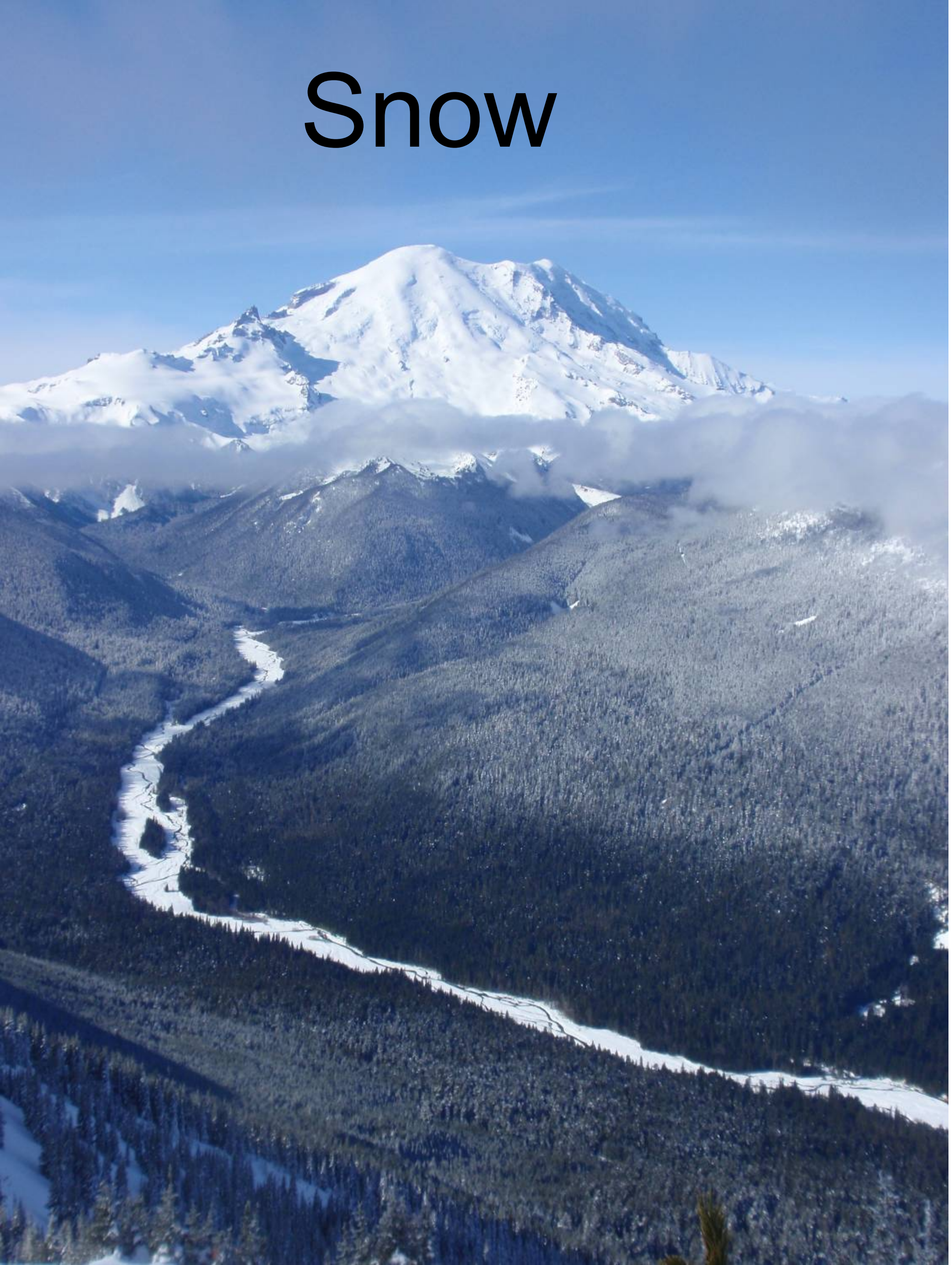
Hydromet Forcings for Snow

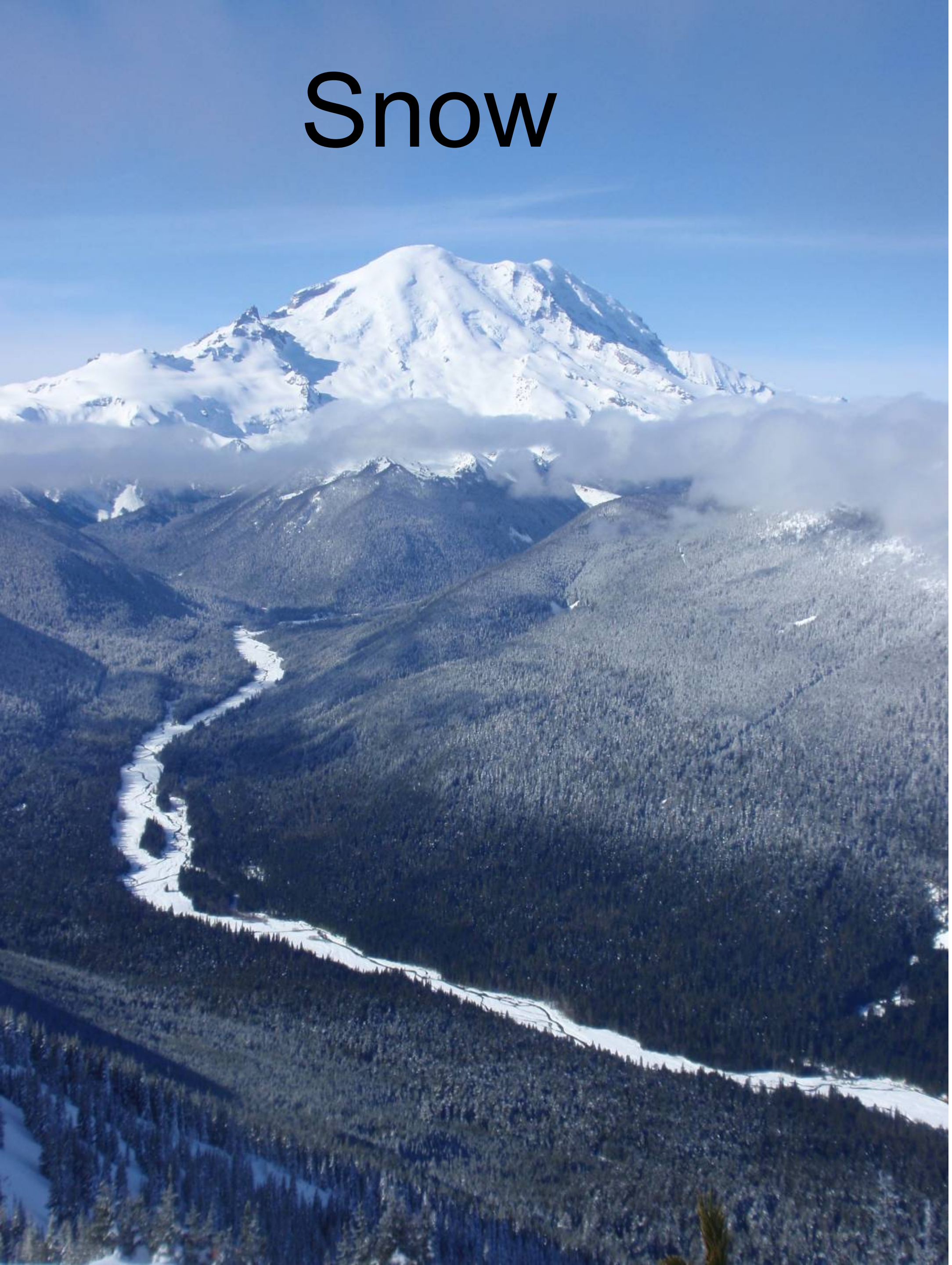
Jessica Lundquist

Civil and Env. Eng.
University of
Washington

Snow



- Major source of water storage and supply in the west (50-80% of annual runoff)
- Most threatened by climate change
- Three part problem:
  - 1) QPE
  - 2) Rain vs. Snow
  - 3) Melt



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- Three part problem:
  - 1) QPE
  - 2) Rain vs. Snow
  - 3) Melt

Energy for Melt:

- Two approaches
  - Temperature-Index

$$Melt = M_f \cdot (T_i - MBASE)$$

  - Full Energy Balance

$$Melt = (1-\alpha)Q_S + Q_L - \varepsilon\sigma T_S^4 + Q_E + Q_H + Q_R + Q_G - \frac{dU}{dt}$$

Temperature-Index Model

Example: Snow-17, Anderson 1976

$$Melt = M_f \cdot (T_i - MBASE)$$

Based on air-temperature

above a threshold, 0°C

Seasonally-varying melt factor accounts for radiation

- Used operationally
- Hard to beat (Franz et al. 2008)
- Parameters must be calibrated – hard to transfer between sites (He et al. 2011)

Full Energy Balance Model

Radiation Terms = about 80% of the energy for melt (Marks and Dozier 1992)

$$Melt = (1-\alpha)Q_S + Q_L - \varepsilon\sigma T_S^4 + Q_E + Q_H + Q_R + Q_G - \frac{dU}{dt}$$

Turbulent Flux Terms = about 20% of the energy for melt (Marks and Dozier 1992)

Heat from rain and the ground (negligible)

Internal energy of snowpack (heat required to raise to isothermal 0°C)

For 5-yr horizon, focus on the big one: Radiation

Shortwave Radiation: Incoming - Reflected

$$Melt = (1-\alpha)Q_S + Q_L - \varepsilon\sigma T_S^4$$

albedo

Incoming Longwave

Outgoing Longwave: depends on snow surface temperature

For 5-yr horizon, focus on the big one: Radiation

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albedo

Incoming Longwave

Outgoing Longwave: depends on snow surface temperature

None of these are measured at a typical snow site.

Conditions good for snow are bad for observations.

- Harsh weather
- Power limitations
- Difficult access
- Infrequent maintenance

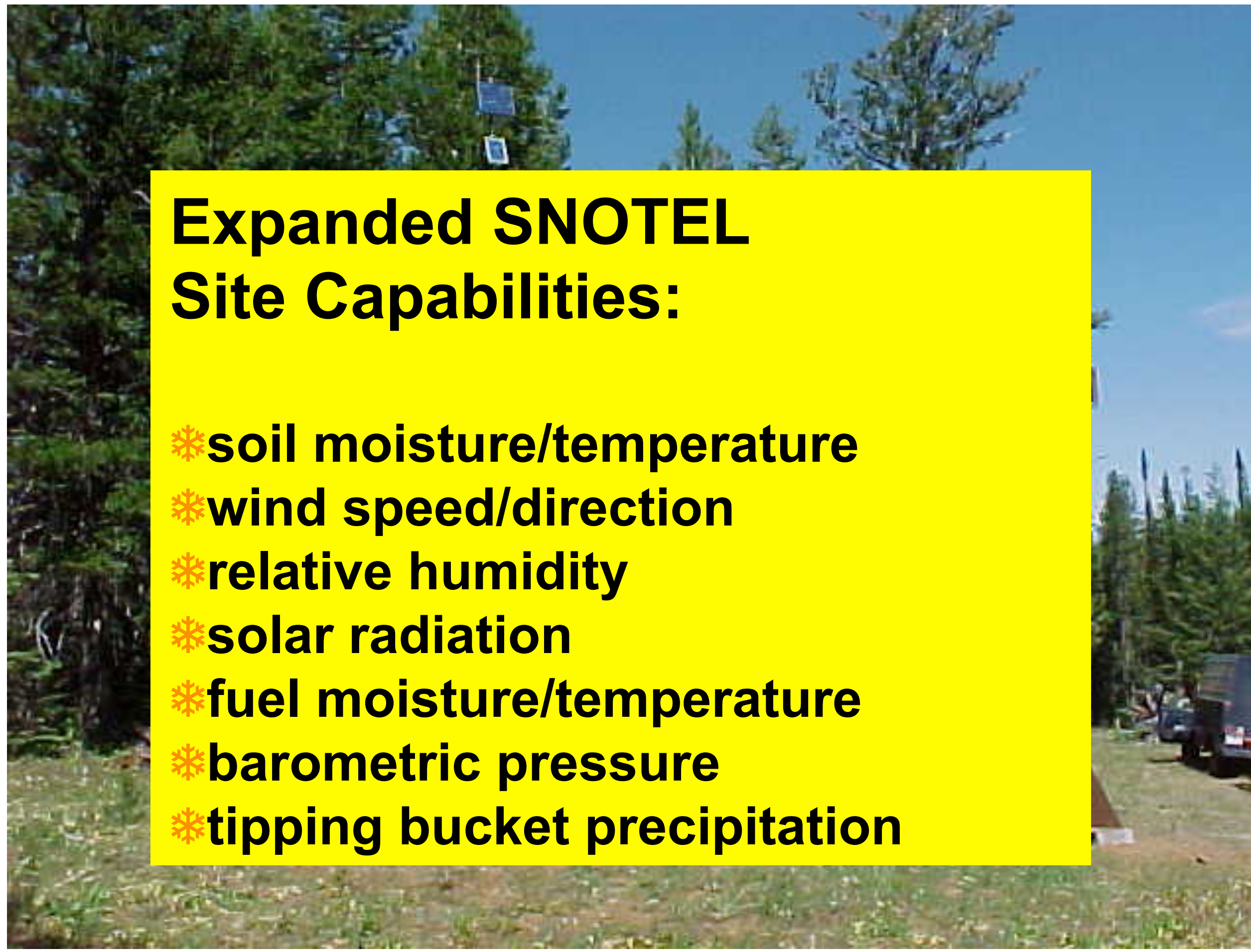
= Temporal and Spatial gaps (missing data must be estimated)

Onion Creek HMT station April 2011
(photo courtesy of Nic Wayand)

SNOTEL LAYOUT

Standard SNOTEL Site Components:

- snow pillow
- snow depth sensor
- precipitation gauge
- temperature sensor



Expanded SNOTEL Site Capabilities:

- **soil moisture/temperature**
- **wind speed/direction**
- **relative humidity**
- **solar radiation**
- **fuel moisture/temperature**
- **barometric pressure**
- **tipping bucket precipitation**

Slide courtesy of Scott Pattee, NRCS, Washington

NRCS Natural Resources Conservation Service

Even at enhanced snotel, only incoming shortwave is measured

Shortwave Radiation: Incoming - Reflected

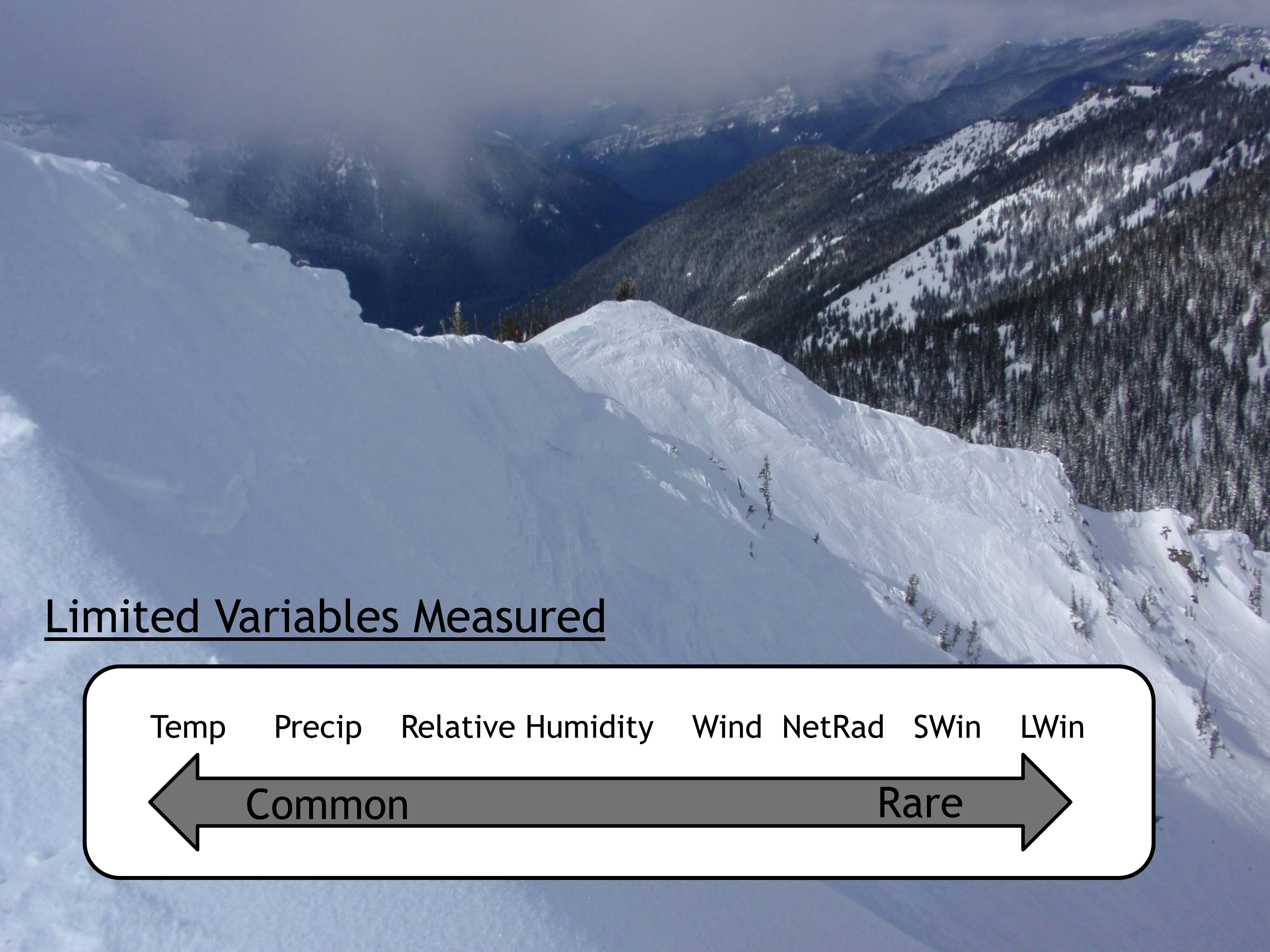
$$Melt = (1-\alpha)Q_S + Q_L - \varepsilon\sigma T_S^4$$

albedo

Incoming Longwave

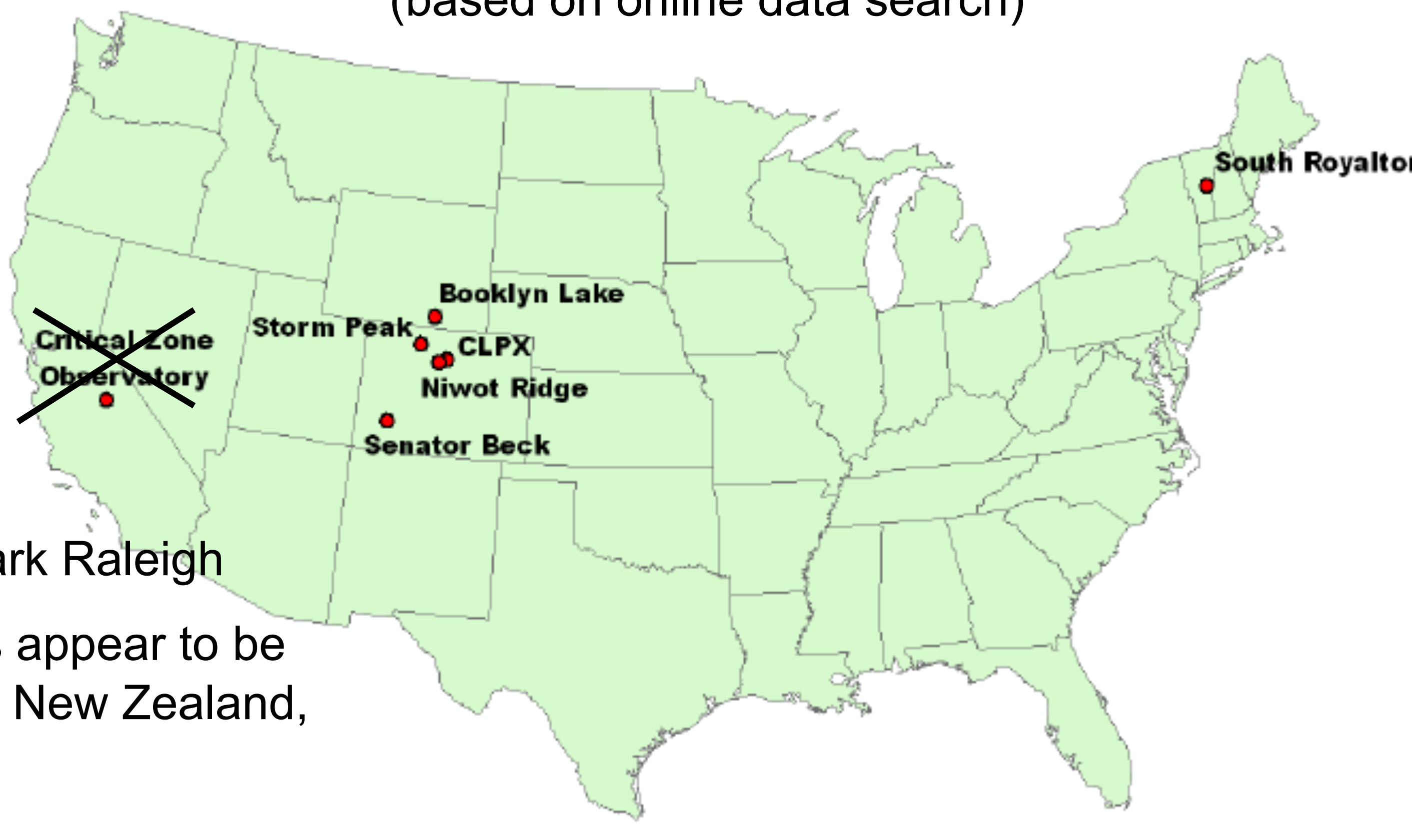
Outgoing Longwave: depends on snow surface temperature

Limited Variables Measured



Sites with co-located snow and LW radiation measurements of any duration

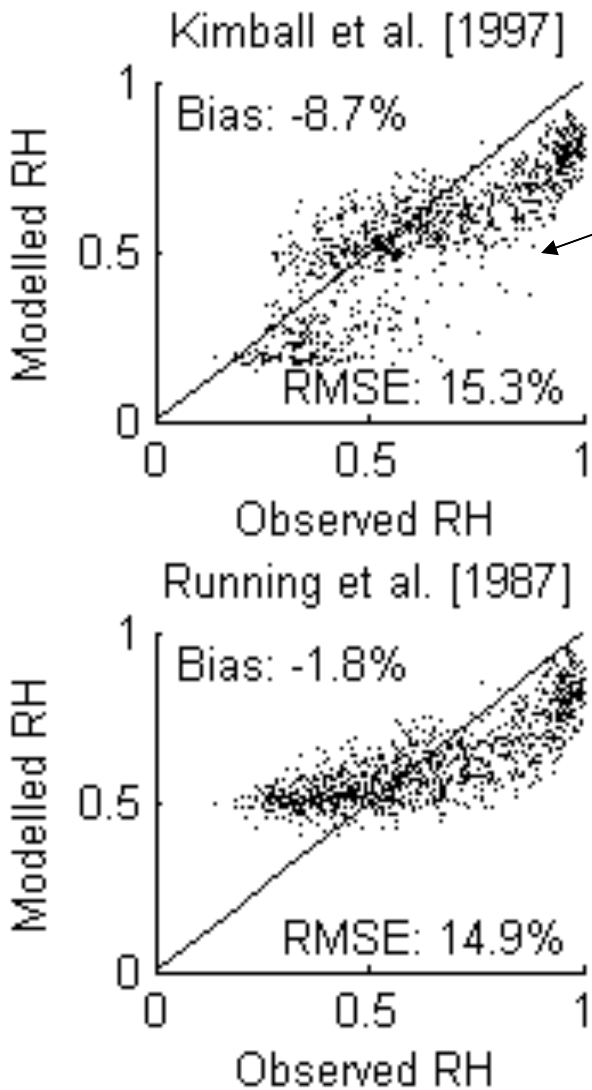
(based on online data search)



Slide courtesy of Mark Raleigh

Note: good datasets appear to be available in Norway, New Zealand, and Switzerland

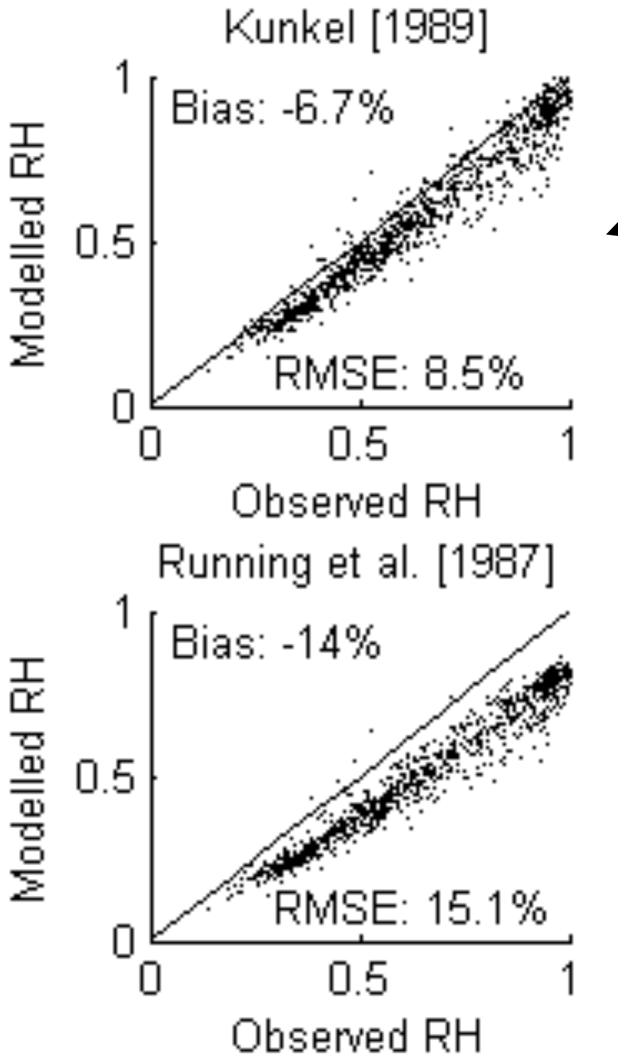
Estimation methods often not transferable from continental to maritime mountains: Testing Relative Humidity in California HMT



Estimating RH at a point, based on Tmin

Graphic courtesy of Shara Feld

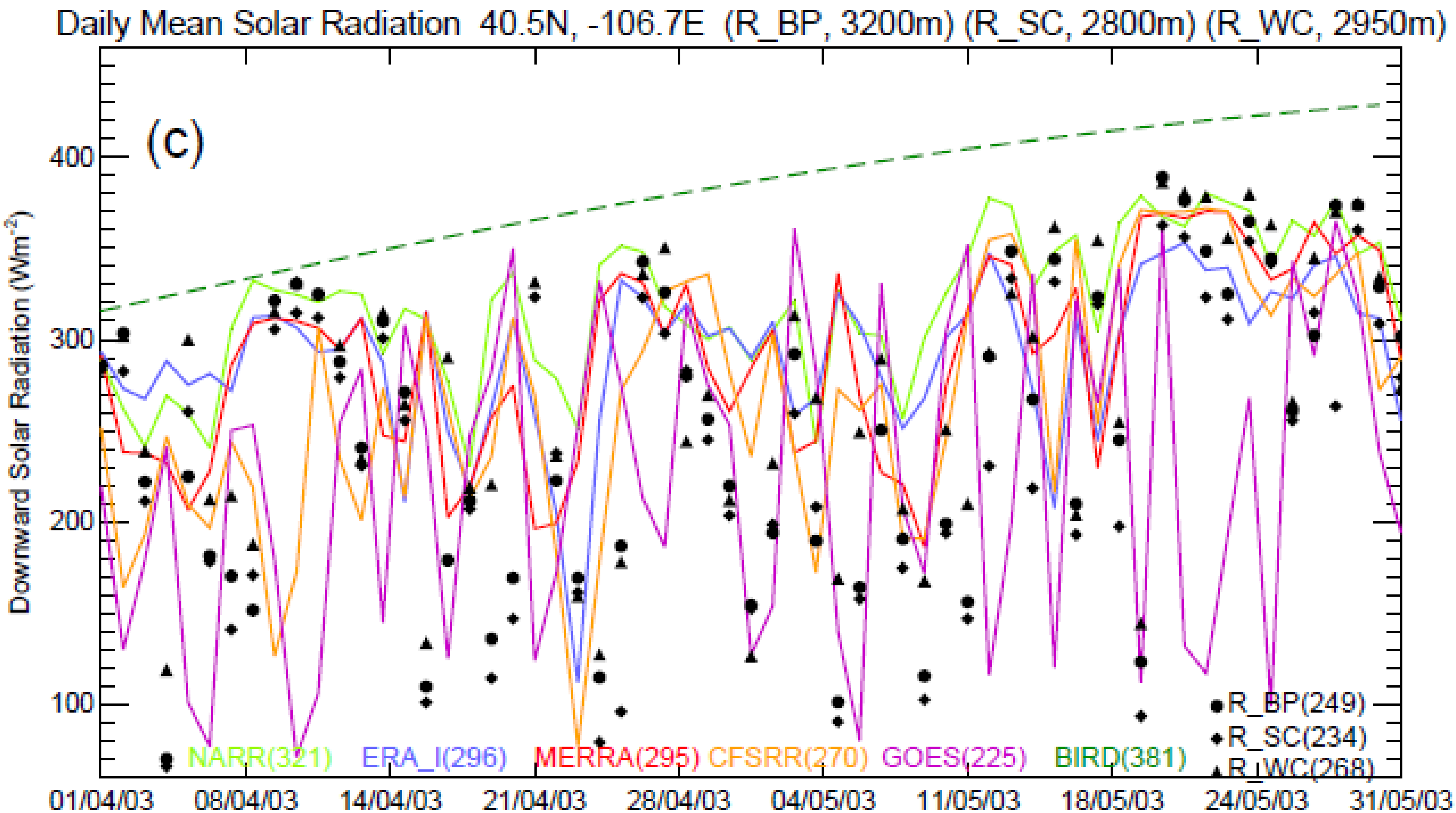
Estimation methods often not transferable from continental to maritime mountains: Testing Relative Humidity in California HMT



Estimating RH at another location, given one RH measurement in the basin

Graphic courtesy of Shara Feld

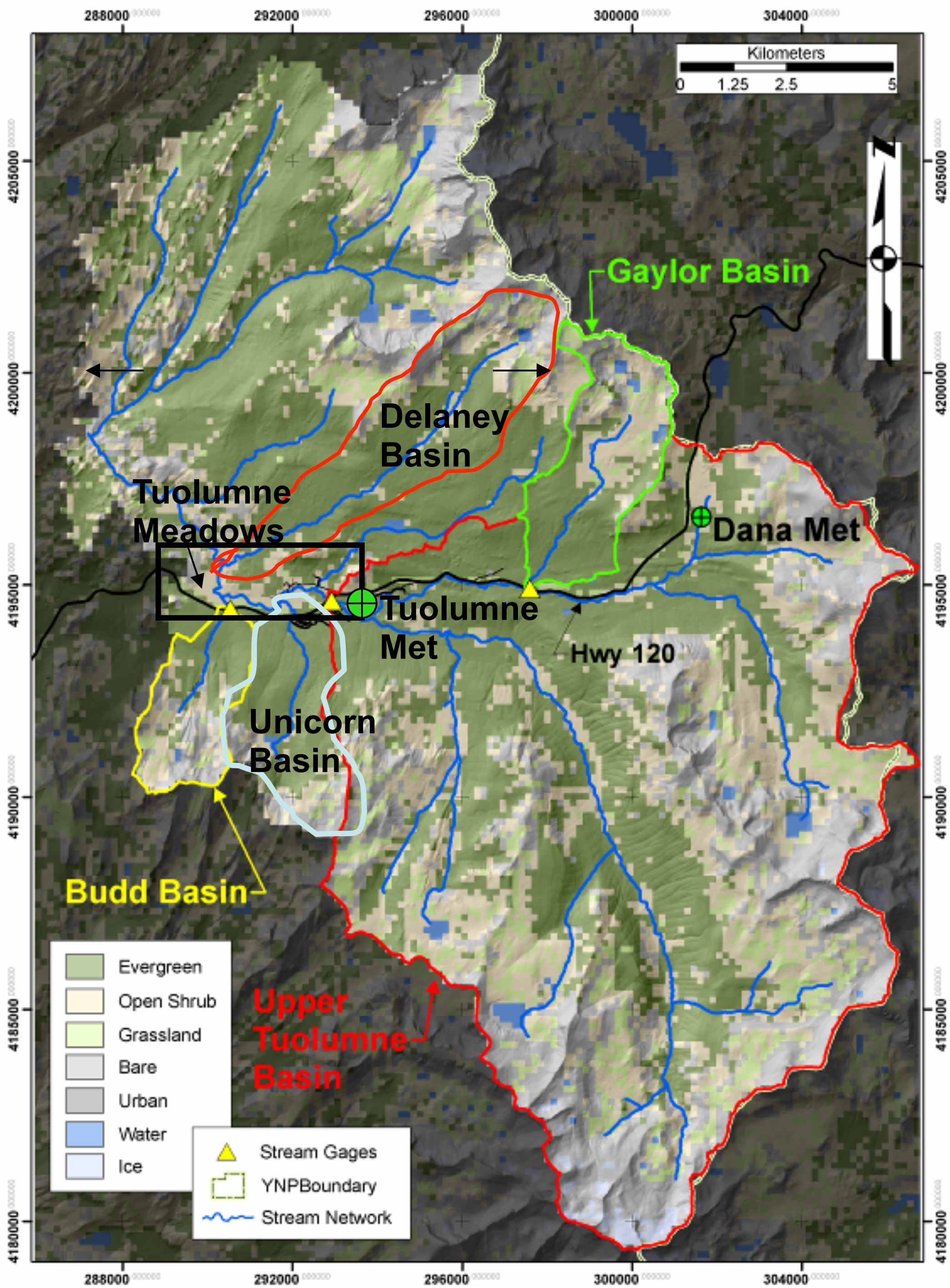
Satellite and Reanalysis Products: Promising but need more validation



Graphic courtesy of Drew Slater, showing various Reanalysis and Satellite products vs. surface measurements at Rabbit Ears during CLP-X

So do these issues really matter for streamflow?

- We have the computing power for physically-based, distributed models
- But do we have the observations to support them?



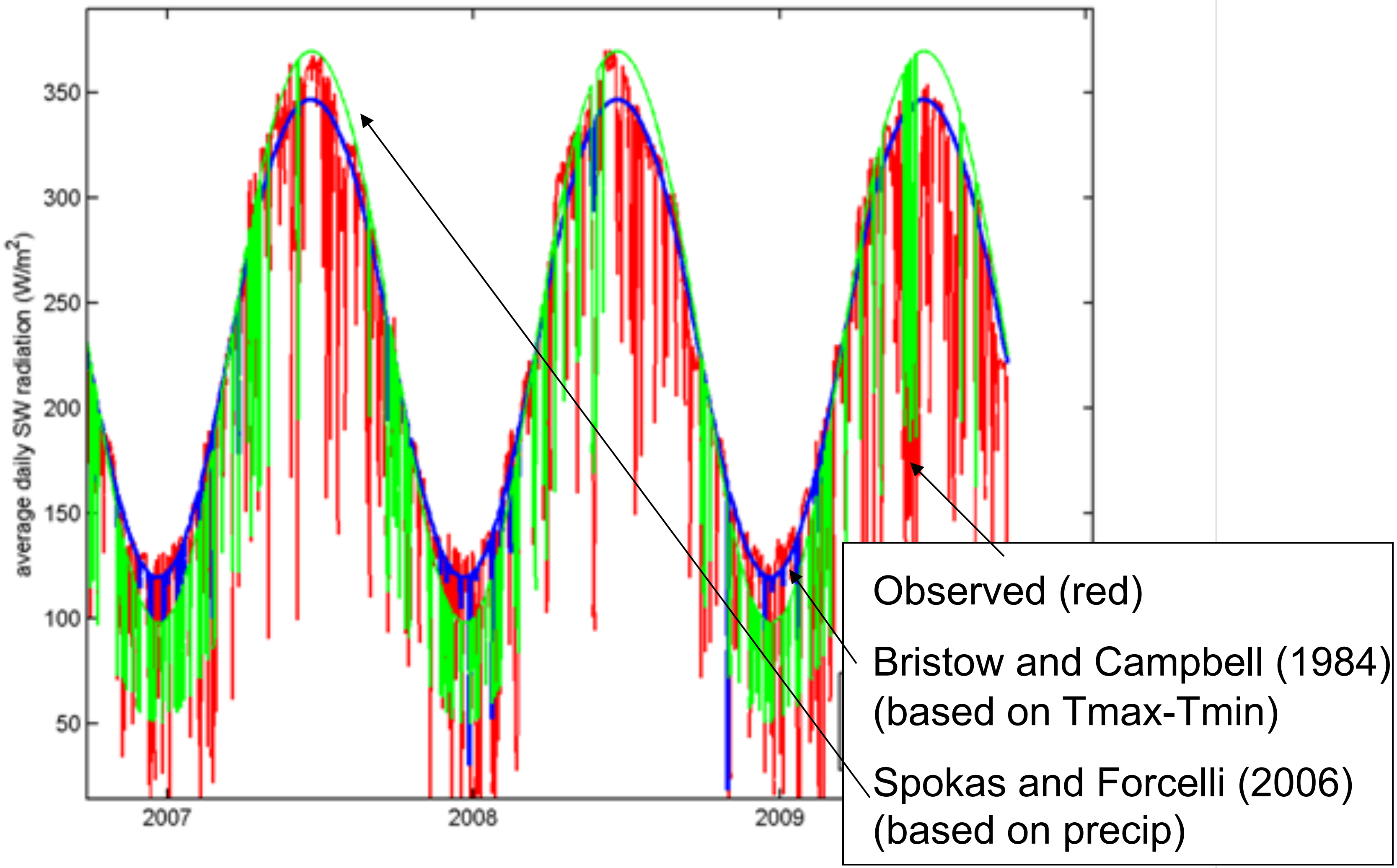
Example:

Modeling Tuolumne River in Yosemite, California with the Distributed Hydrology Soil Vegetation Model (DHSVM)

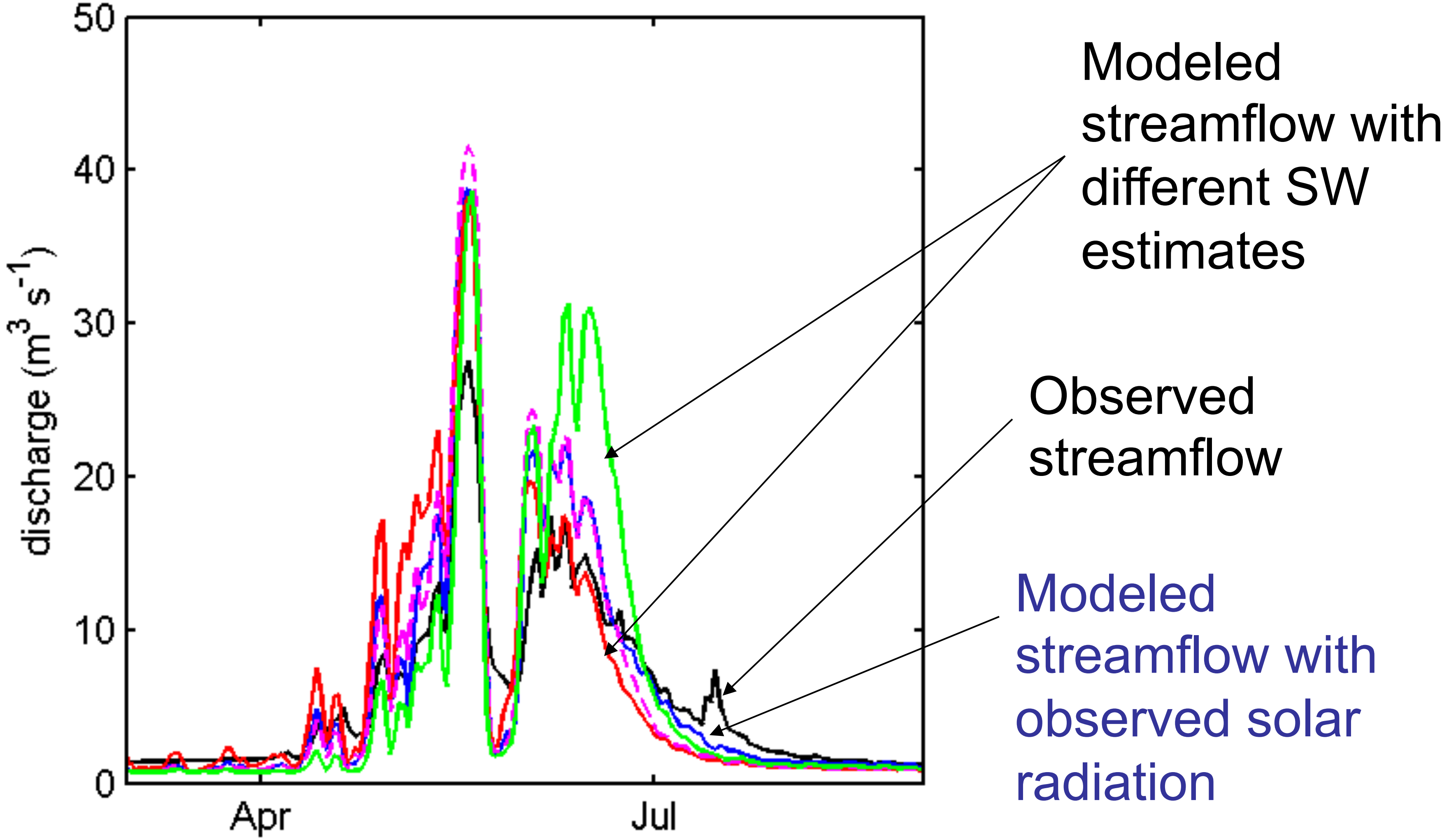
-High altitude, sunny Sierra, granite-lined

-Essentially all snow, little to no baseflow

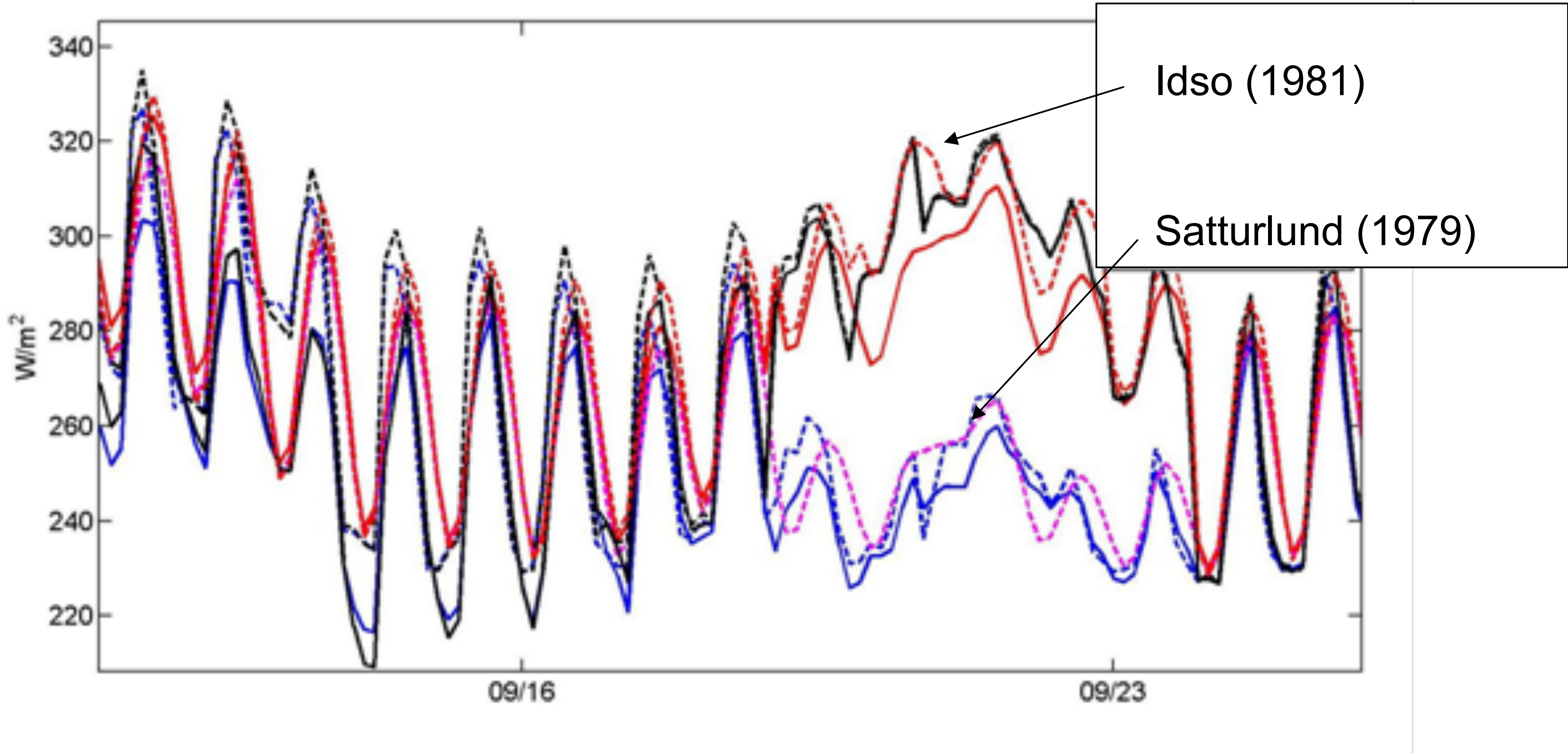
Daily average SW radiation: observed and 2 different estimates



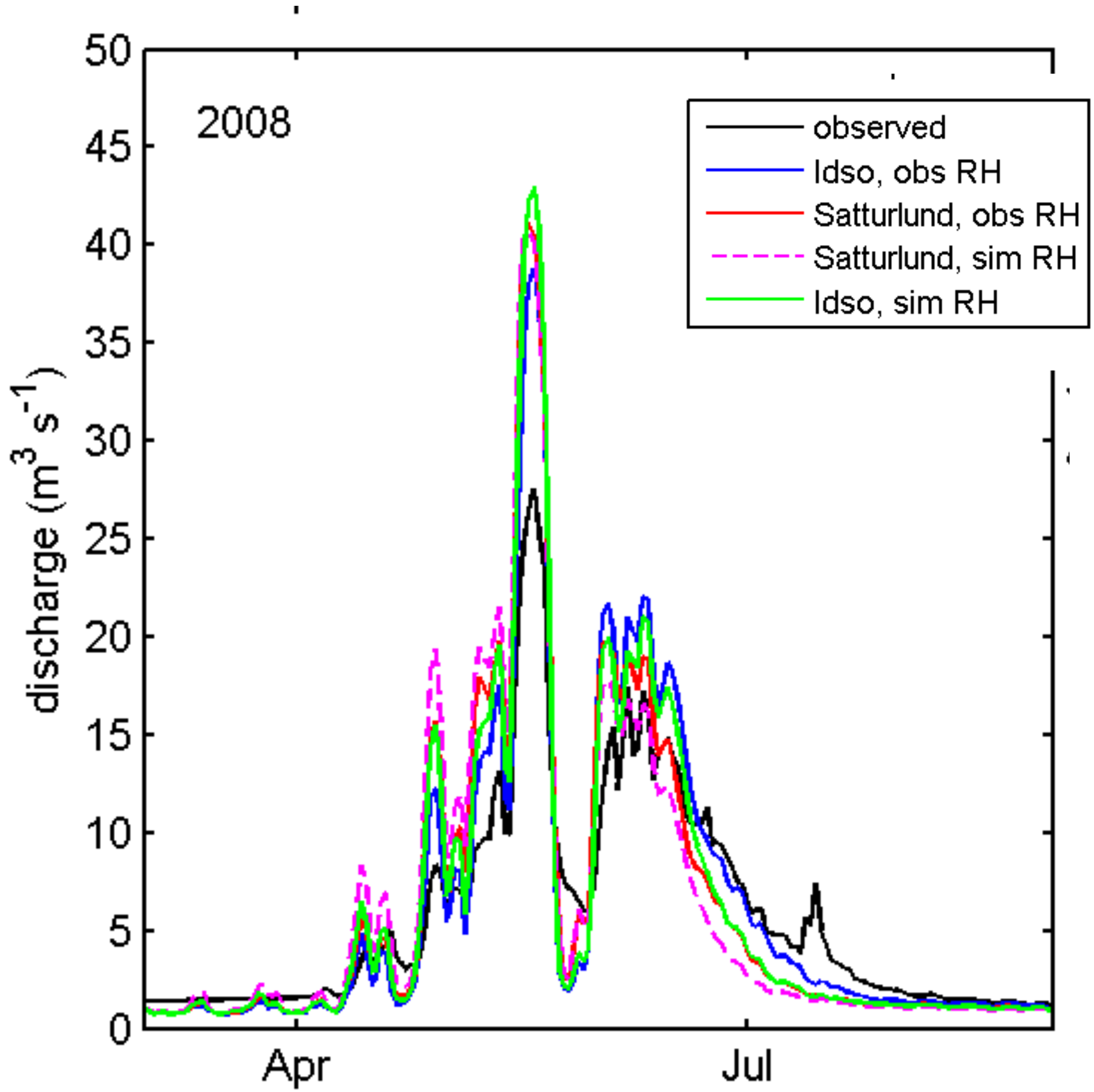
Modeled snowfed streamflow (particularly late season) is sensitive to how you parameterize solar radiation.



Incoming LW radiation not measured, estimated from humidity and diurnal T range



Solid lines are with observed RH; Dashed lines with estimated RH



Streamflow is sensitive to the LW algorithm chosen and to whether relative humidity is estimated or measured

Concluding Thoughts

- Most areas (especially higher elevations) dominated by radiation (SW + LW) – we need to measure and/or estimate this better
- Instruments will only be useful if properly maintained – not trivial
- We can equip Snotel with upward and downward pyranometers (SW & albedo) + infrared snow temperature (outgoing LW)
- Incoming longwave will require representative snow observatories with dedicated staffing (could only afford a few, so need remote sensing and/or estimation techniques that work)

Table 1. Algorithms for Estimating Clear-Sky Emissivity Following the Form of the Stefan-Boltzmann Equation or for Estimating Downwelling Long-wave Radiation Directly[a]

Source	Clear-Sky Algorithm
Ångström [1918][b]	$\varepsilon_{clr} = \left(0.83 - 0.18 \times 10^{-0.067 e_o}\right)$
Brunt [1932][b]	$\varepsilon_{clr} = \left(0.52 + 0.205\sqrt{e_o}\right)$
Brutsaert [1975]	$\varepsilon_{clr} = 1.723\left(\frac{e_o}{T_o}\right)^{1/7}$
Garratt [1992]	$\varepsilon_{clr} = 0.79 - 0.17\exp(-0.96 e_o)$
Idso and Jackson [1969]; referred to as Idso-1	$\varepsilon_{clr} = 1 - 0.261\exp\left(-0.00077(T_o - 273.16)^2\right)$
Idso [1981]; referred to as Idso-2	$\varepsilon_{clr} = 0.7 + 5.95 \times 10^{-4} e_o \exp\left(\frac{1500}{T_o}\right)$
Iziomon et al. [2003][d]	$\varepsilon_{clr} = 1 - X\exp\left(\frac{-Y e_o}{T_o}\right)$
Keding [1989]	$\varepsilon_{clr} = 0.92 - 0.7 \times 10^{-1.2 e_o}$
Niemelä et al. [2001]	$\varepsilon_{clr} = \begin{cases} 0.72 + 0.09(e_o - 0.2) & for \quad e_o \geq 0.2 \\ 0.72 - 0.76(e_o - 0.2) & for \quad e_o < 0.2 \end{cases}$
Prata [1996][c]	$\varepsilon_{clr} = 1 - (1 + w)\exp\left(-(1.2 + 3w)^{1/2}\right)$
Satterlund [1979]	$\varepsilon_{clr} = 1.08\left[1 - \exp\left(-(10 e_o)^{T_o/2016}\right)\right]$
Swinbank [1963]	$L_{clr} = 5.31 \times 10^{-13} T_o^6$
Dilley and O'Brien [1998][c]	$L_{clr} = 59.38 + 113.7\left(\frac{T_o}{273.16}\right)^6 + 96.96\sqrt{w/25}$

[a]Coefficients are based on vapor pressure (e_o) in kilopascals, temperature (T_o) in kelvins, and precipitable water (w) in centimeters.
[b]As cited by *Niemelä et al.* [2001].
[c]$w = 4650 e_o / T_o$ [*Prata*, 1996].
[d]Values for X and Y in the algorithm of *Iziomon et al.* [2003] were interpolated between a lowland site at 212-m elevation (X = 0.35 and Y = 100 K kPa^{-1}) and a mountain site at 1489-m elevation (X = 0.43 and Y = 115 K kPa^{-1}).

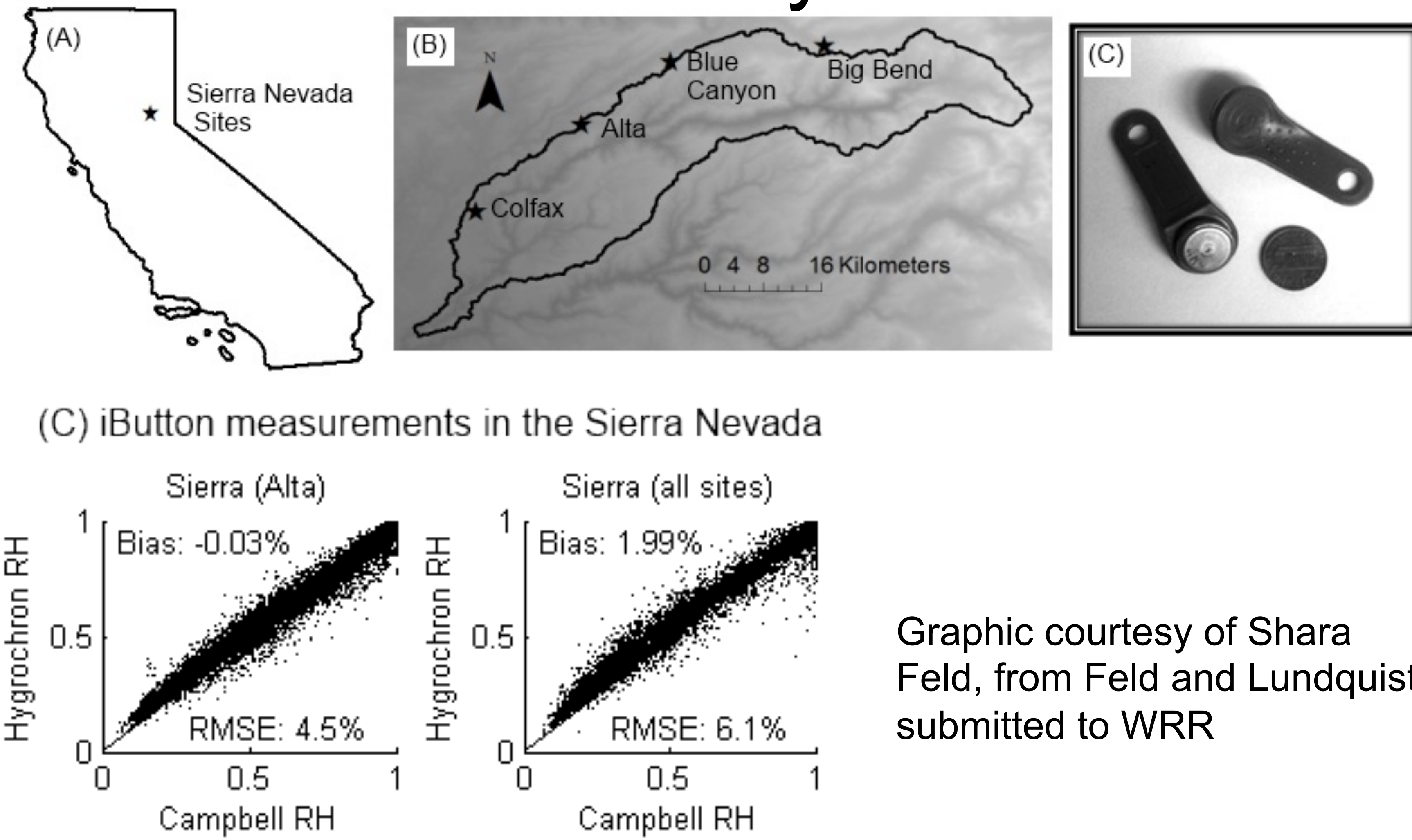
Used in several Land Surface Models (Idso [1981])

Used in Liston snowmodel (Iziomon et al. [2003])

Used in Vic, dhsvm and UEB (Satterlund [1979])

recommended (Dilley and O'Brien [1998])

But RH sensors are cheap and easy



Graphic courtesy of Shara Feld, from Feld and Lundquist, submitted to WRR

Extra Slides Follow

Map of Snotel Sites

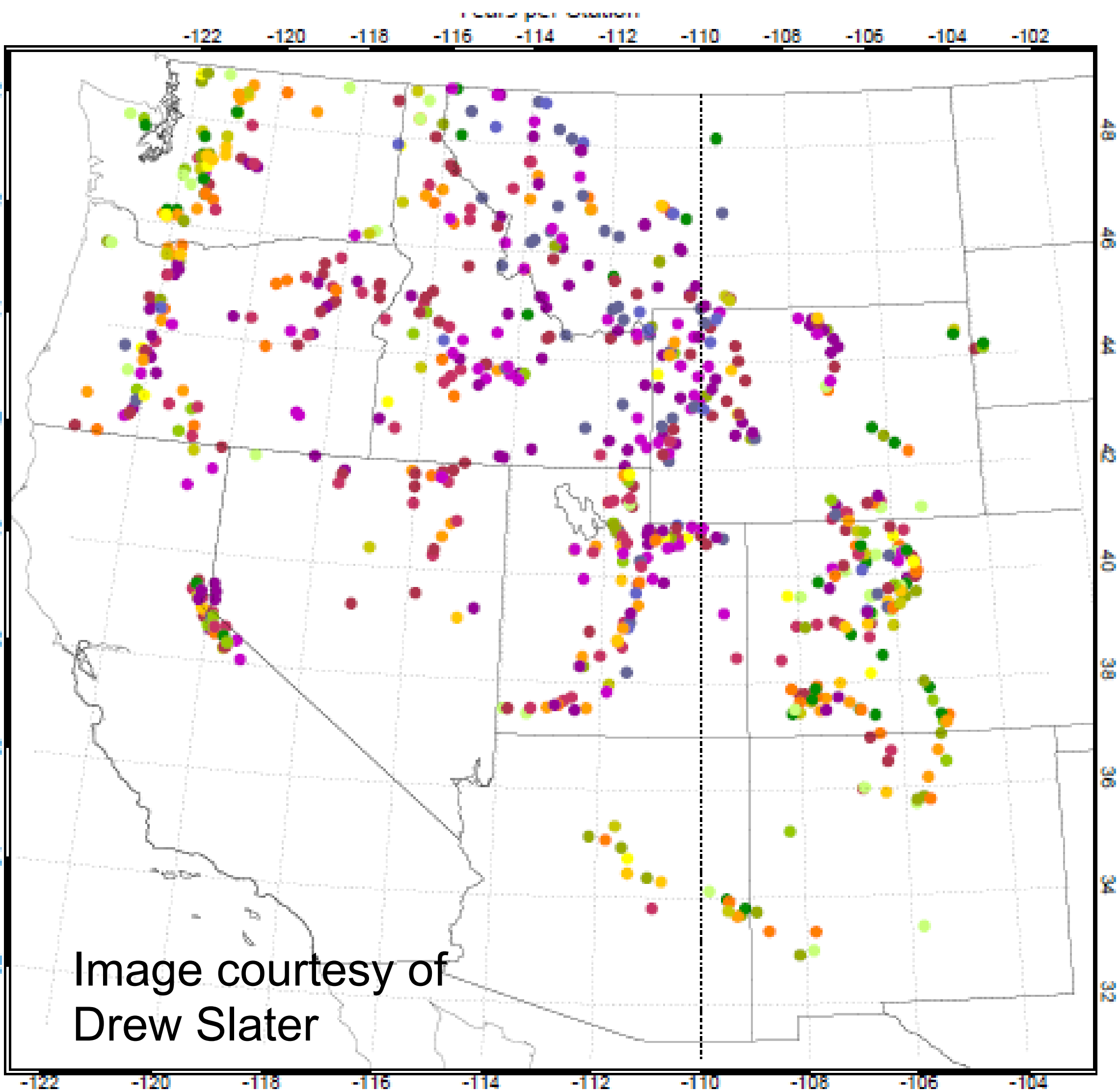
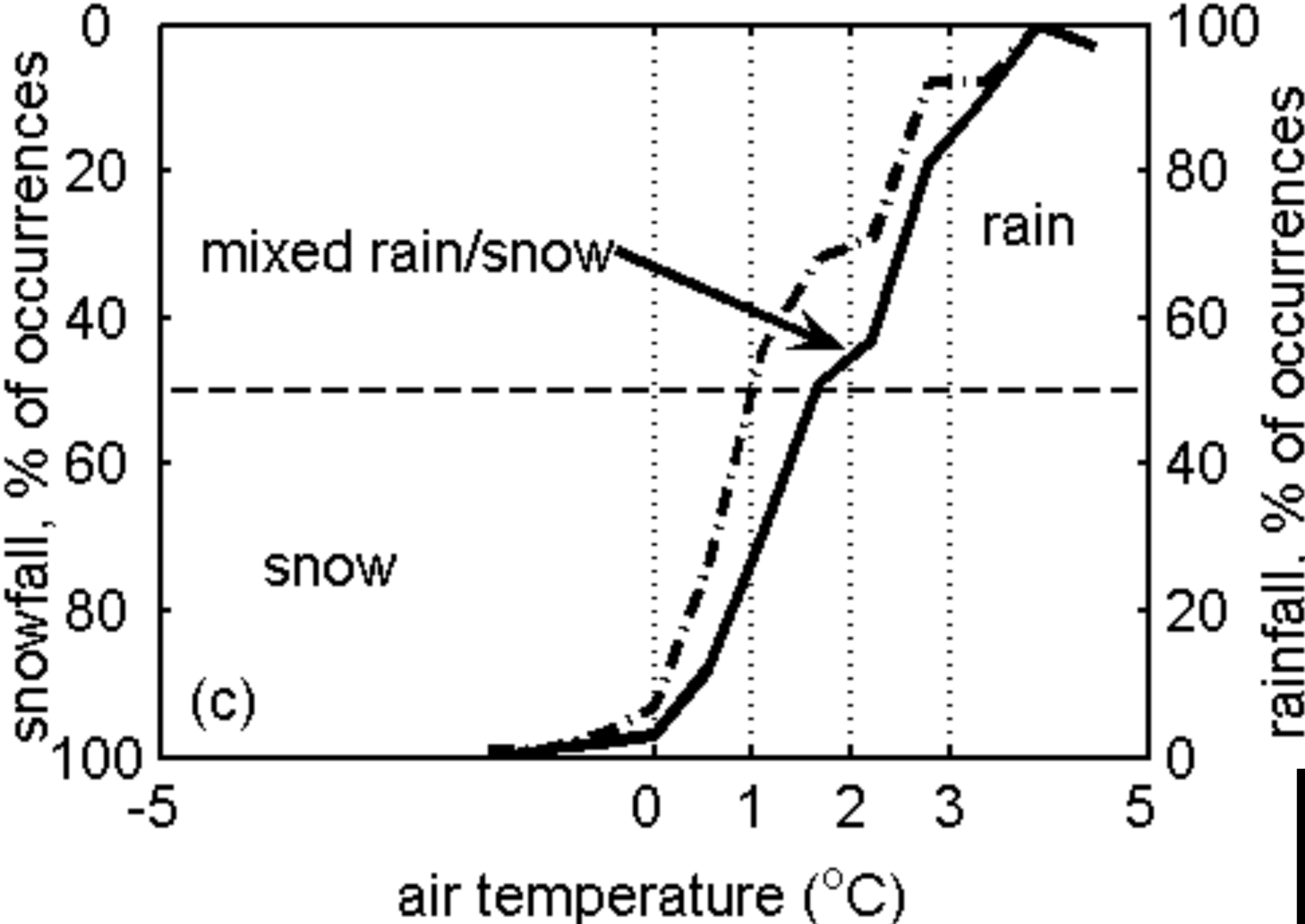


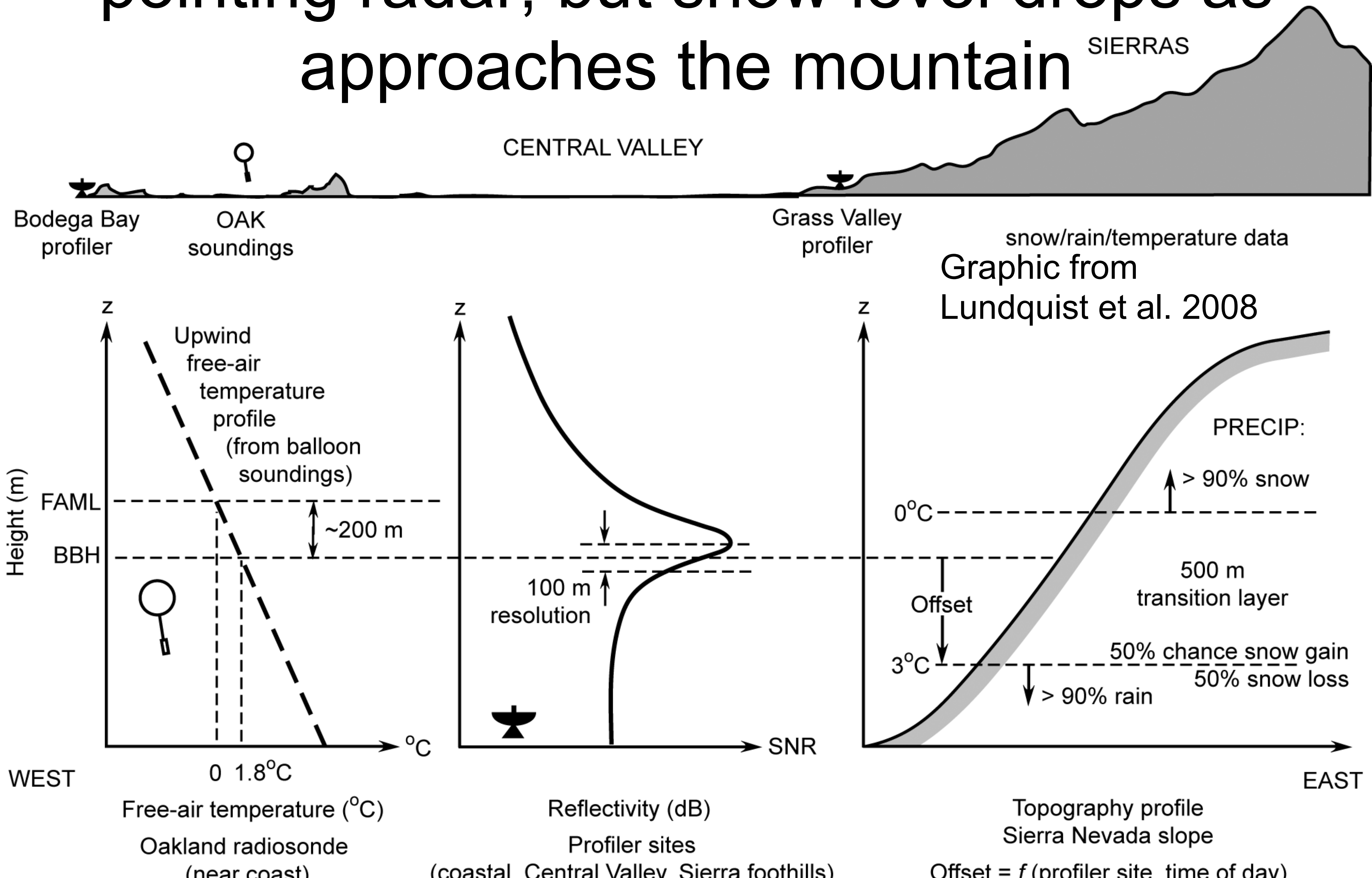
Image courtesy of
Drew Slater

First, determine whether rain, snow, or a wintry mix



Graphic from US Army Corps of Engineers in *Snow Hydrology*, 1956

Can get rain vs snow from vertically-pointing radar, but snow level drops as approaches the mountain



Graphic from Lundquist et al. 2008

Where does snow change to rain? Surface Validation Options:

- Human observers
- Laser disdrometer
- Co-located precip and snow depth + snow pillow to determine fate of precip on the surface
- Digital camera (web cam)

ICE & SNOW
TAKE IT SLOW

Path Forward: Partner with Transportation Agencies

Full Energy Balance Model

- Physically based, but when we estimate all the input, it has many more tunable parameters than the temperature index model

$$Melt = (1-\alpha)Q_S + Q_L - \varepsilon\sigma T_S^4 + Q_E + Q_H + Q_R + Q_G - \frac{dU}{dt}$$

How do we arrive at solar radiation in snow modeling?

1) **Use latitude, longitude, solar geometry to calculate potential radiation**
2) **Modify potential radiation for slope, aspect, shading by surrounding topography**
3) Determine some transmittance factor (or other scaling) to decrease potential radiation based on clouds/atmospheric moisture content
4) Further reduce solar radiation for areas under forest cover

These are pretty good.

How do we arrive at solar radiation in snow modeling?

1) Use latitude, longitude, solar geometry to calculate potential radiation
2) Modify potential radiation for slope, aspect, shading by surrounding topography
3) **Determine some transmittance factor (or other scaling) to decrease potential radiation based on clouds/atmospheric moisture content**
4) Further reduce solar radiation for areas under forest cover

This is generally a big guess.
Based on Tmax-Tmin and/or Precip

Commonly used formulas

Bristow and Cambell, 1984

$$R_s = R_a[A[1 - \exp(-B(\Delta T)^C)]$$

Hargreaves and Samami, 1985

$$R_s = R_a(k_R)\sqrt{(T_{max} - T_{min})}$$

R_a is potential radiation (from geometry)

A, B, C, and k_R are empirical coefficients.

Both are based on the diurnal temperature range.

Alternate method is to look at precipitation records to determine transmissivity

TABLE 1. Decision matrix used to assign value for atmospheric transmitivity (τ).

Conditions	Value of τ
No precipitation at $\Delta T > 10C$ (assumed clear sky conditions)	$\tau = 0.70$
No precipitation today, but precipitation fell the previous day	$\tau = 0.60$
Precipitation occurring on present day	$\tau = 0.40$
Precipitation today and also the previous day	$\tau = 0.30$

[a] ΔT is defined as ($Tair_{max} - Tair_{min}$).

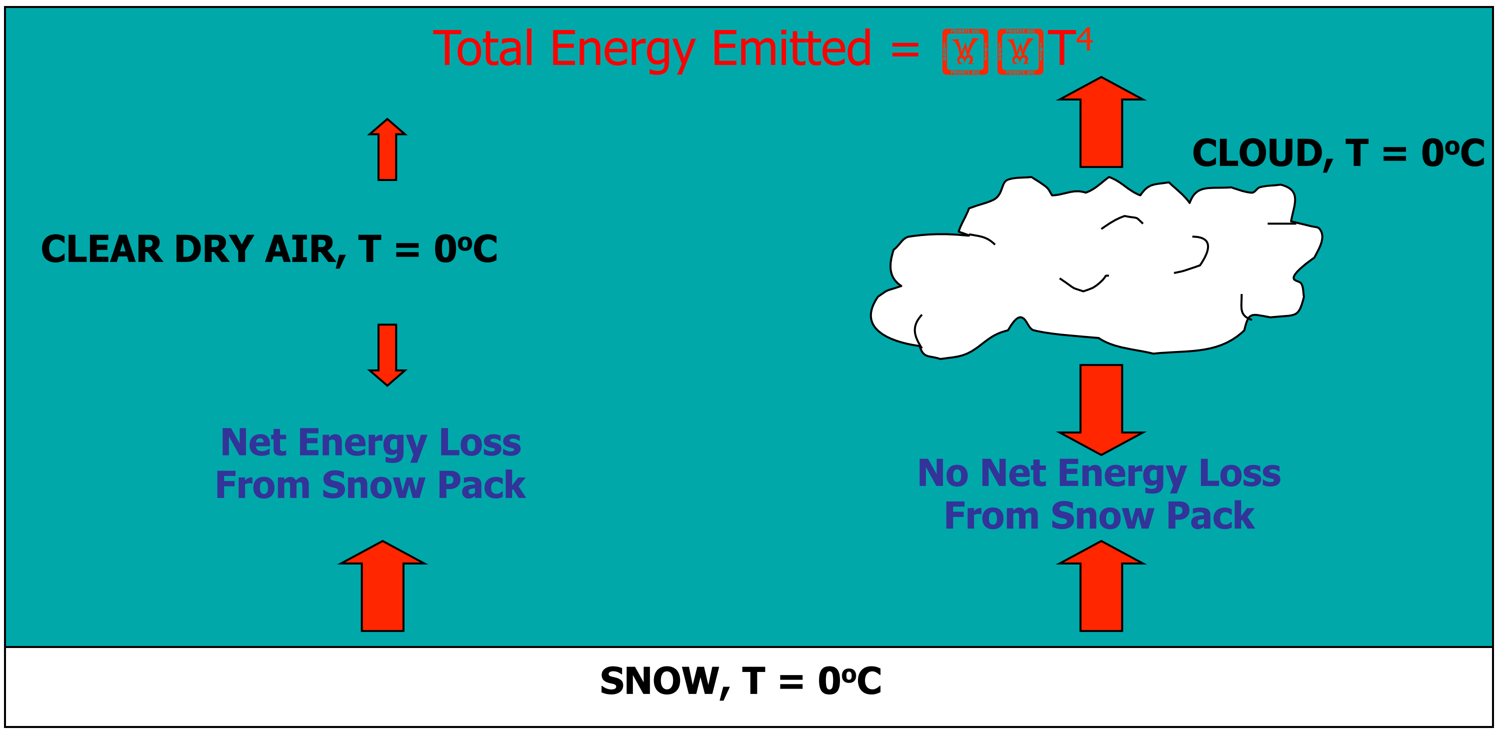
Spokas and Forcella 2006, *Weed Science*

How do we arrive at longwave radiation in snow modeling?

1) Estimate the emissivity of the atmosphere. (Function of Tmax-Tmin and Relative Humidity)
2) Estimate the effective temperature of the atmosphere. (May adjust for clouds)
3) Use the Stefan-Boltzman equation.
4) Can also add in longwave emitted from surrounding terrain
5) Further modify longwave for areas under forest cover

Snow Energy Exchanges

- Atmospheric (Longwave) Radiation

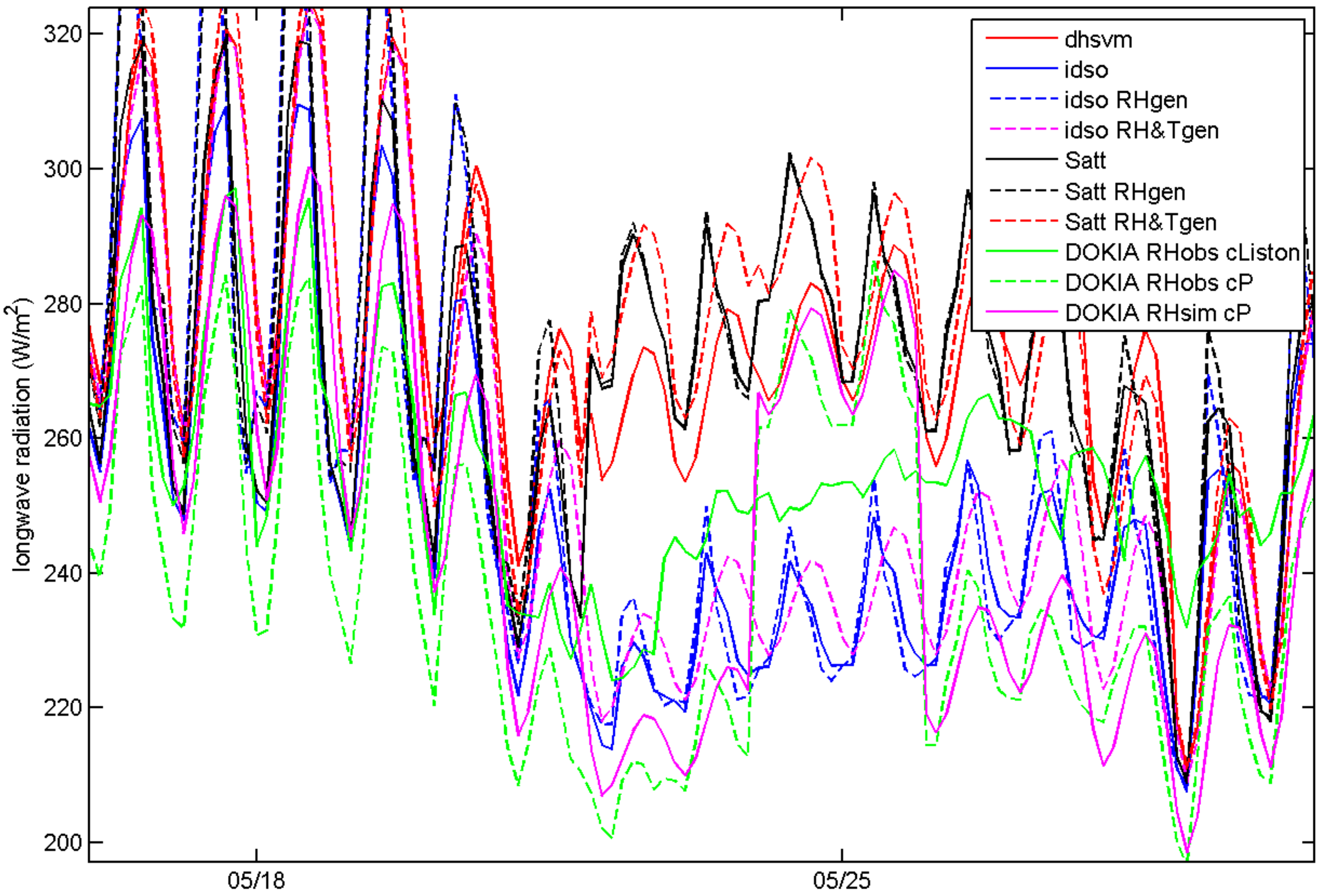


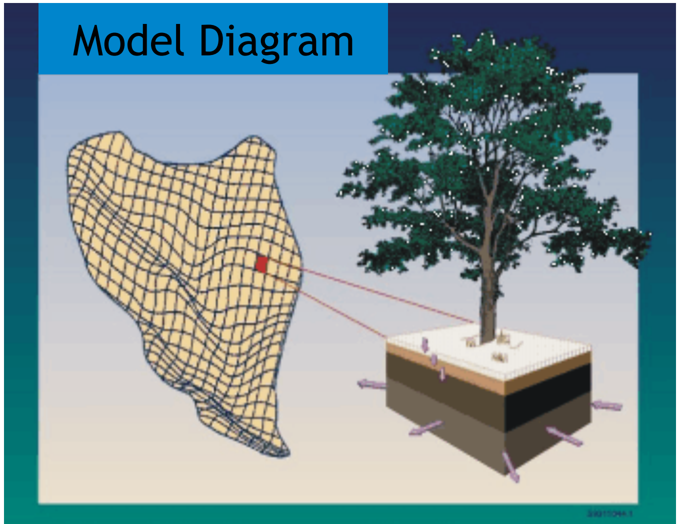
Emissivity

Air	**0.60 - 0.70**
Water, Ice, Snow	**0.92 - 0.97**

Slide from
Danny Marks

Choice of scheme, source of RH, and cloud parameterization all matter



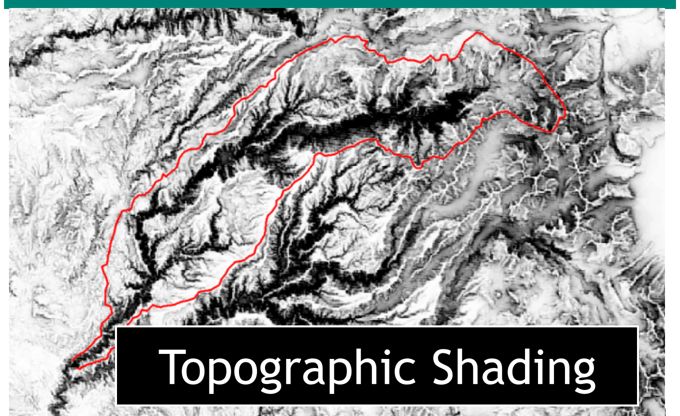


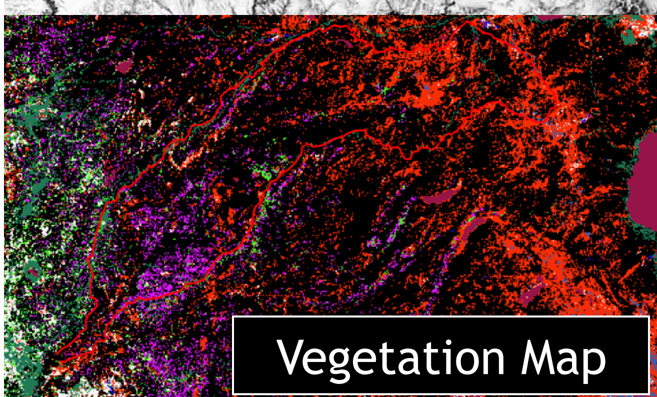
DHSVM

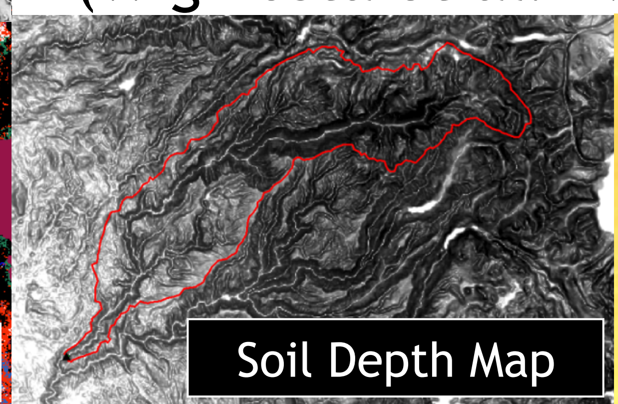
• Distributed model at 150m resolution. (39,348 grid cells in North Fork Basin)

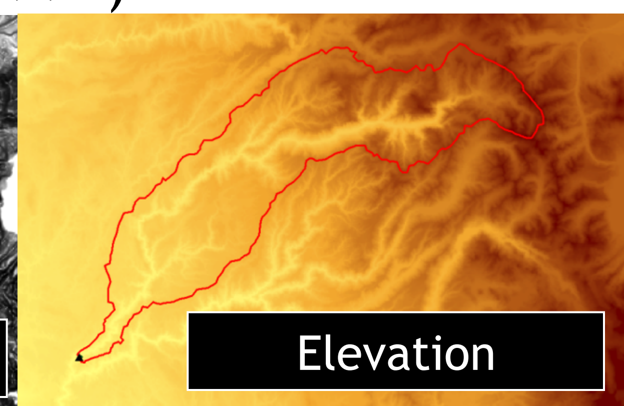
• Simulates vertical and horizontal fluxes of water through vegetation, snow and soil.

• Used extensively for Land use change and Climate change research. (Wigmosta et al. 1994)



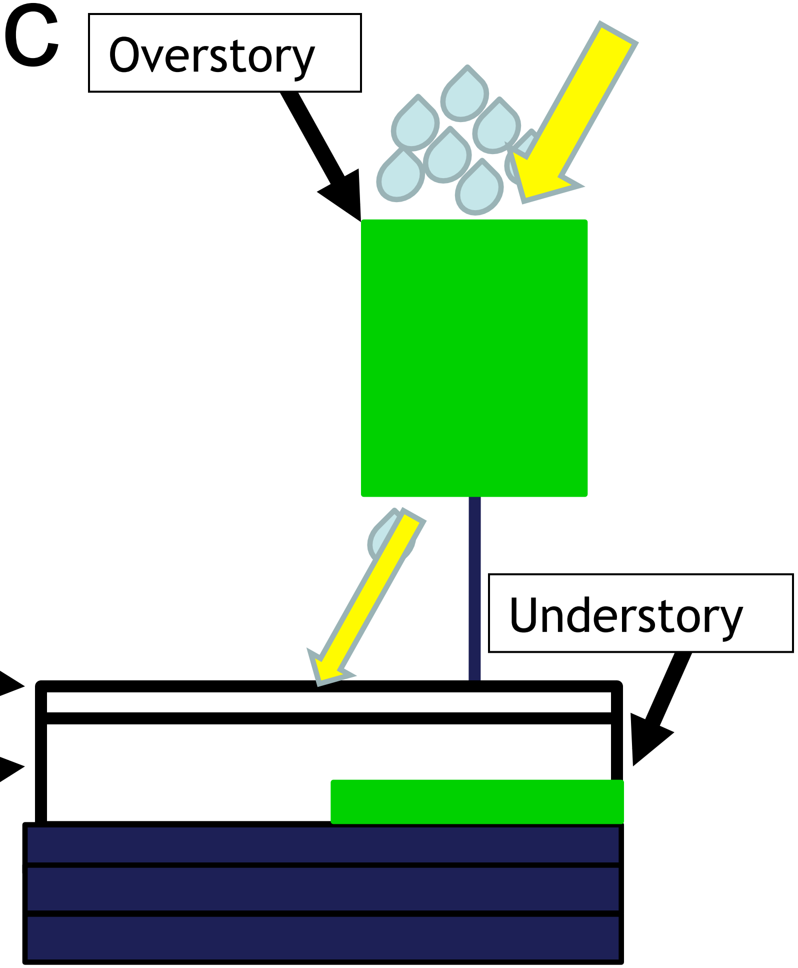






DHSVM Snow Model Schematic

- Two Layer Vegetation
  - Precipitation Interception and Fall through
  - Radiation attenuation
  - Aerodynamic attenuation
- Two Layer Snow pack
  - Surface → Controls fluxes
  - Pack → Stores Energy, Water, Ice etc.



Storck and Lettenmaier (1999) and Storck (2000)

Energy Balance

- $Qnet = (Qr + Qs + Qe + Qp) * dt$

- *Qr = NetRad*
- *Qs = Sensible Heat*
- *Qe = Latent Heat*
- *Qp = Advected energy via the input of water*

- Qnet > 0 → Warms pack to 0°C, then melts
- Qnet < 0 → Refreezes water, then cools

Energy Balance approach requires more Meteorological Input

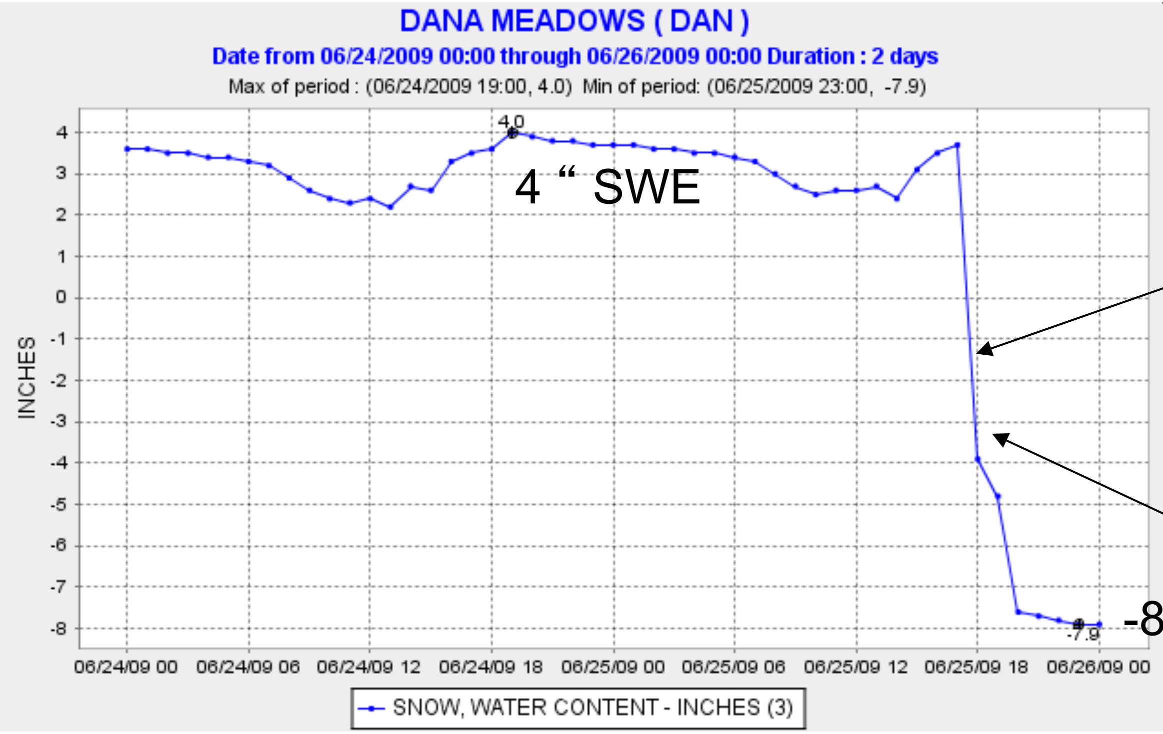
What is required at each time step:

- Temperature
- Precipitation
- Wind Speed
- Relative Humidity
- Shortwave Rad
- Longwave Rad

Let’s visit the Dana Meadows snow pillow.

June 25, 2009

Dana snow pillow, evening of June 25 2009



12" SWE difference before and after this event.

How long does it take a tree to grow?