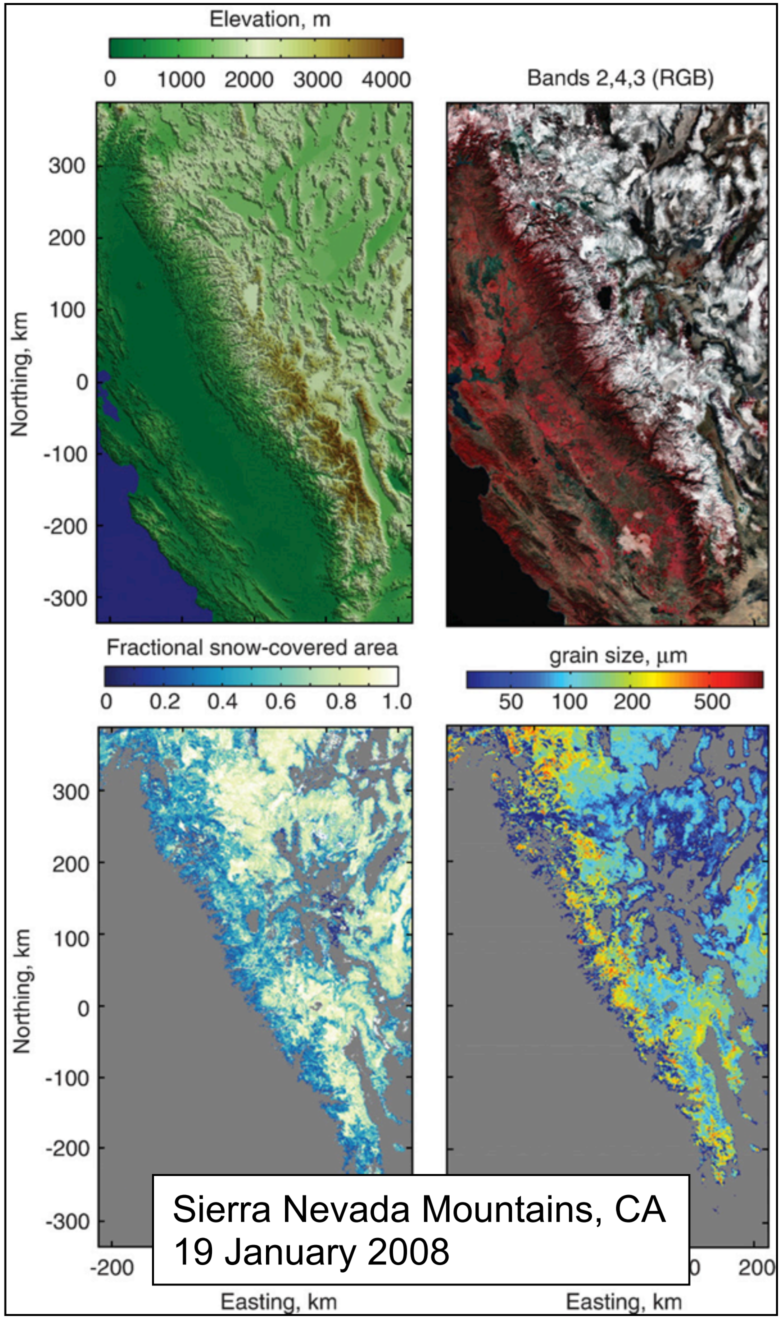
Measuring reflected solar radiation at specific wavelengths

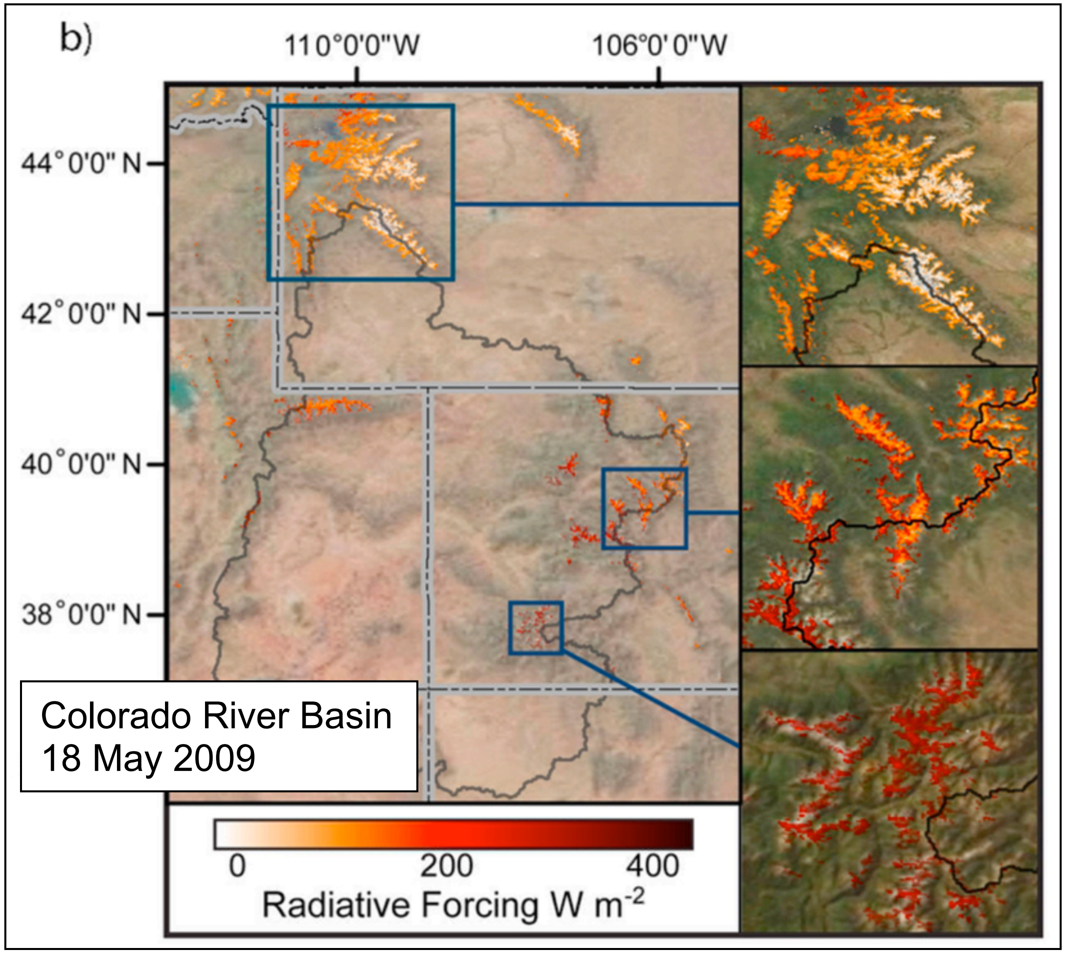




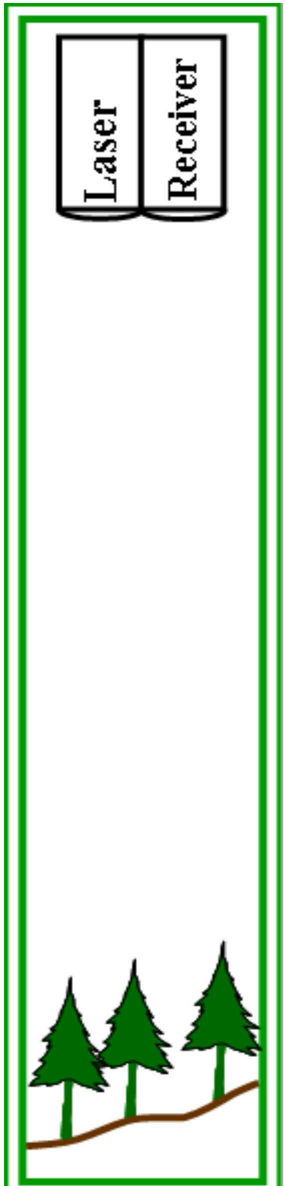
Snow Properties from MODIS

- SCA
- Grain Size
- Albedo
- Dust radiative forcing

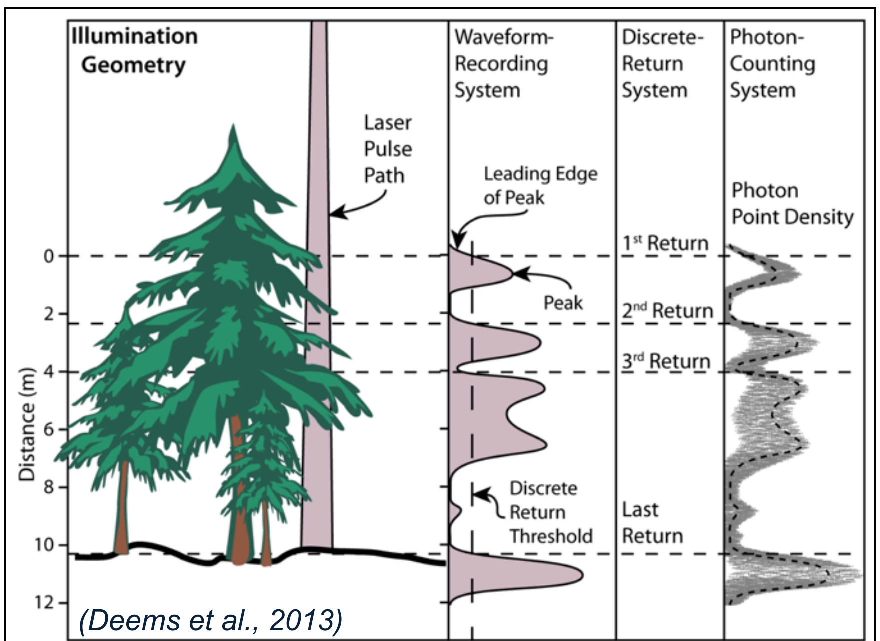




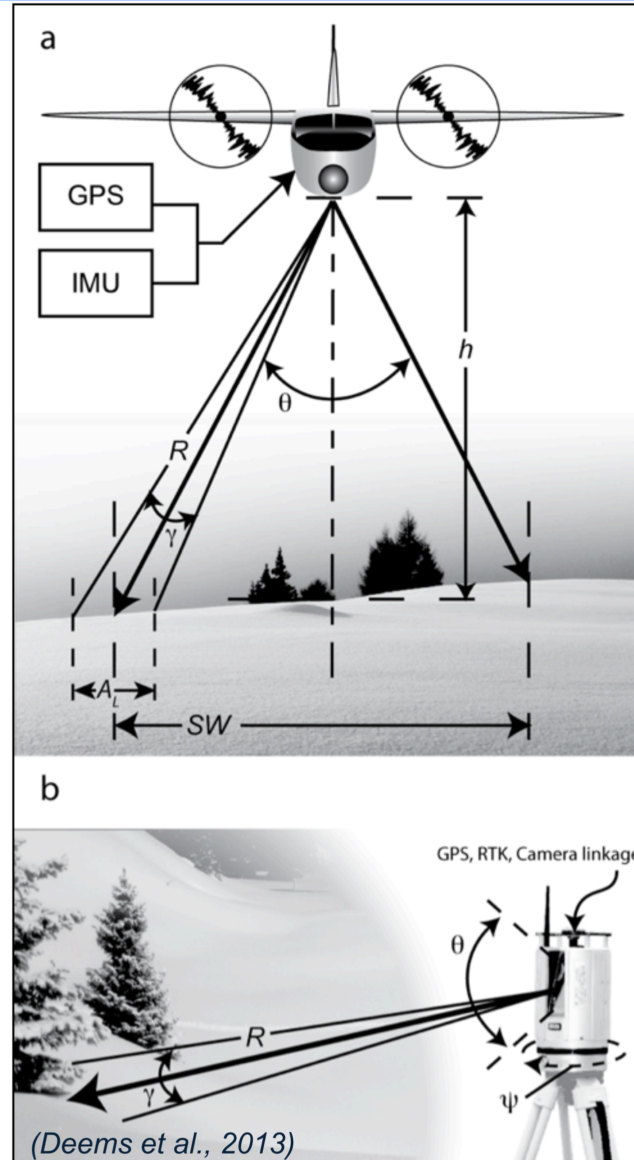
LIDAR surface elevation mapping



- 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)



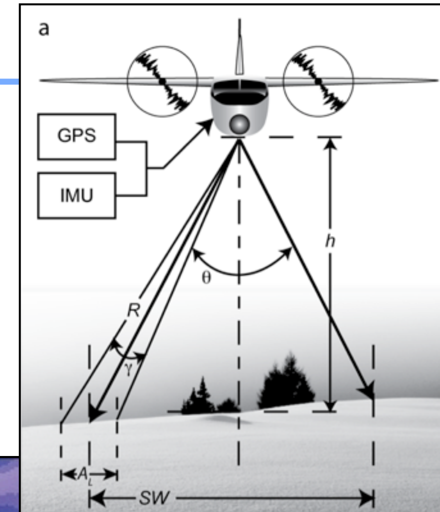
(Deems et al., 2013)

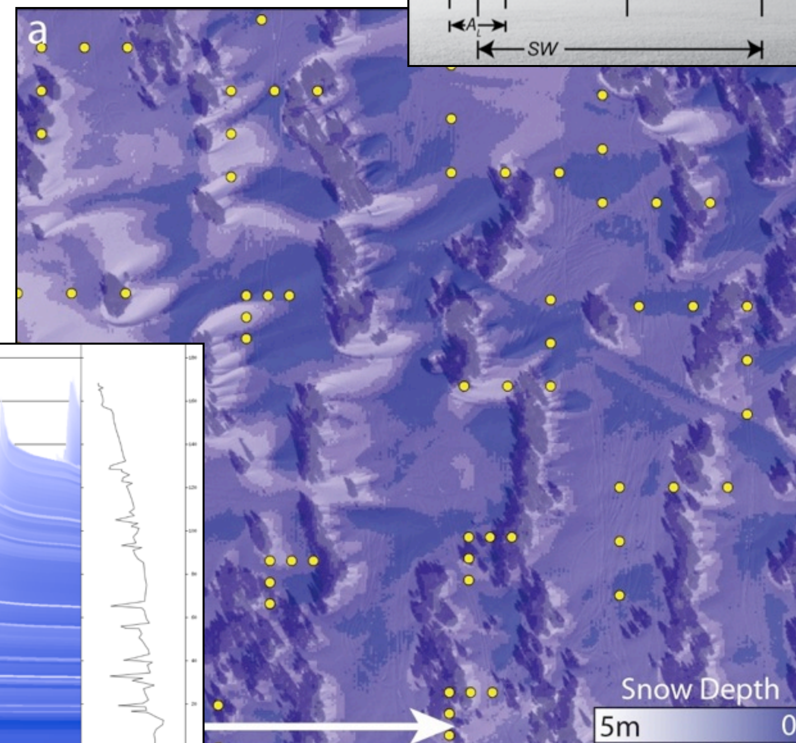
beam spread allows sub-canopy mapping in forests

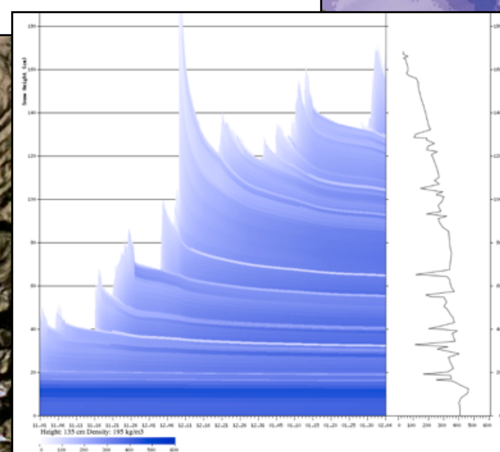
Western Water Assessment   CIRES   University of Colorado Boulder

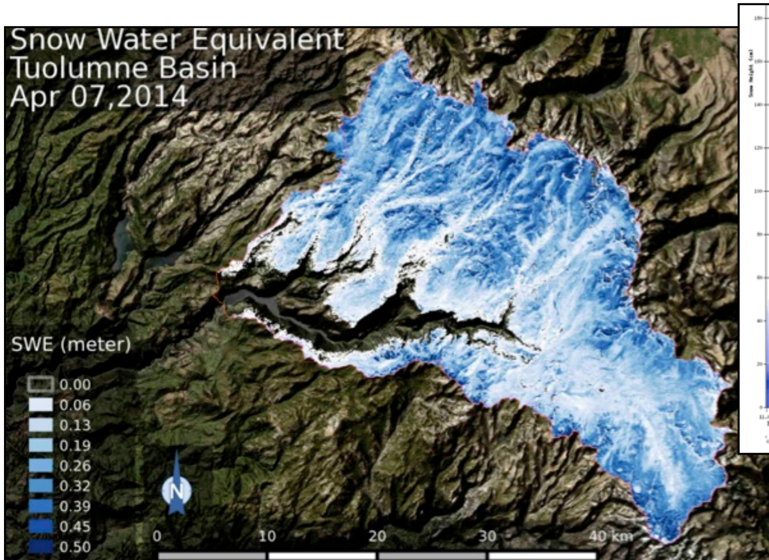
Snow depth & SWE from LiDAR

- 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

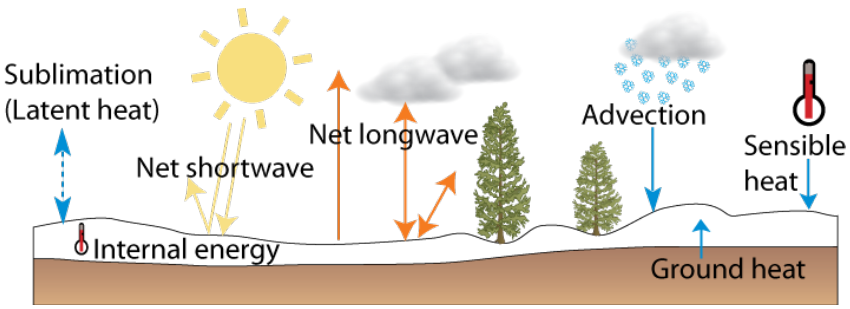








Integrating spatial snow products with snowmelt & runoff simulations



Temperature index runoff model

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

Statistical water supply forecast

- e.g. NRCS
- *$Q = f(SWE)$*
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Physically-based hydrology model

- e.g. PRMS

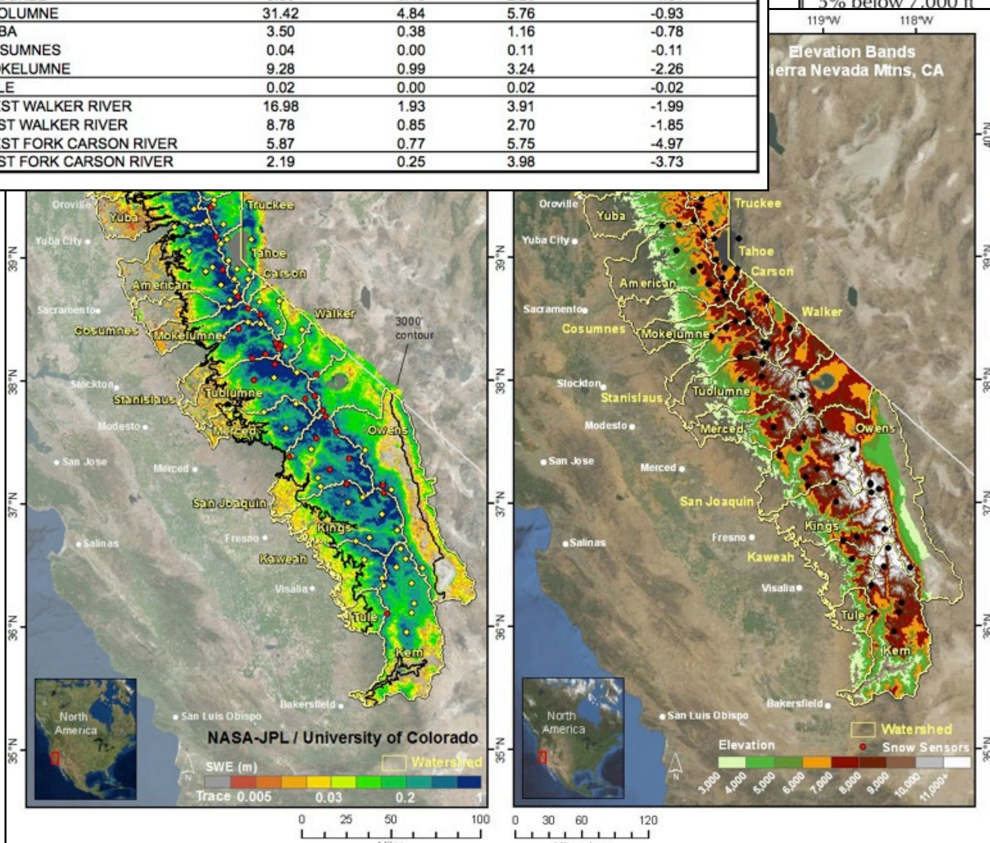
$$Q_m + \frac{dU}{dT} = (1 - \alpha)S + L^* + Q_s + Q_v + Q_g$$

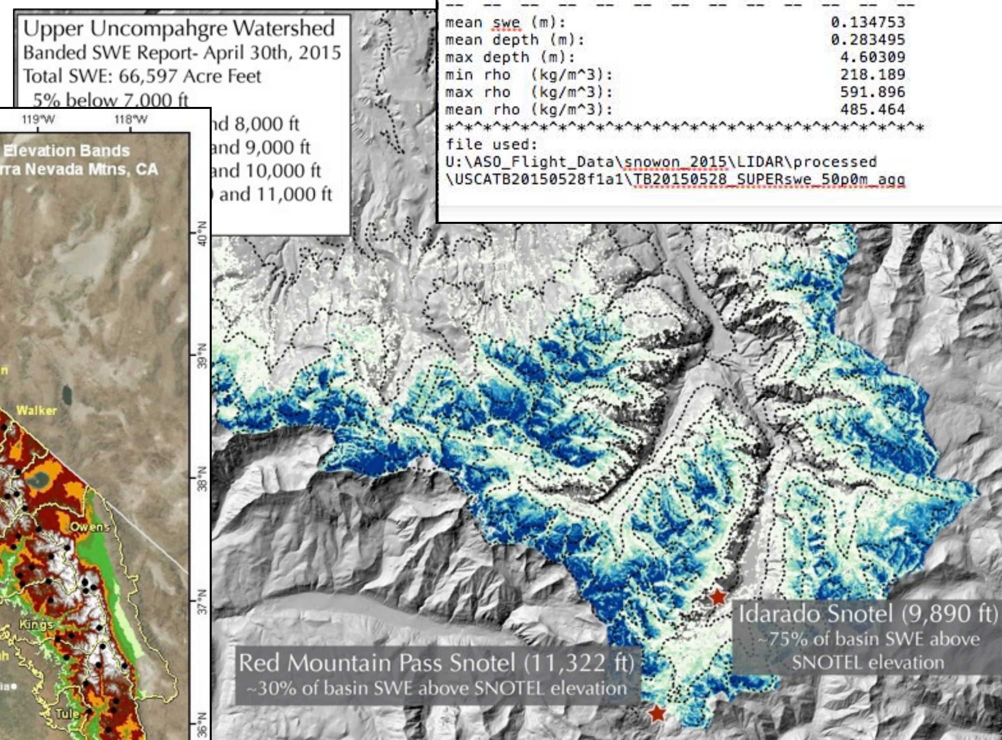
- Common research tool

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:
U:\ASO_Flight_Data\snowon_2015\LIDAR\processed
\USCATB20150528f1a1\TB20150528_SUPERswe_50p0m_agg
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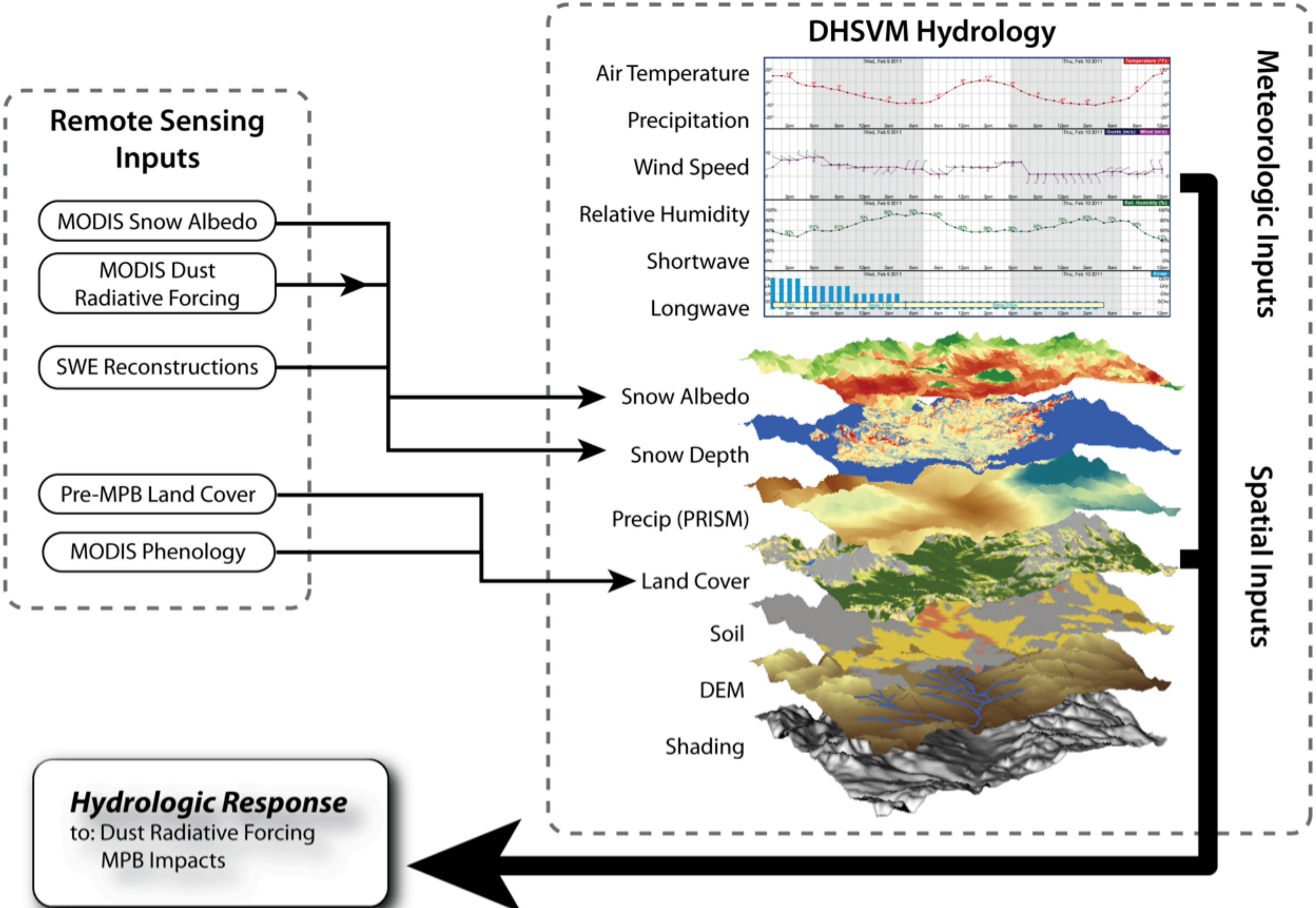
Integration of spatial snow products & models:
Distributed energy balance models



Spatial products discussed today

JPL MODIS/MODSCAG products

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

MODIS-modeled SWE estimates

- Range/regional-scale retrospective & real-time

Airborne Snow Observatory snow depth, SWE, albedo

- Watershed-scale near-real time airborne measurements