Snow Hydrology:
Guest Lecture

Kristi R. Arsenault

<u>Course</u>: The Hydrosphere (EOS 656)
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Introduction

- ***Snow*** – is an important variable and component of the hydrosphere.
- All forms of snow and ice on the Earth's surface, including both land and ocean surfaces, are part of the Earth's ***cryosphere***.
- These cryospheric components can influence global, regional, and local climate and environmental conditions at different timescales.
- In this lecture, we'll explore some of these components, and how they are observed and modeled.

Importance of Snow

- **Water Resource Supply**
  - Mountain-area snowpack can provide up to 90% of the water supply to growing populations in semi-arid regions (e.g., Western United States)
  - Agricultural, hydropower, and other human uses
  - Ecological and environmental needs (e.g., species survival)
- **Flood Prediction**
  - Knowledge of antecedent winter snowpack can lead to improved forecasts of flooding and associated effects
- **Input in to Climate and Numerical Weather Prediction Models**
  - Snow's albedo and thermal insulation on the ground can impact radiation, energy and moisture budgets which play significant role in improving these models predictive capabilities.

Snow Hydrology Lecture

BASIC SNOW HYDROLOGY PRINCIPLES AND PHYSICS

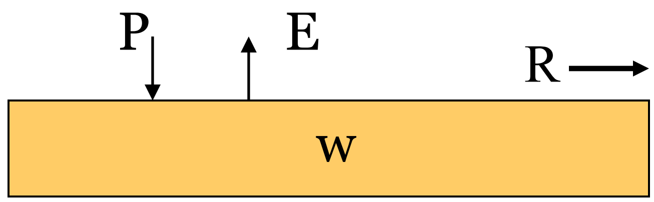
Snow Characteristics

- Snow – Basic Physics and Descriptions
- Snow – Properties
- Snow – Distribution
- Snow – Something

Water Balance for a Single Land Surface Slab, Without Snow

(e.g., standard bucket model)

Terms on LHS come from the climate model. Strongly dependent on cloudiness, water vapor, etc.



Terms on RHS come are determined by the land surface model.

$$\boxed{P \quad = E + R + C_w \Delta w / \Delta t + \text{miscellaneous}}$$

where

P = Precipitation

E = Evaporation

R = Runoff (effectively consisting of surface runoff *and* baseflow)

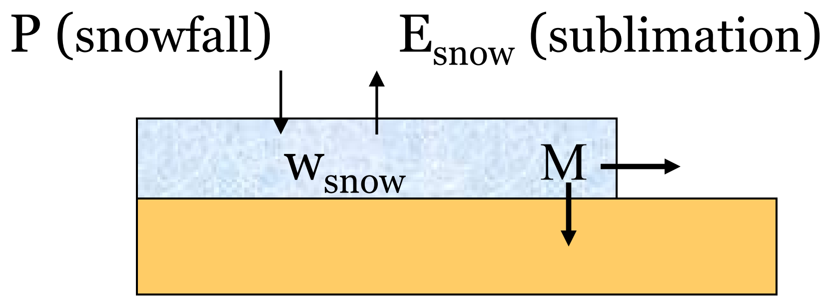
C_w = Water holding capacity of surface slab

Dw = Change in the degree of saturation of the surface slab

Dt = time step length

(From R. Koster; NASA)

Water Balance for a Snowpack Slab



$$\boxed{P_{snow} = E_{snow} + M + \Delta w_{snow}/\Delta t}$$

where

P_{snow} = Snowfall, freezing rain, etc. (typically when temps: $\leq$ 273 K)

E_{snow} = Sublimation from snow surface

M = Snowmelt

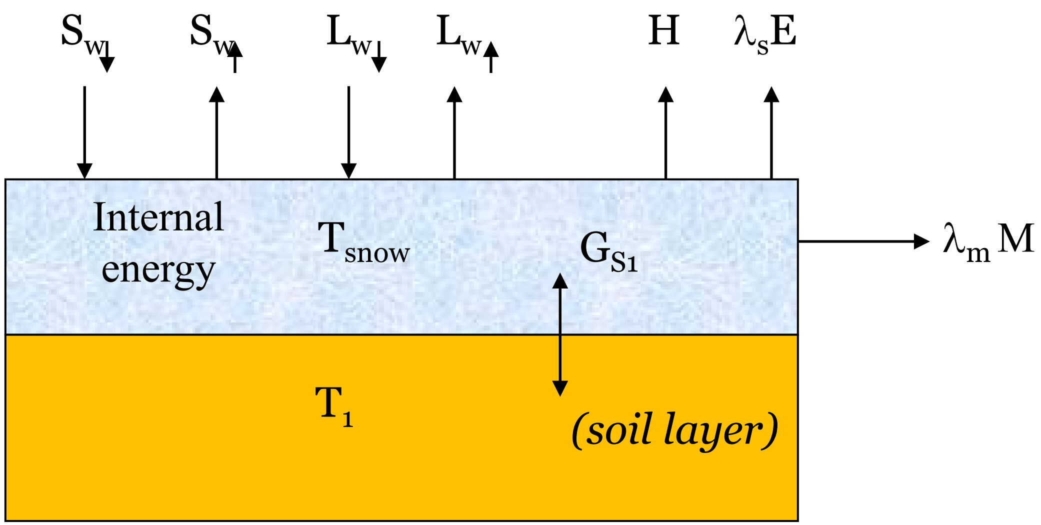
ΔW_{snow} = change in snow amount ("infinite" capacity possible)

Δt = time step length

Liquid water amount in snow is also called *snow water equivalent (SWE)*.

(From R. Koster; NASA)

Energy Balance for a Snowpack Slab



where,

l_m = latent heat of melting

l_s = latent heat of sublimation

M = snowmelt rate

G_{S1} = heat flux between bottom of pack and soil layer

(From R. Koster; NASA)

Snow Characteristics

- Snow – Basic Physics and Descriptions
- Snow – Properties
- Snow – Distribution
- Snow – Something

Reflected Shortwave Radiation: Albedo

Assume: $$S_w\downarrow = \sum_{b=1}^{\#\,\text{bands}} S_w\downarrow_{\text{direct, band b}} + \sum_{b=1}^{\#\,\text{bands}} S_w\downarrow_{\text{diffuse, band b}}$$

reflectance for spectral band

Compute: $$S_w\uparrow = \sum_{b=1}^{\#\,\text{bands}} S_w\downarrow_{\text{direct, band b}}\, a_{\text{direct, band b}} + \sum_{b=1}^{\#\,\text{bands}} S_w\downarrow_{\text{diffuse, band b}}\, a_{\text{diffuse, band b}}$$

Simplest description:
Consider only one band (the whole spectrum) and do not differentiate between diffuse and direct components:

$$\boxed{Sw_{\uparrow} = Sw_{\downarrow}\, \mathbf{a}}$$

albedo

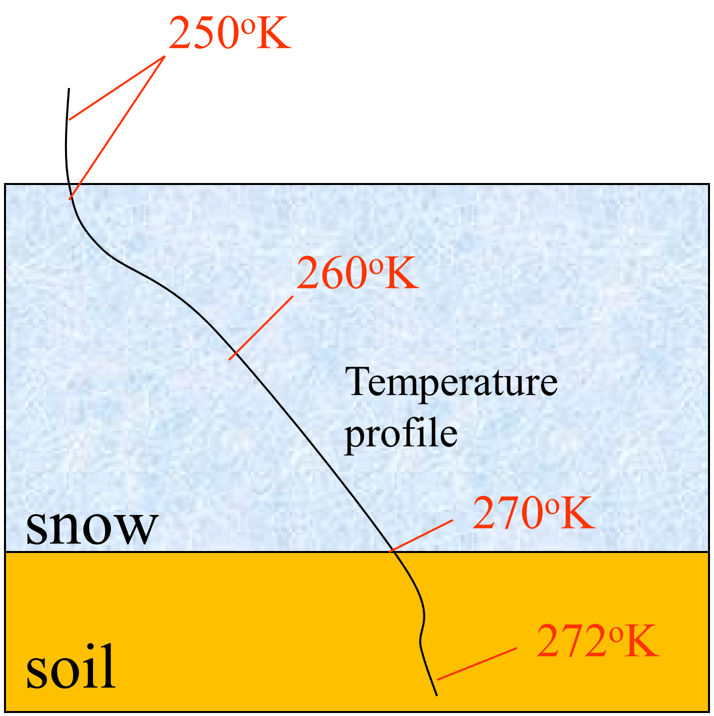
Typical albedoes (from Houghton):

sand	.18-.28
grassland	.16-.20
green crops	.15-.25
forests	.14-.20
dense forest	.05-.10
fresh snow	**.75-.95**
old snow	**.40-.60**
urban	.14-.18

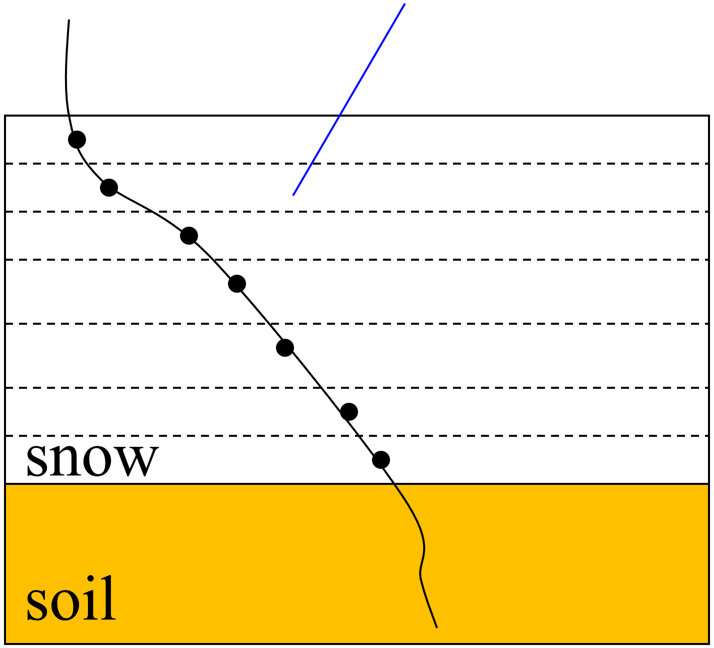
(From R. Koster; NASA)

Critical property of snow: Low thermal conductivity

⇨ Strong insulation …



To capture such properties, the snow can be modeled as a series of layers, each with its own temperature.



(From R. Koster; NASA)

Snow surfaces are also considered to be at or near "saturated" conditions, whether melt is occurring or not

Saturation vapor pressure, $e_s(T)$:

The vapor pressure at which the condensation vapor onto a surface is equal to the upward flux of vapor from the surface.

Clausius-Clapeyron equation:

$$e_s(T) \text{ varies as } \exp\left(-0.622\frac{\lambda}{R_d T}\right)$$

Potential Evaporation, E_p:

The evaporative flux from an idealized, extensive free water surface under existing atmospheric conditions.

Snow evaporation (or sublimation):

$$\lambda_s E = \frac{0.622\lambda_s \rho}{p} \frac{e_s(T_s) - e_r}{r_a}$$

Evaporation from a fully wetted surface ($=E_p$)

Here's the famous Penman equation:

"equilibrium evaporation for a saturated air mass passing over a wet surface"

contribution due to subsaturated air

$$E_{Penman} = \frac{(R_{net} - G)\Delta + (\rho c_p / r_a)\,(e_s(T_r) - e_r)}{\Delta + \gamma}$$

$\Delta = d(e_s)/dT$ $\gamma = c_p p/(0.622\lambda)$ G = heat flux into ground R_{net} = net radiation

Contains terms that are relatively easy to measure

(From R. Koster; NASA)

Snow Cover Distribution

Three Major Spatial Scales

- **Macroscale**
  - Areas up to 10^6 km^2
  - Characteristic Distances of 10-1000 km
  - Dynamic meteorological effects are important
- **Mesoscale**
  - Characteristic Distances of 100 m to 10 km
  - Redistribution of snow along relief features due to wind
  - Deposition and accumulation of snow may be related to terrain variables and to vegetation cover
- **Microscale**
  - Characteristic Distances of 10 to 100 m
  - Differences in accumulation result from variations in air flow patterns and transport

** (from J. S. Price, U. of Waterloo)*

Snow Cover Distribution

Effect of Topography:

- The depth of seasonal snow cover usually increases with elevation, depending mostly on slope, aspect and elevation height
  - Though the rate of increase with elevation may vary widely from year-to-year

Other factors include:

- Vegetation effects,
- Wind characteristics,
- Temperature, and
- Characteristics of the parent weather systems
  - E.g., Rainfall can contribute more significantly to snow melt processes than temperature can

** (from J. S. Price, U. of Waterloo)*

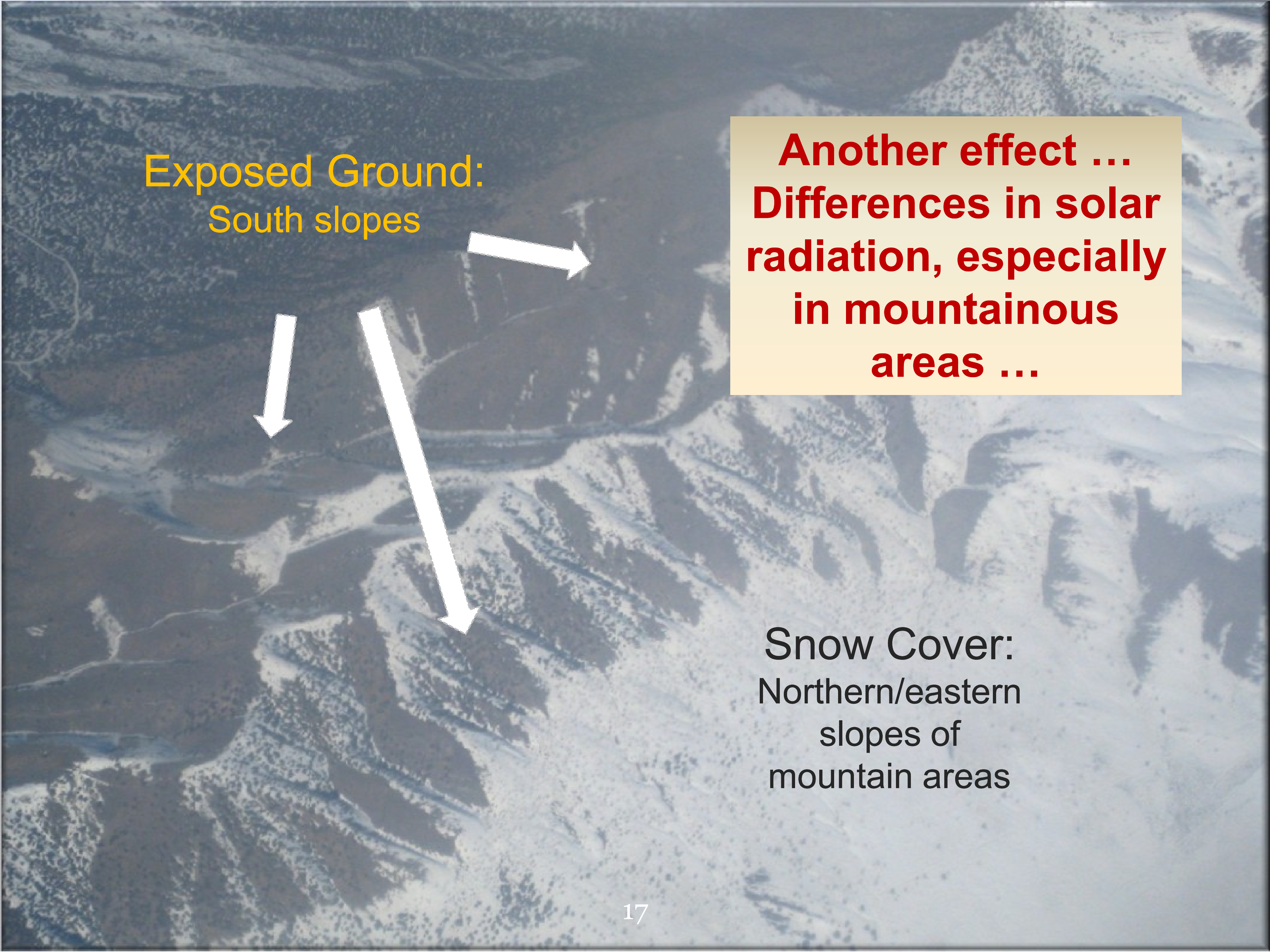
Snow Cover Distribution

Open areas exposed to more accumulated snowfall

- Influences of meso- and micro-scale differences in vegetation and terrain features may produce wide variations in snow distribution.

** (from J. S. Price, U. of Waterloo)*

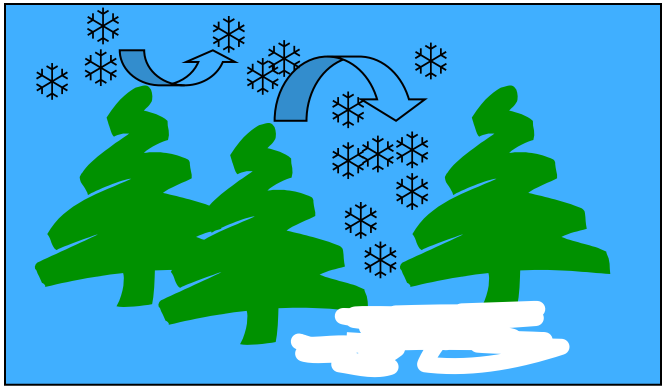
Another effect … Differences in solar radiation, especially in mountainous areas …

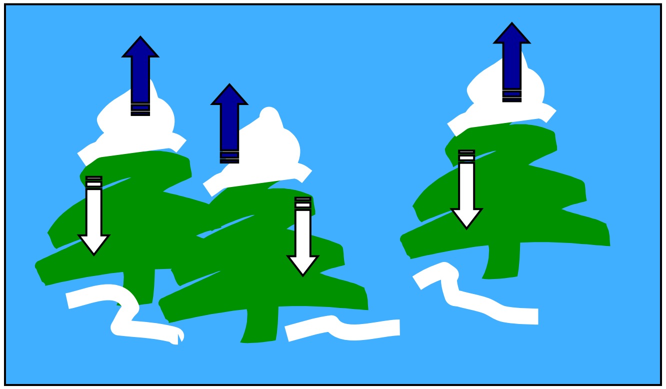


Snow Cover Distribution

Vegetation Effects:

- Vegetation canopies affect snowfall by:
  1) Turbulent air flow involving the canopy
  2) Direct interception of snowfall by the canopy which can lead to sublimation or throughfall to the ground
- Vegetation type, density, and the proximity of nearby open areas all play roles in distribution as well



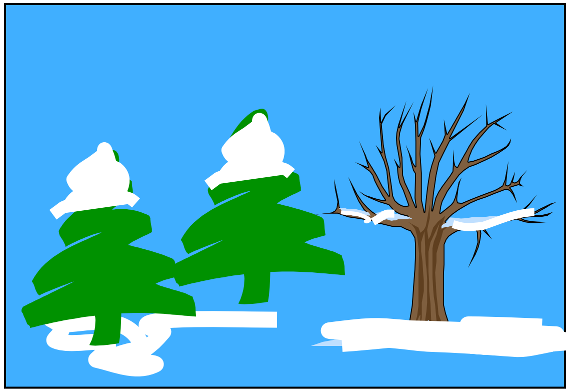


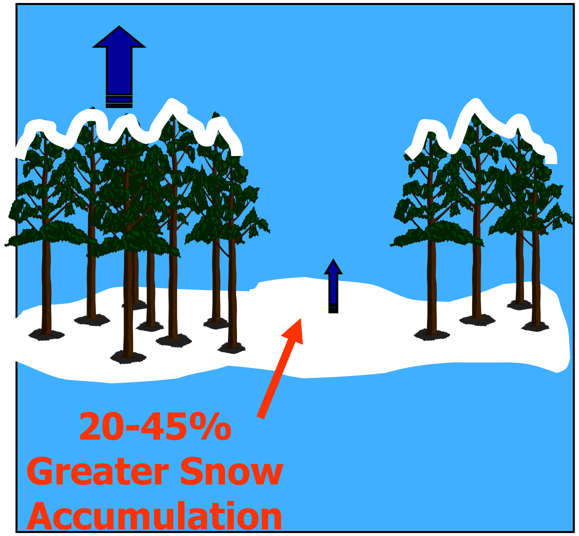
* *(from J. S. Price, U. of Waterloo)*

Snow Cover Distribution

Forested Environments

- Greatest snow accumulation differences occur between different coniferous and deciduous stands than within species of conifers
  - Coniferous stands are all relatively efficient snow interceptors
  - Snow is more susceptible to sublimation losses in the canopy than on the forest floor
- Typically greater snow accumulation in clearings than in the forest
- Interception and subsequent sublimation are the major factors contributing to the difference
  - Up to 40% of tree-based snow can be lost to sublimation





** (from J. S. Price, U. of Waterloo)*

Wind Effects on Snow

Snow transported by wind processes undergo:

Redistribution of Snow Water Equivalent

1. **Shear velocity**
2. **Threshold windspeed**
3. **Transport mechanism**

Loss of Water by Sublimation

1. **Atmospheric condition: e.g.temperature, humidity, windspeed**
2. **Transport distance**

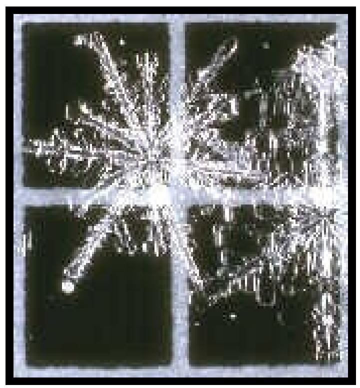
** (from J. S. Price, U. of Waterloo)*

Wind Effects on Snow

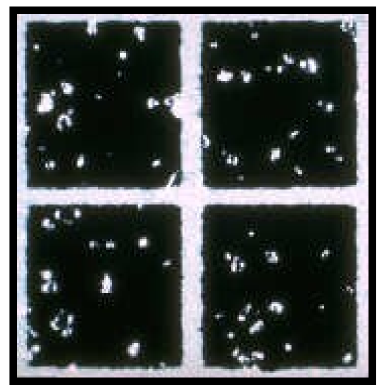
Wind Effects on Snow Characteristics

- Mechanical fragmentation and sublimation losses result in small, rounded particles
- Windblown snow deposits are inherently more dense

Snow crystal collected during snowfall under calm winds



| 2 mm |



Windblown snow particle collected during transport

** (from J. S. Price, U. of Waterloo)*

Blowing Snow

Shear Velocity - Wind

- The friction velocity u* is usually calculated from wind profiles, but can be estimated from a single 10-m wind speed (u_{10}):

		u_{10} = 5 m/s
Antarctic Ice Sheet	**$u^* = u_{10}/26.5$**	$u^* = 0.19$
Snow-covered Lake	**$u^* = u_{10}^{1.18}/41.7$**	$u^* = 0.16$
Snow-covered Fallow Field	**$u^* = u_{10}^{1.30}/44.2$**	$u^* = 0.18$

* *(from J. S. Price, U. of Waterloo)*

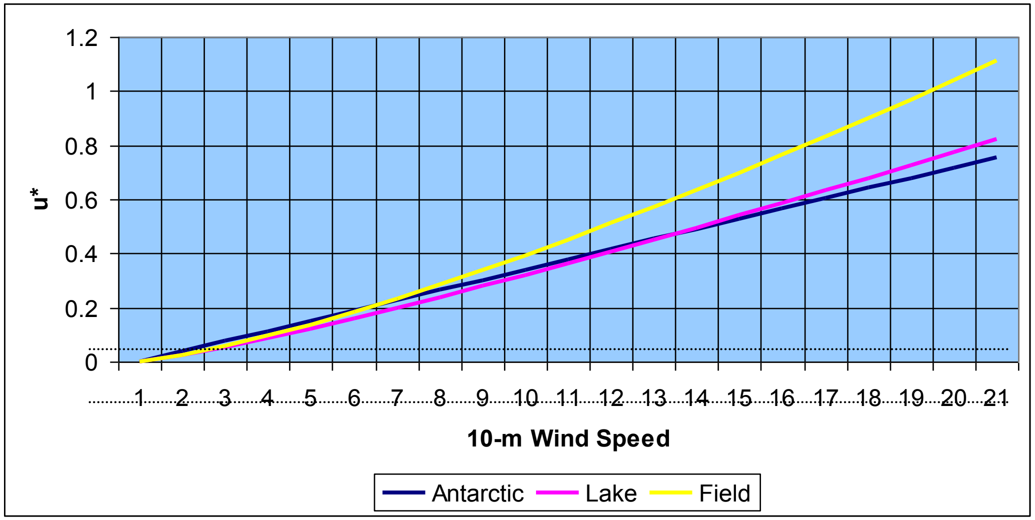
Blowing Snow

Threshold Shear Velocity - Snow

- u^*_t is the friction velocity at which snow transport begins (depends on snow characteristics)

Older, wind-hardened, dense or wet-snow:
$u^*_t = 0.25 - 1.0$ m/s

Fresh, loose, dry snow, and during snowfall:
$u^*_t = 0.07 - 0.25$ m/s



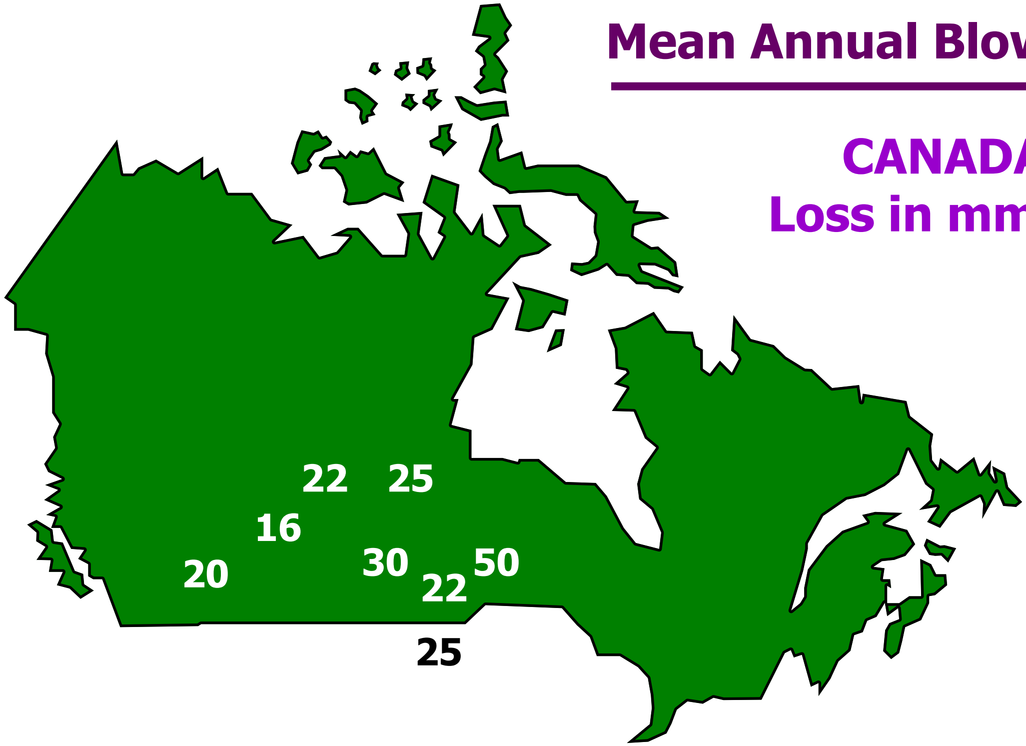
Three Types of Transport

TYPE	MOTION	HEIGHT	WINDSPEED
Creep	Roll	< 1 cm	<< 5 m/s
Saltation	Bounce	1 cm - 10 cm	5 - 10 m/s
Turbulent Diffusion	Suspended	1 m - 100 m	> 10 m/s

** (from J. S. Price, U. of Waterloo)*

Blowing Snow

Sublimation Losses



Mean Annual Blowing Snow Sublimation

CANADA, 1970-1976
Loss in mm SWE over 1 km

Frozen Soil Effects

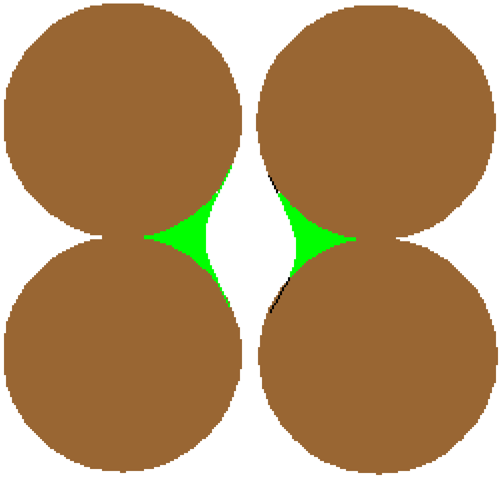
- **Thermal effects:** **Enhances the soil heat capacity through diurnal and seasonal freezing-thawing cycles.**
- **Hydrological effects:** **Affects snowmelt runoff and soil hydrology by reducing soil permeability. In turn, for example, runoff from Arctic river systems affects ocean salinity and the thermohaline circulation.**
- **Ecological effects:** **Affects ecosystem diversity and productivity and carbon decomposition and release.**

** (Z.-L. Yang, U.Texas – Austin)*

Supercooled Liquid Water Exists in Frozen Soil

- When soil water freezes, the water closest to soil particles remains in liquid form due to the absorptive and capillary forces exerted by the soil particles.

- The supercooled liquid water at subfreezing point is equivalent to a depression of the freezing-point (0°C).



* (Z.-L. Yang, U.Texas – Austin)

Frozen Soil Is Permeable?

Early Russian literature and recent works showed that frozen soil has very weak or no effects on runoff. For example …

- Russian laboratory and field experiments in 1960s and 1970s (Koren, 1980).
- Shanley and Chalmers (1999), Lindstrom et al. (2002
- Stahli et al. (2004): Dye tracer techniques revealed that water can infiltrate into deep soil through preferential pathways which are air-filled pores at the time of freezing.

** (Z.-L. Yang, U.Texas – Austin)*

The Importance of Snow-Atmosphere Interactions

Snow surfaces have the ability not only to alter the land surface and landscape properties, like albedo and roughness, but can also impact the atmosphere from local to global scales.

On a regional to global scale, a large body of research emphasizes the importance of snow to the climate system:

e.g., Robock (1983); Cohen and Rind (1991); Walland and Simmonds (1997); Cohen and Entekhabi (1999); Watanabe and Nitta (1998); Watanabe and Nitta (1999); Gong et al. (2003); Hahn and Shukla (1976); Dickson (1984); Dey and Kumar (1982); Vernekar et al. (1995); Bamzai and Shukla (1996); Douville and Royer (1996); Harzallah and Sadourny (1997); Kripalani and Kulkarni (1999); Ferranti and Molteni (1999); Wu and Qian (2003); Fasullo (2004); Dash et al. (2005); Barnett et al. (1989); Qian and Saunders (2003); Saito et al.(2001); and Shinoda (2001); Yang et al. (2001); Toshi et al. (2003), Hawkins et al. (2002); and Jin and Miller (2007), and many others.

DIFFERENT METHODS OF OBSERVING SNOW

Snow Observations Overview

- Observing snow, ice and frozen ground characteristics is critical to better understanding the hydrological cycle and managing water resources.
- However, making accurate snow measurements can be quite challenging when dealing with different scales, environments and instrument limitations.
- This next section provides an overview of some of the different snow observation and instrument types
- <u>These include</u>: Station (or in-situ) ground and remotely sensed observations
- Also some of the issues faced with each will be addressed

Some of the Problems with Snow Measurements

- Most in-situ snow observation networks tend to be sparse in mountain regions
- This can make it difficult to obtain accurate representation of highly spatial snow variability
- Also, remotely sensed products encounter many issues, like they can either have too coarse of a resolution to map the snow well or clouds obscure the detection of snow

Snow Observations

- In-situ Measurements – Station Networks
- In-situ Measurements – Field Measurements
- Remote Sensing Retrievals

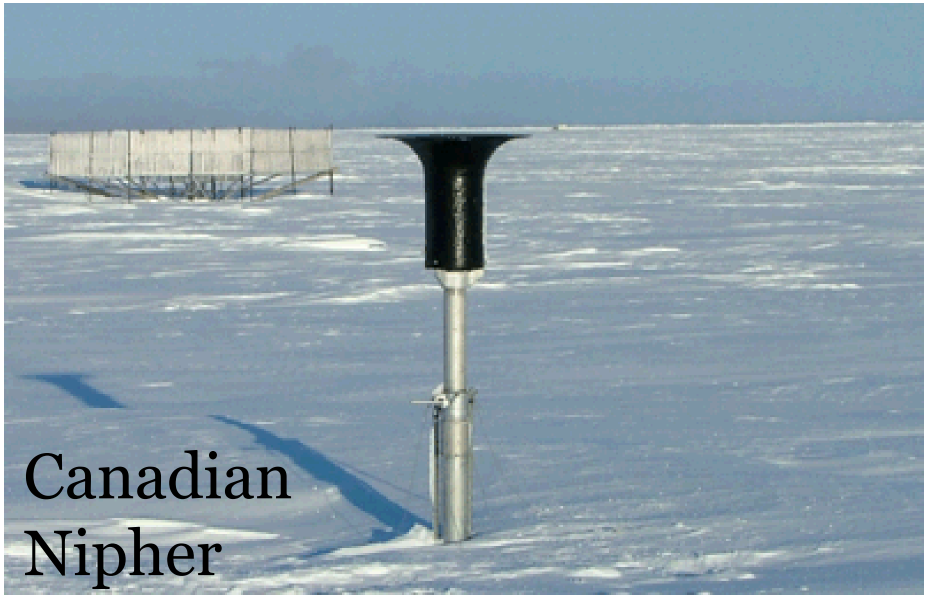
Gage Measurement Networks

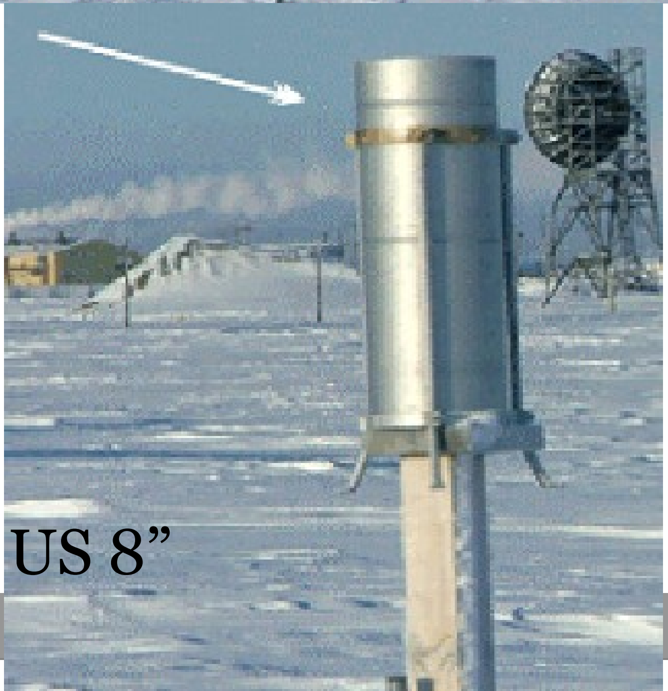
- Global coverage with various operational, national/regional networks.
- Manual and automatic gauges, measuring water equivalent (amount), not snow particle size.
- Manual gauges can measure snowfall (rate) at 6-hour to daily time intervals, and auto gauges can provide hourly (or sub-hourly) snowfall (rate).
- Snow rulers are also used for snowfall observations at the national/regional networks, providing snow depth info, not SWE.
- Snow pillow/snowboard/snow depth sensor record snow accumulation changes over time - (in)direct info of snowfall.
- Gauge networks/data are long-term and fundamental, defining global snowfall/climate regimes and changes.

Precipitation Component: Snow Accumulation

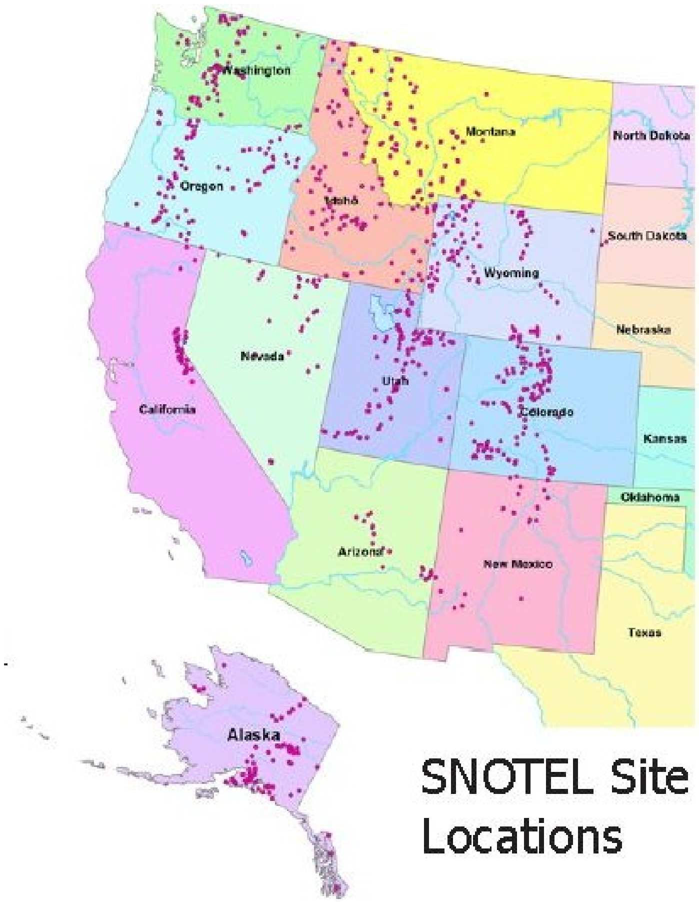
- Input to winter snowpack and spring snowmelt runoff in mountain and polar regions – *critical element of basin water cycle and regional water resources*
- Influence on large-scale land surface radiation and energy budget particularly during accumulation
- Effect on glacier/ice sheet accumulation/mass balance, lake/river and sea ice, seasonal frozen-ground and permafrost
- Impact to human society and activity, such as air/ground transportation, disaster prevention, agriculture, water resources management, and recreation…

Some national standard gauges (here tested in Barrow, AK)





USDA/ NRCS SNOw TELemetry (SNOTEL) Gage Network in Mountainous Western U.S.



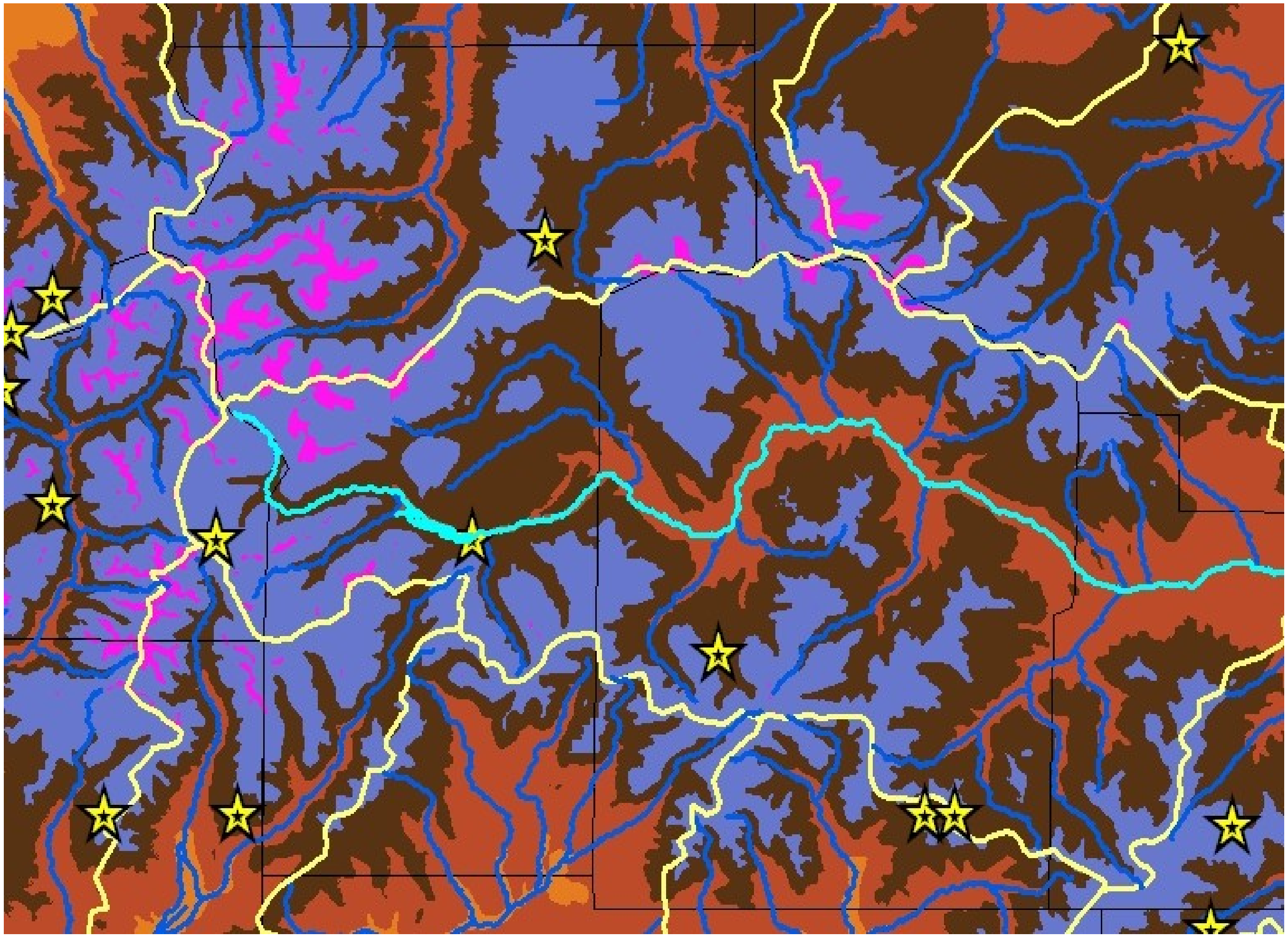
SNOTEL Site Locations

SNOTEL sites record and transmit SWE, precipitation, temperature, and soil moisture/temperature for hundreds of sites in 13 western states.

SNOTEL sites typically are found in higher elevation – watershed locations, but the data are used for many different hydrological and water resources applications.

From http://www.wcc.nrcs.usda.gov/snotel/SNOTEL-brochure.pdf

Rio Grande Headwaters Basin Topography & SNOTEL Sites



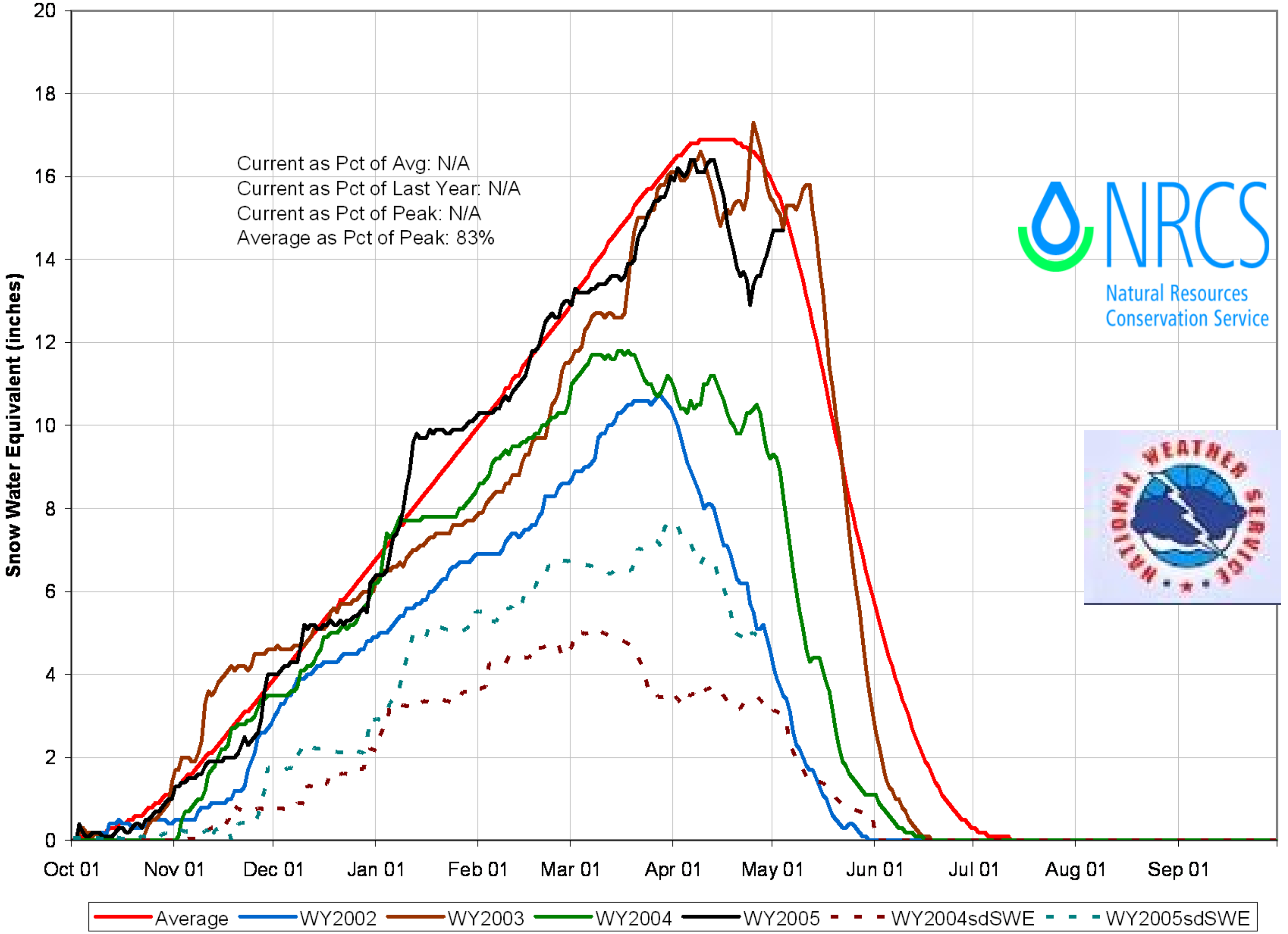
Elev (ft. MSL)

- 12767 - 14400
- 11137 - 12766
- 9506 - 11136
- 7878 - 9505

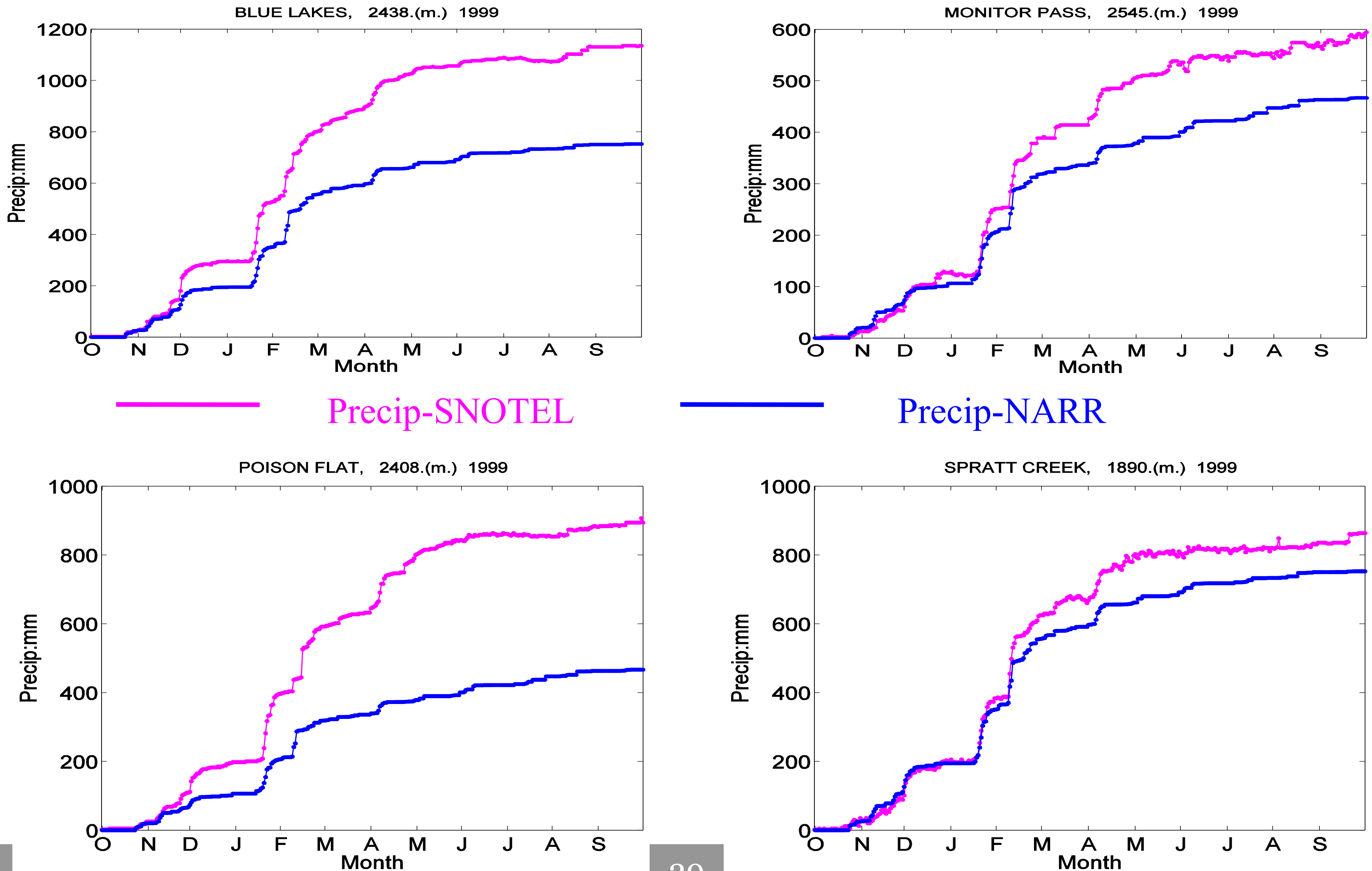
Yellow Stars: SNOTEL sites

Upper Colorado River Basin Snowpack

Based on Provisional SNOTEL data as of Mar 09, 2005



SNOTEL vs. North American Regional Reanalysis (NARR) Accumulated Precipitation Comparison



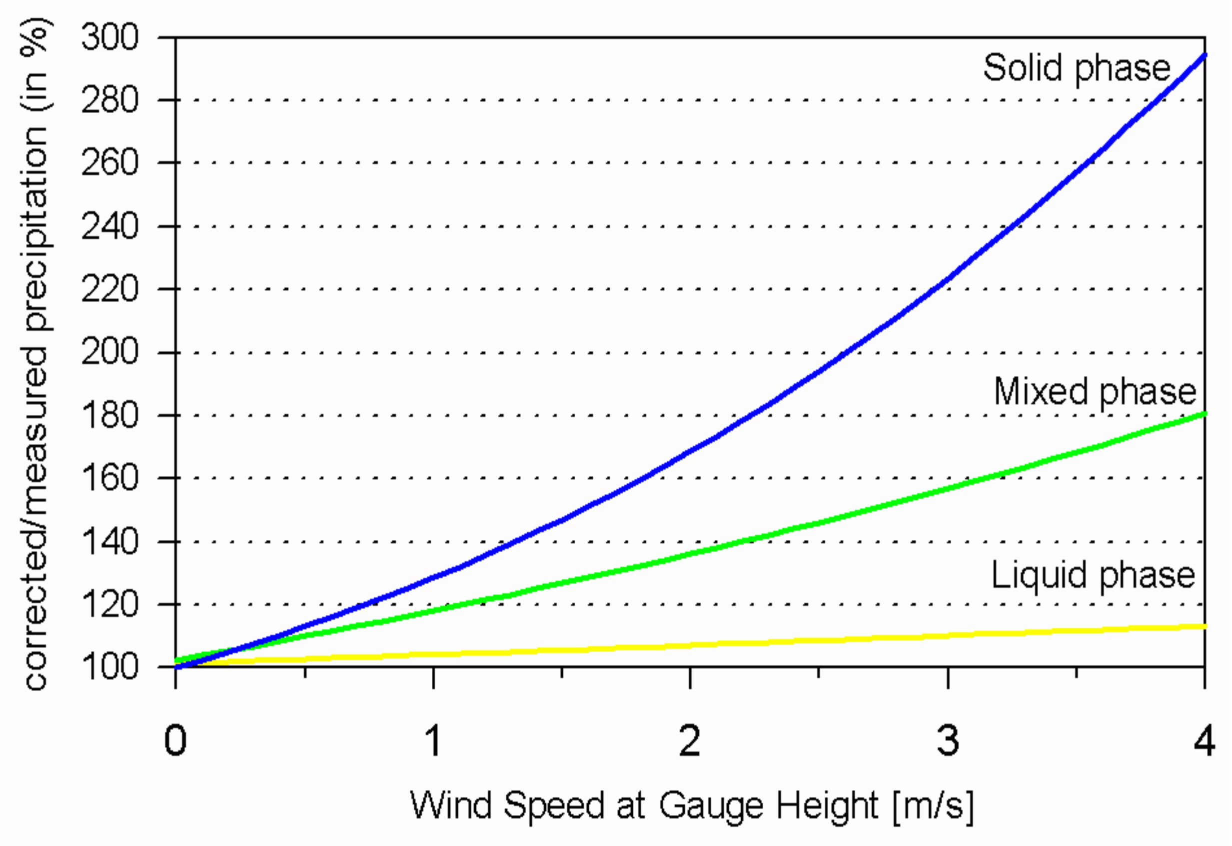
Some Biases in Gauge Measurements

- Wind-induced gauge under-catch
- Wetting and evaporation losses
- Underestimate of trace precipitation events
- Blowing snow into gauges at high winds
- Uncertainties in auto gauge systems

Systematic gauge measuring error

WMO Solid Precipitation Measurement Comparison Study

Precipitation phase and wind speed are the most important meteorological parameters for the systematic error



The GPCC has developed a method to estimate wind speed, precipitation phase, air temperature and humidity from synoptic data, which are needed to calculate the bias corrections on a daily "on event" basis.

(Figure: T. Günther in Goodison et al, 1998)

Note that there are also spatial sampling errors and process errors (virga)

Snow Observations

- In-situ Measurements – Station Networks
- In-situ Measurements – Field Measurements
- Remote Sensing Retrievals

Snow Course Surveys

A **snow course** is a permanent site where manual measurements of snow depth and snow water equivalent are taken by trained observers.*

- Measurements usually taken near beginning of month during the winter and spring.
- Courses typically ~1,000 feet long and situated in small, wind-protected meadow.
- Snow samples collected with a "snow sampling set" – a series of aluminum tubes, which are weighed along with the snow cores to obtain SWE and snow depth.

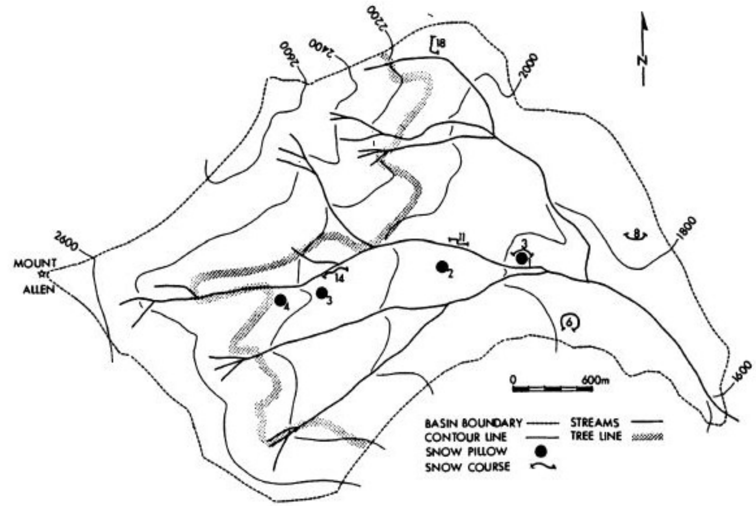
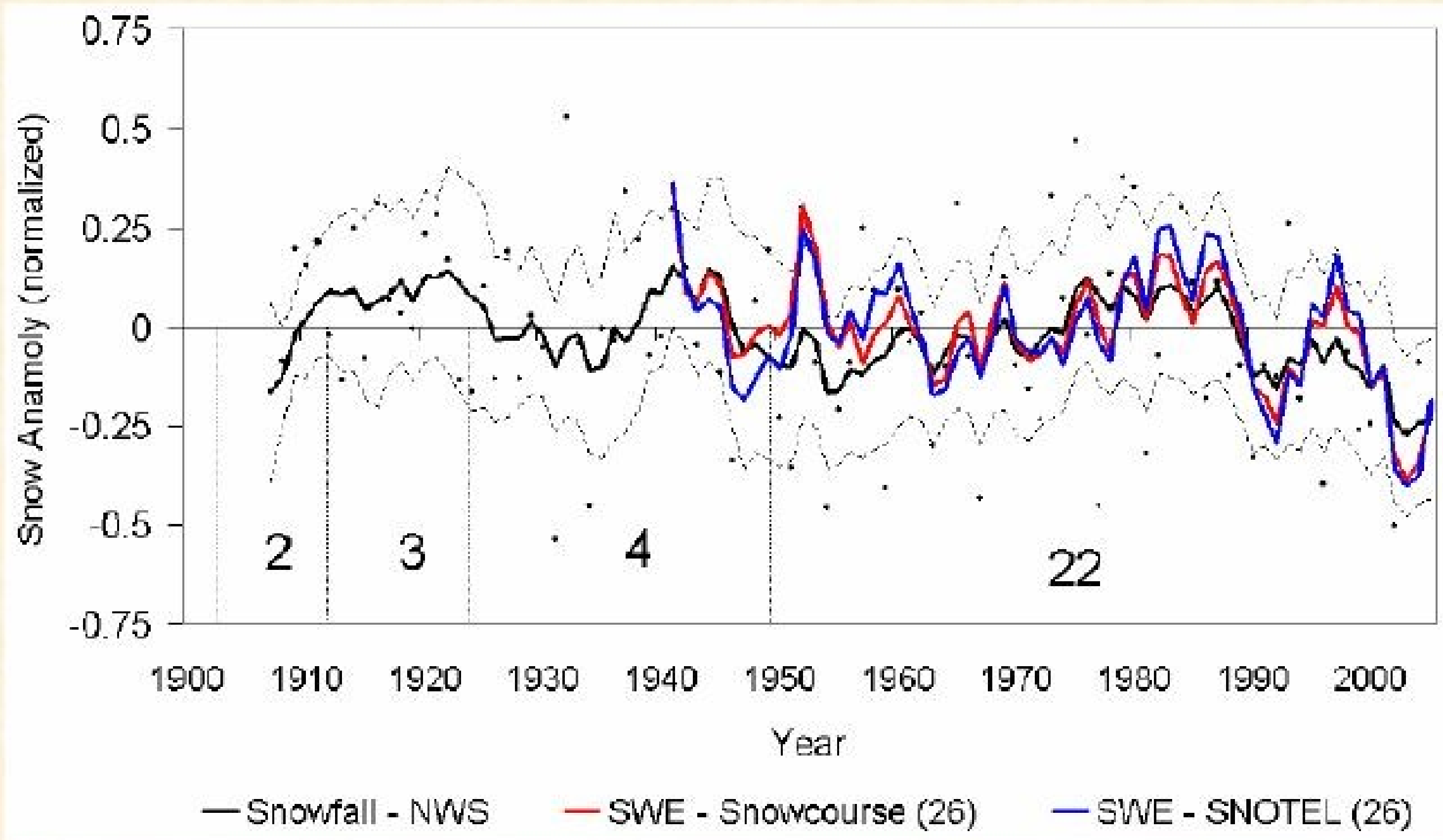


Fig. 1. Map of Marmot Creek Experimental basin showing the location of snow courses and snow pillows. The contours are in m.

Snowfall And SWE



- 40% decrease in SWE during 1995-2005
- Decrease in the total annual snow residence time

Snowfall vs SWE: r = 0.83
SWE (Snow Course vs SNOTEL):
r = 0.96

27

(From I. Rangwala – Rutgers U.)

From:
http://www.comet.ucar.edu/class/hydromet/09_Oct13_1999/docs/cline/comet_snowhydro/index.htm

Snow Measurement

Taking A Sample

Researcher carefully takes a sample of a layer while the other in the background reaches for a plastic bag

Layers and Measuring Tape

A measuring tape is fastened to the wall of the pit after the layers are exposed with the trowel.

Snow pit measurements taken in Antarctica.

Snow depth measurement.

Probes are graduated in centimeters, and measurements are to be recorded to the nearest centimeter. This probe has two sections, so the measured depth here is 165 cm.

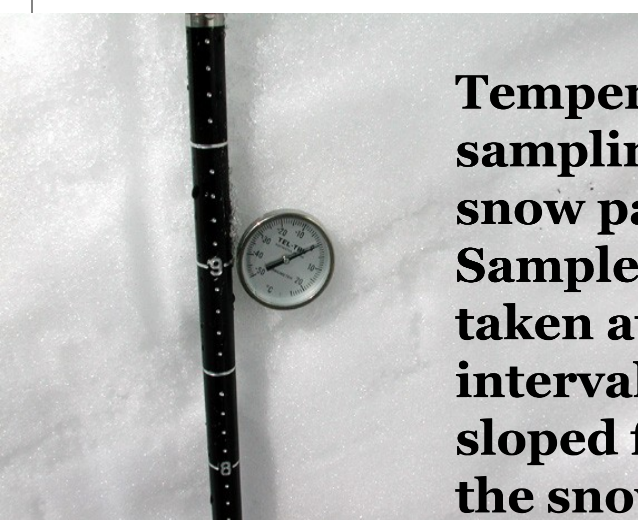
http://www.nohrsc.nws.gov/%7Ecline/clp/field_exp/clpx_plan/chapters/CLPX_plan_chap10.htm#10.4.%20SNOW%20PIT

Pits deeper than 1-m require excavation of a larger area. Steps need to be excavated to facilitate access to the base of the pit, and for personnel to stand on in order to reach the top of the pit for sampling.

Shallow pits (1 meter depth or less) do not need to be very large. A pit 1.5-m x 1.5-m square is adequate to allow room for sampling.

http://www.nohrsc.nws.gov/~cline/clp/field_exp/clpx_plan/figures/CLPX_plan_fig62.htm

Demonstration of shaving the face of the pit wall to create a clean, flat sampling sample area. For photo purposes, the unshaded-side of this pit is being shaved. For data collection, the shaded side of the pit will be shaved.



Temperature sampling of a snow pack. Samples are taken at 10-cm intervals on the sloped face of the snow pit.

http://www.nohrsc.nws.gov/~cline/clp/field_exp/clpx_plan/figures/CLPX_plan_fig64.htm

Importance of Measuring Turbulent Energy Fluxes over Snow and Ice Surfaces

- **Latent Heat Flux**: This flux component accounts for the ***sublimation* from** the snow/ice surface or local vegetation canopy.
  - This flux is typically a small component of the wintertime hydrological cycle, but it can become large under windy conditions

- **Sensible Heat Flux**: This flux component accounts for the ***energy into*** the snow/ice surface and can contribute to either snow melt or sublimation processes.
  - Sensible heat is usually downward into the snowpack during the day, due to snow temperatures being $\leq$ 273K
  - Local energy sources, like local vegetation, can contribute to enhanced downward sensible heat flux into the snowpack

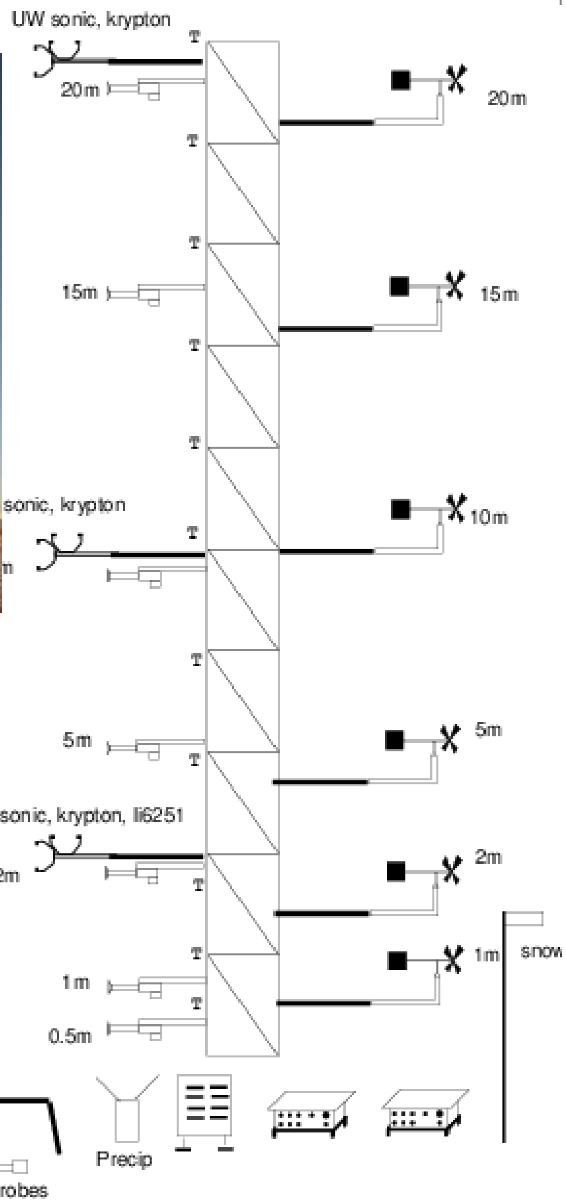
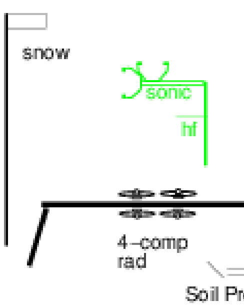
FLOSS II Tower

(FLuxes Over Snow Surfaces)

34-meter FLOSS2 Tower with 8 measurement levels (Humidity at 2-, 10-,20- and 30-m heights)

Radiation components and snow depth measurements on a separate stands

Data obtained from both OSU (Mahrt, Vickers, Sun) and NCAR (Oncley)

Site:	Tower	Sage	Lake
Obs. Heights (m)	.5, 1, 2, 5, 10, 15, 20, 25, 30	2	2
Elev. (m)	2476	2475	2474
Soil Type	Sandy loam		Sandy
Veg. Type	Grass	Sage	Bare

NCAR FLOSS2 Report: http://www.eol.ucar.edu/rtf/projects/FLOSSII/

Eddy Covariance Flux Measurements over Snow

Snow can lead to very stable boundary layer conditions in association with temperature inversions and low wind speeds near the surface.

An example given to the right using the FLOSS2 data.

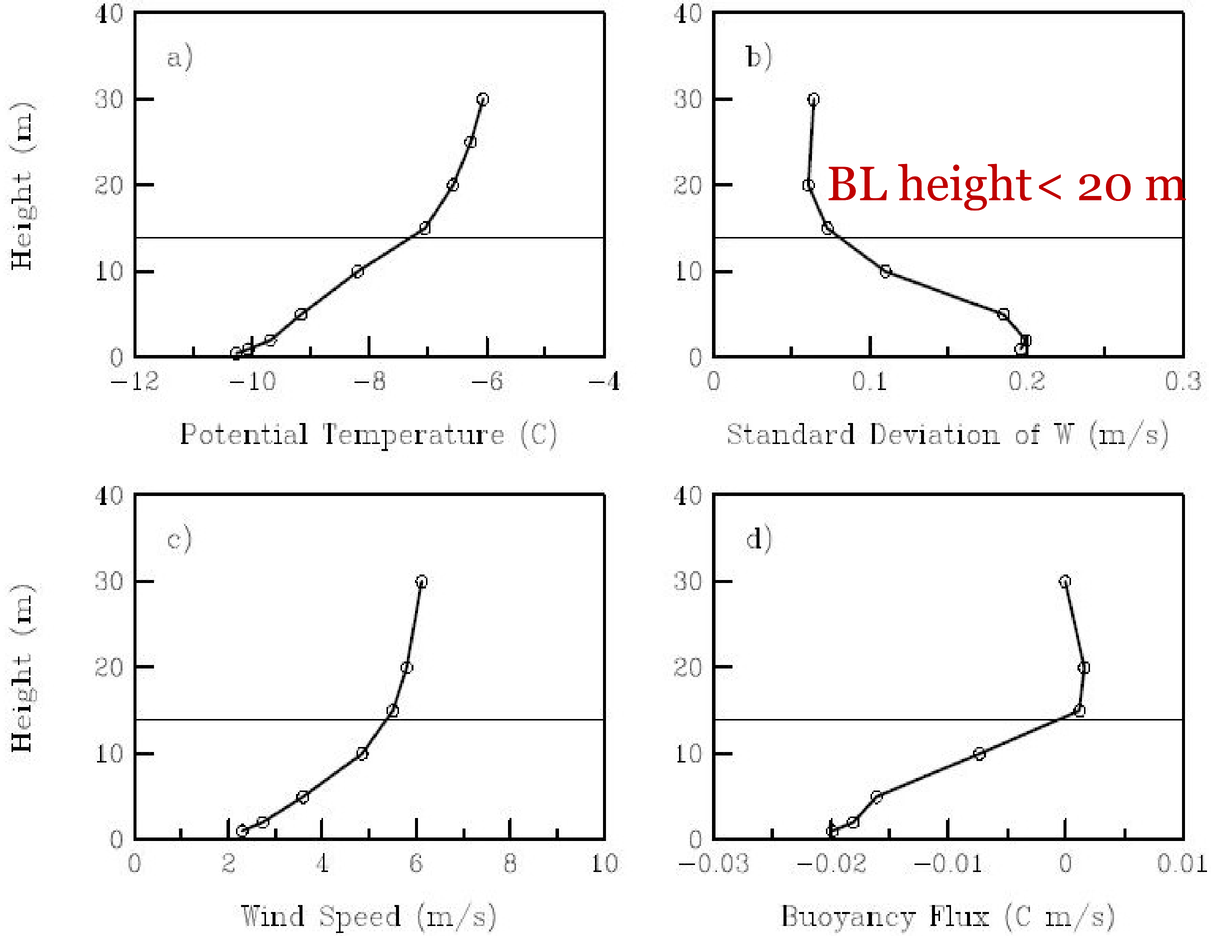


Figure 3: FLOSS profiles (1-hour averages) on 20 February over a snow-covered surface. Horizontal lines show boundary-layer depth.

(Vickers and Mahrt, 2004)

Eddy Covariance (EC) Flux Measurements over Snow

- **EC Flux method**: More directly estimates sensible heat flux, if the instruments on the tower are above the surface layer (SL) then this method could generate the wrong results (Arck and Scherer, 2002).

- **Profile method:** (i.e., *measurements taken at two different heights*) is compared against the eddy covariance method (Figure 7 to the right).
- **Bulk method**: Measurements are only taken at one height level, and if above the SL, then the fluxes may be underestimated.

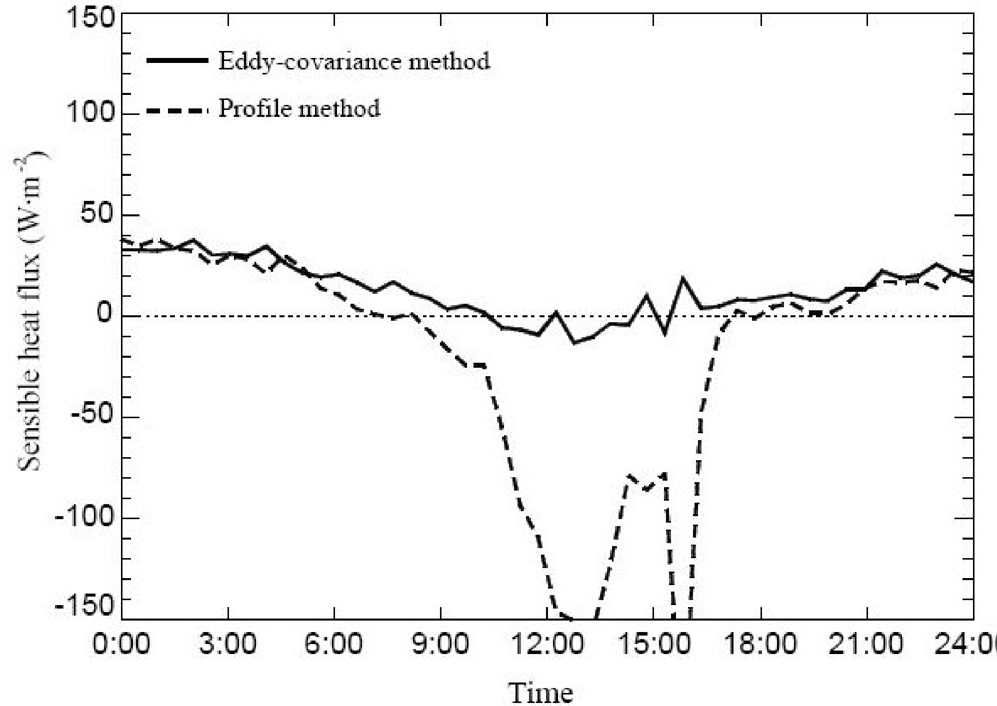


Fig. 7. Sensible heat fluxes (30 min means) on 15 May 1995 calculated with the profile method, using original air-temperature data of the lowest and the middle levels, and directly measured with the eddy-covariance system.

Snow Observations

- In-situ Measurements – Station Networks
- In-situ Measurements – Field Measurements
- Remote Sensing Retrievals

Remote Sensing of Snow

Reflected Solar Radiation (0.4 – 3.0 µm)

• Visible, near-infrared (0.4 - 1.1 µm): e.g., **snow cover**, contaminants in snow

• Short-wave infrared (1.1 µm- 2.5 µm): e.g., snow vs. clouds, grain size

Emitted Thermal Radiation (3.0 – 14.0 µm)

• Mid-wave and thermal infrared (3-5 µm, 8-14 µm): e.g., Temperature, emissivity

• Microwave (1-20 mm): e.g., Dry vs. wet snow, snow water equivalence (SWE)

RADAR (2-70 cm):

- e.g., Topography, roughness, ice velocity

MODIS Snow Cover and Albedo

Moderate-Resolution Imaging Spectro-radiometer (MODIS)

- **Visible, near-infrared and thermal infrared.**
- **Snow Cover Map Algorithm: *[Hall et al, 2000]***
- **Normalized Difference Snow Index:**

NDSI=(*B6-B4)/(B6+B4)

- **Thermal threshold: 4ºC**
- **NDVI/NSDI to distinguish forested snow**
- **"Validated" Algorithm**

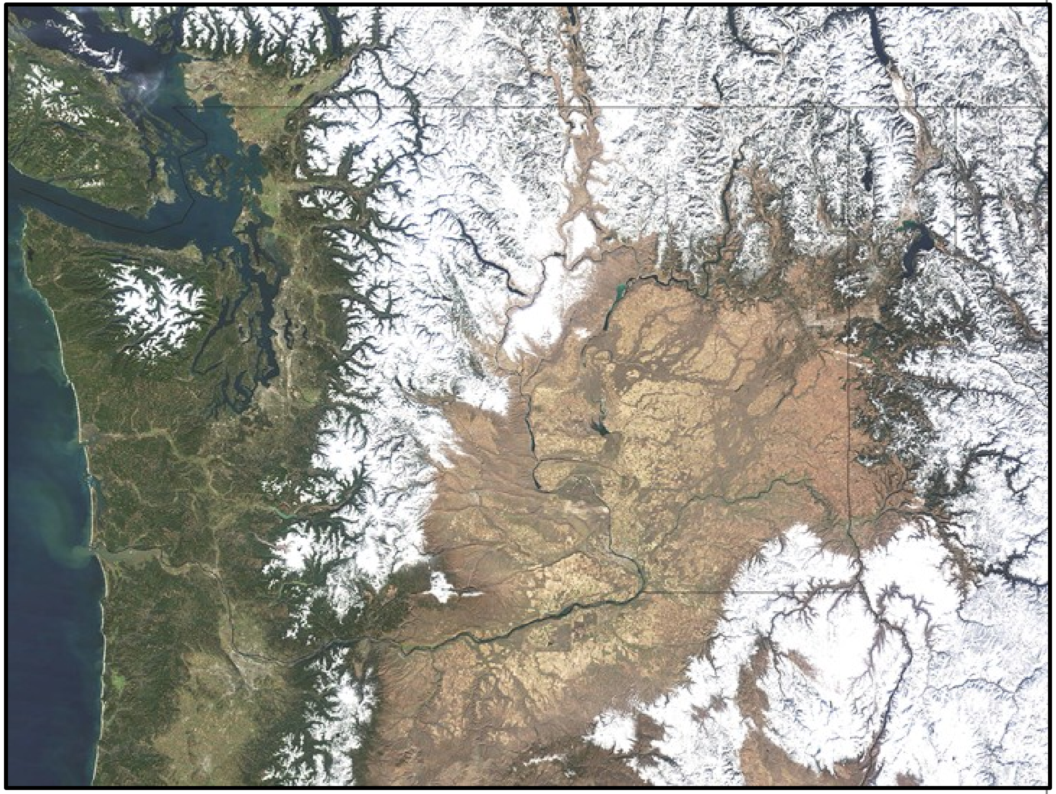


Image courtesy of Jeff Smaltz of MODIS Land Rapid Response Team, NASA GSFC

*Note: "B" indicates "band"

MODIS Snow Cover

MODIS (visible/infrared):

500 m and 1 km resolutions

Two satellites: Terra and Aqua

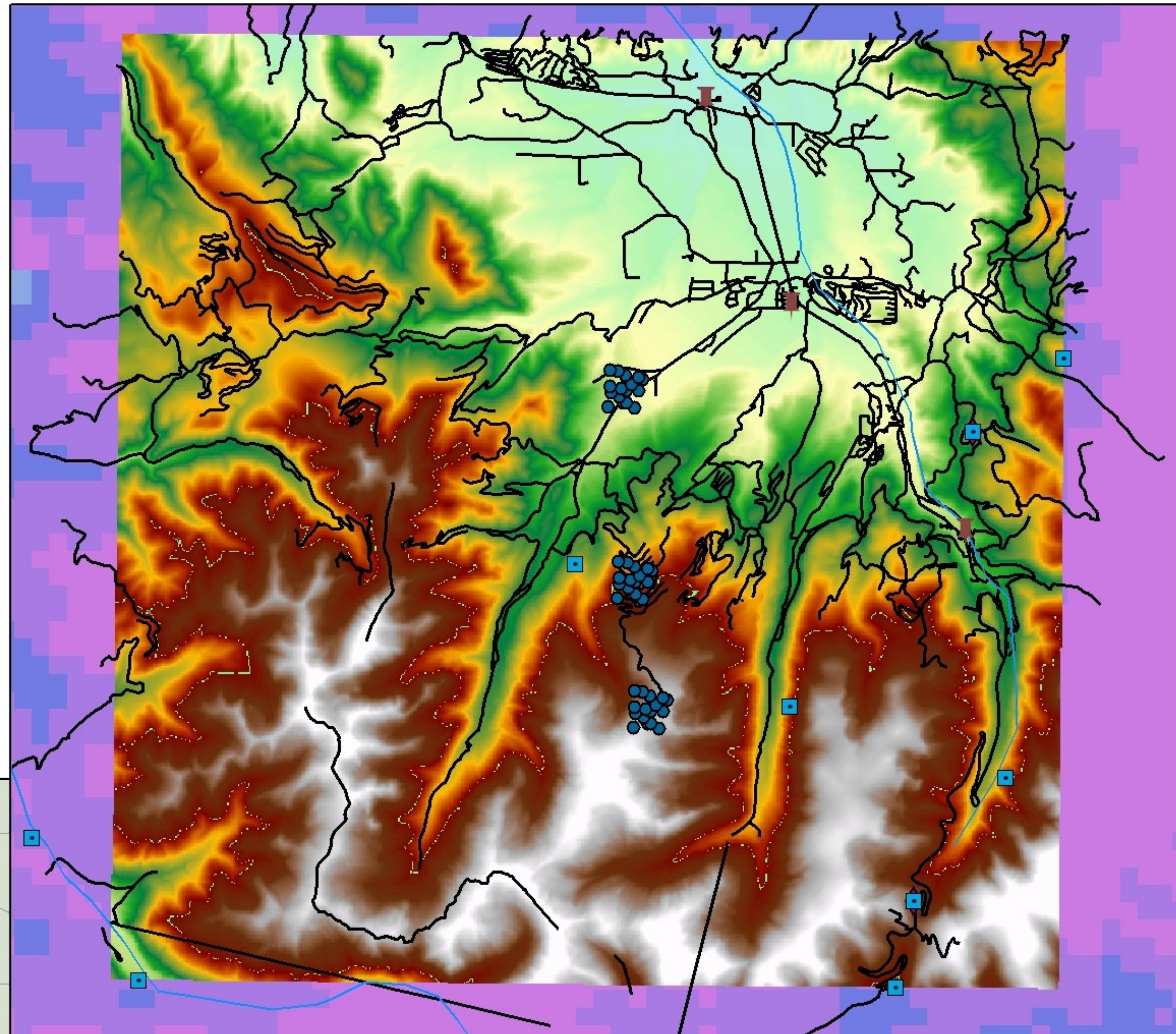
→ Giving 2x daylight passes (and 2x nighttime passes)

Sinusoidal Projection

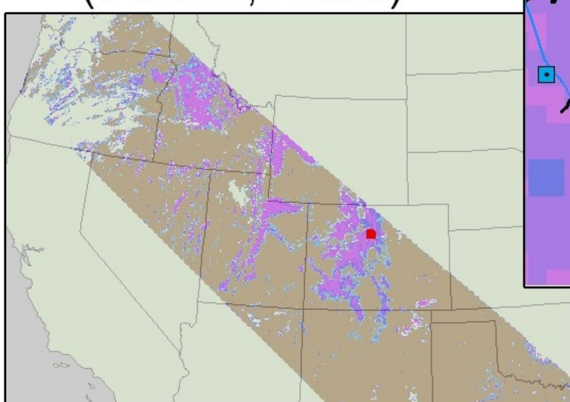
Main limitations – cloud obstruction, and

Difficult to identify cirrus clouds vs. snow

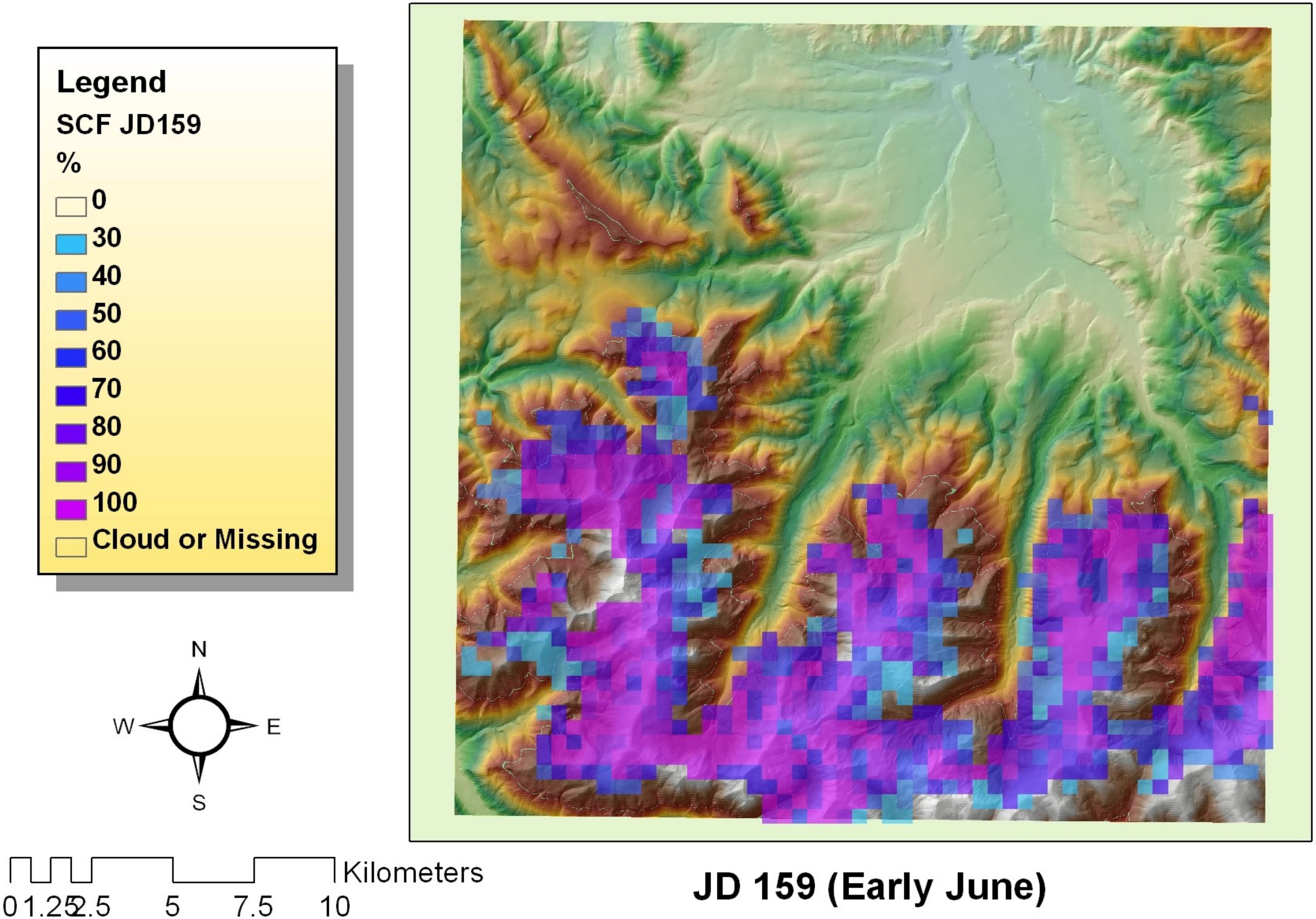
Project Area of Interest: Fraser, Colorado



MODIS Snow Cover Fraction (JD098, 2003)



MODIS SCF - 2003



JD 159 (Early June)

Microwave Sensors

- Measure microwave brightness temperatures from emitted radiation from the snowpack surface, since snow crystals are effective scatterers of microwave radiation.
- Deep snowpacks -

  ➔ More snow crystals to scatter microwave energy away from the sensor,

  ➔ Since microwave brightness temperatures are generally lower for deep snowpacks (more scatterers) than they are for shallow snowpacks (fewer scatterers)

SSM/I SWE and Snow Cover

(Defense Meteorological Satellite Program; DMSP)

- Passive Microwave Channels (Ghz): 19V, 19H, 22V, 37V, 37H, 85V,85H
- Empirical "NSIDC Algorithm" *based on [Chang, 1987]:*

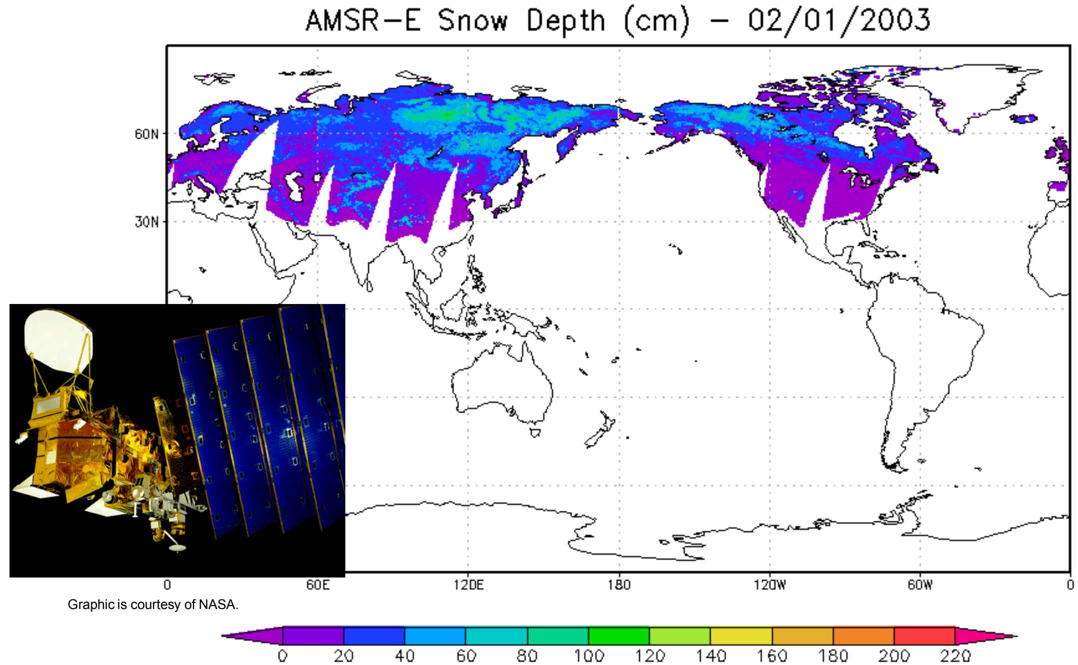
SWE (mm) = 4.77 * ((T19H - 6) - (T37H - 1))

-- (T19H and T37H in Kelvins)

- Global dataset from 1987 to present at 25 km resolution
- EASE-Grid Lambertian Equal Area

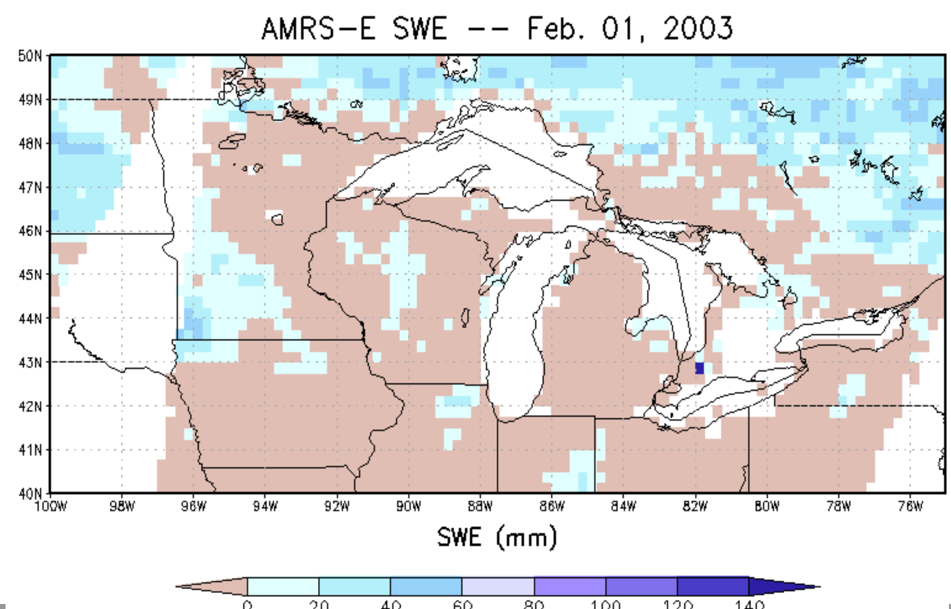
<u>Main limitations</u> – poor spatial resolution, no thin or wet snow, mountain and vegetation impacts on signal

Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) instrument aboard NASA's Aqua satellite

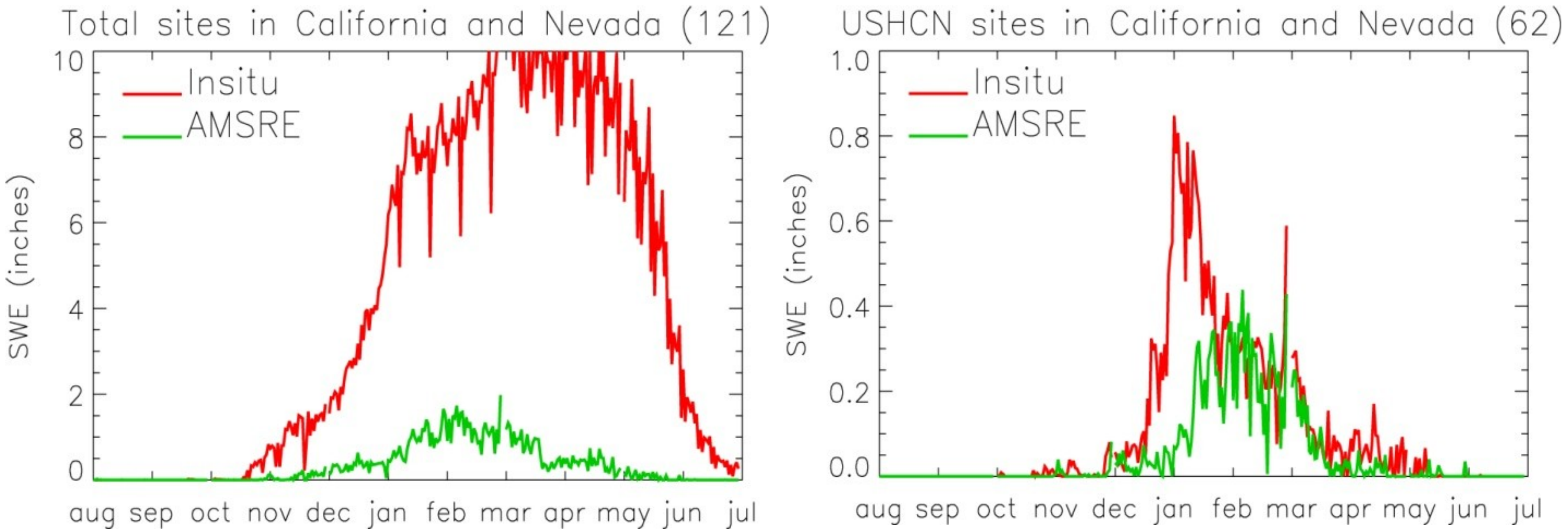


Graphic is courtesy of NASA.

- Global passive MW snow depth retrievals (coverage: 2002-present)
- Forest attenuation effects are corrected for
- Snow density is used to derive SWE from snow depth
- 25 km EASE-grid used



Issues with AMSR-E and Other Passive MW Sensors



<u>Some of AMSR-E SWE issues result from</u>:

(1) underestimation of the SWE retrievals when compared with in-situ measurements (e.g., SNOTEL sites),

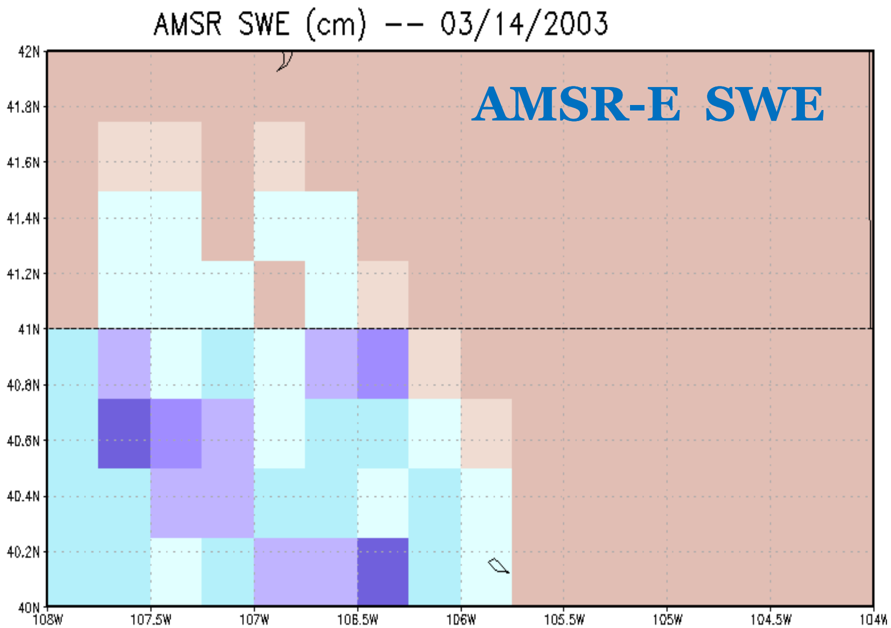
(2) comparisons made on different spatial scales (e.g., point-to-area)

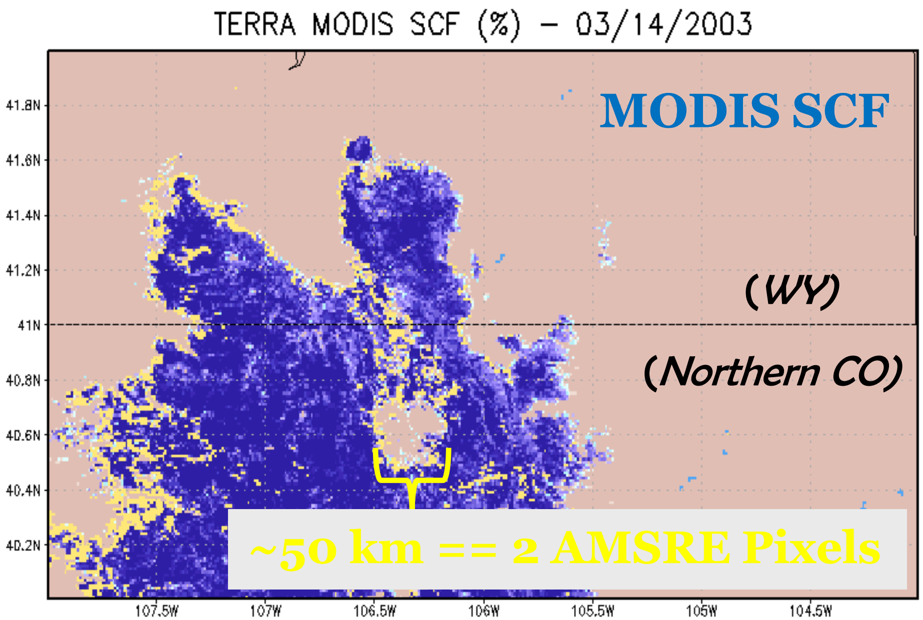
(3) land surface complexities within AMSR-E footprints

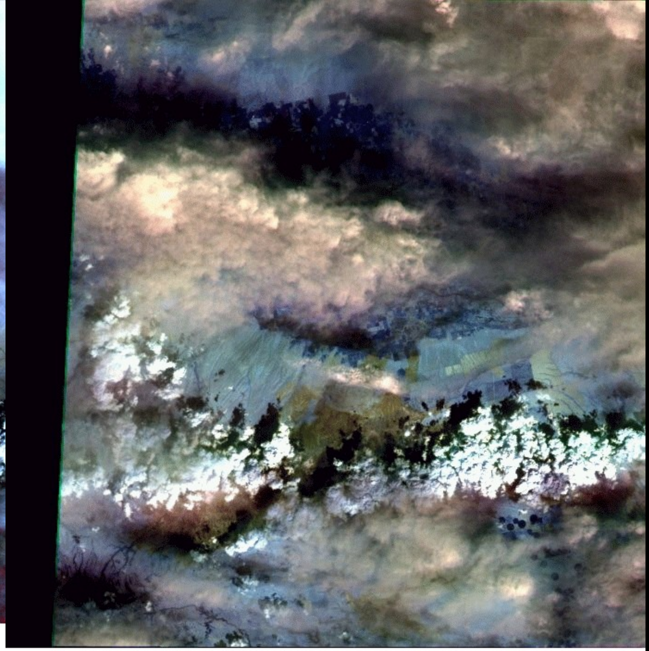
(From J. Dong (NCEP), C. Peters-Lidard (NASA) et al.)

Issues with MW Satellite-derived Snow Products

- Issues also arise from varying terrain, vegetation, soil moisture effects, etc.
- Also, due to its coarse spatial scale, a 25 km pixel could become skewed/shifted (e.g., due to reprojection) and values not be fully representive (see below).

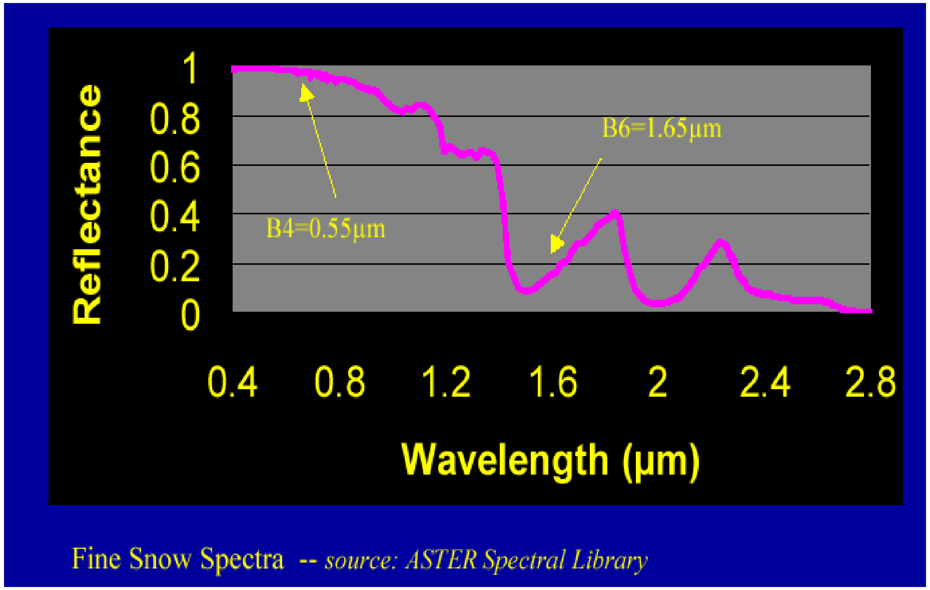






Terra's ASTER Sensor:

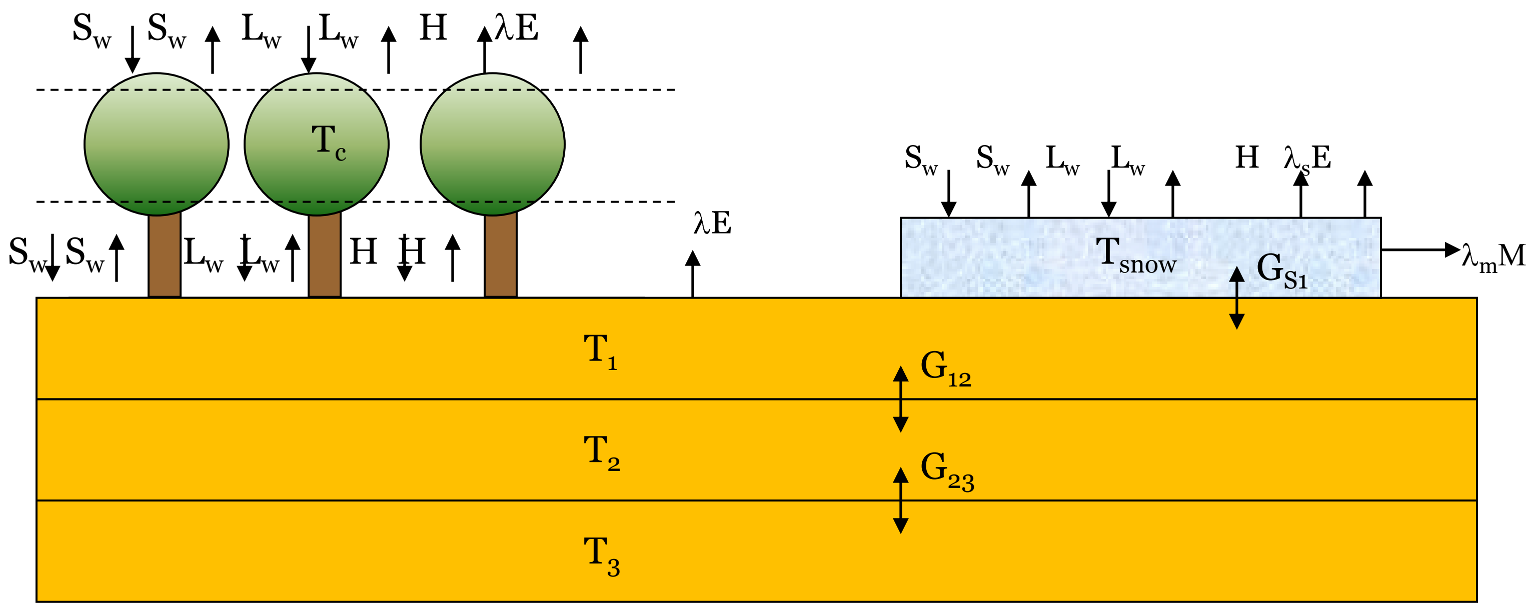
- Visible Snow Cover Retrievals
- Resolution: ~ 100 m
- Only available when clouds are absent
- Similar to Landsat sensor – snow images, but more spectral bands and repeat times



Snow Hydrology Lecture

MODELING SNOWPACK CHARACTERISTICS AND DYNAMICS

In practice, several energy balance calculations may be combined into a single "model" … e.g., a **Land surface model (LSM)**



The trick is to keep the fluxes between the "control volumes" consistent. If the energy balance calculation for the snowpack includes a flux G_{S1} from the bottom of the pack to the ground, then the energy balance for the top soil layer must include an input flux of G_{S1}.

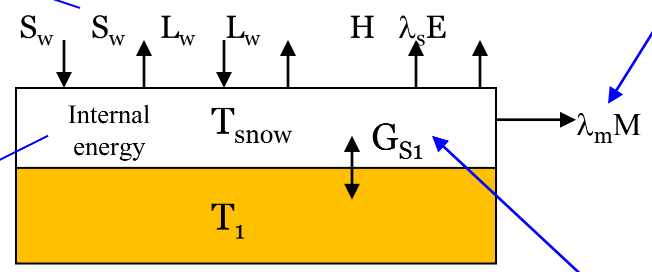
(From R. Koster; NASA)

Some Basic Snow Modeling Elements

Albedo is high when the snow is fresh, but it decreases as the snow ages.

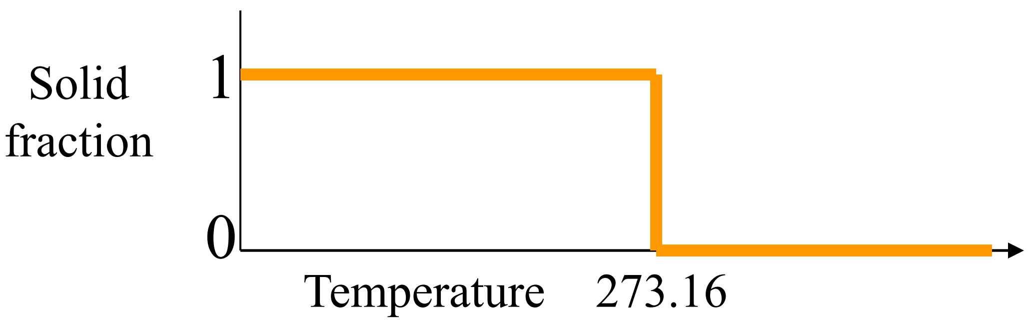
Internal energy a function of snow amount, snow temperature, and liquid water retention

Energy balance in snowpack



Snowmelt occurs only when snow temperature reaches 273.16°K.

Thermal conductivity within snow pack varies with snow age. It increases with snow density (compaction over time) and with liquid water retention.



(From R. Koster; NASA)

One Simple Snowmelt Model Approach …

1. Solve the energy balance for a layer and determine the updated temperature.
2. If the new temperature is **≤ 273.16ºK**, move to next timestep.
3. If the new temperature is **> 273.16ºK**, then recompute the energy balance, assuming the new temperature is exactly 273.16ºK.

   The **excess energy flux** obtained should be used to melt snow:

$$\textit{Excess energy flux} = \lambda_m M$$

where λ_m = latent heat of melting
M = snowmelt rate

(From R. Koster; NASA)

Importance of Modeling Snowmelt Timing Correctly

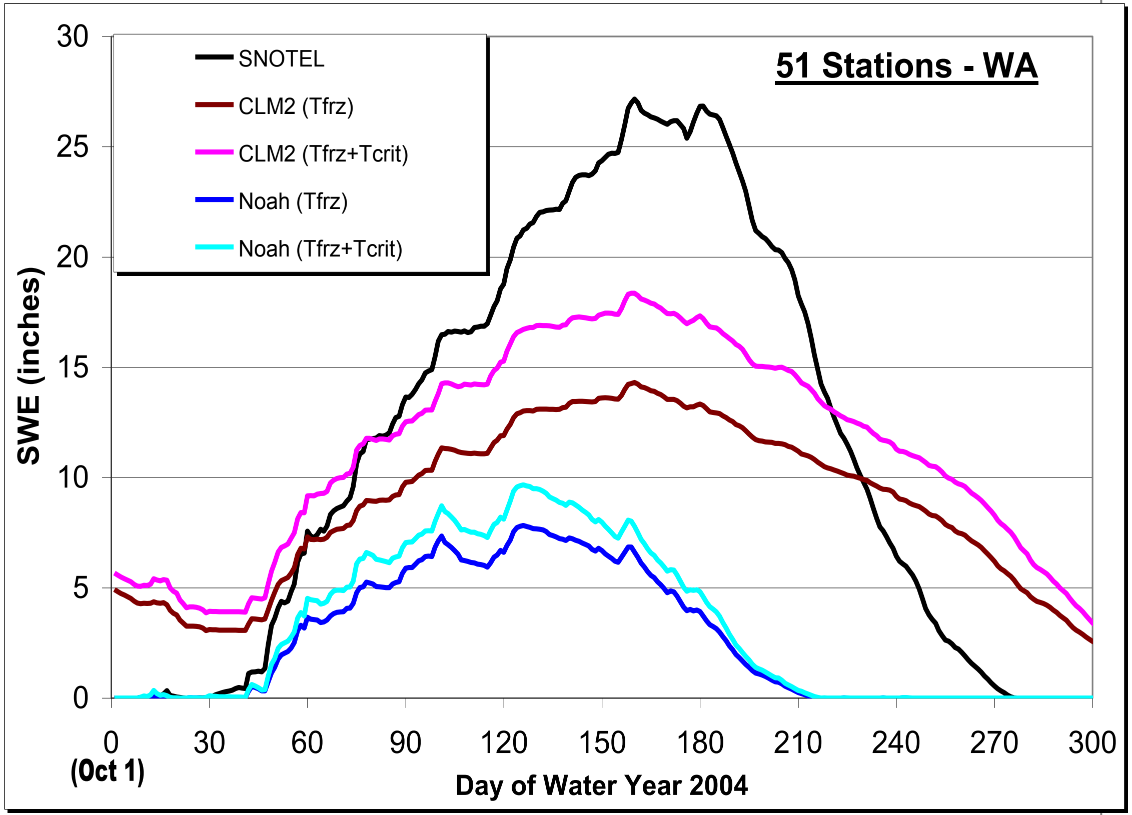
Land surface models and snow schemes are known to have biases and errors in their physics and physical parameterizations

(e.g., Slater et al., 2001; Sheffield et al., 2003; Pan et al., 2003; Feng et al., 2008).

For example, the Noah LSM tends to melt off its snowpack too early in the spring (e.g., Jin and Miller, 2007; Feng et al., 2008), even when a higher temperature threshold is used to determine snowfall

(in figure to the right).

With the snow melting off too soon, the errors in the land surface would potentially feedback onto an atmospheric model it's coupled to.



Representations of Snow Cover and SWE

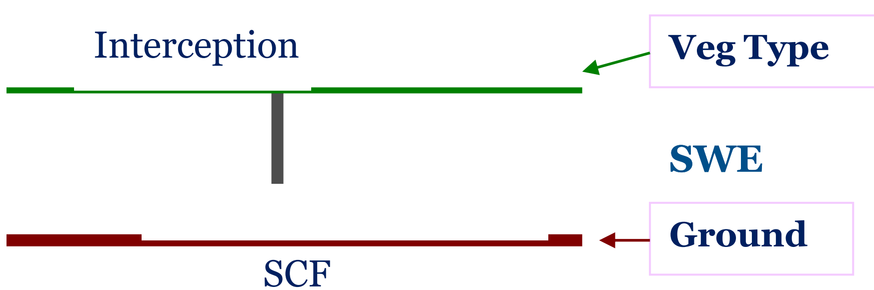
Climate Modeling

1. A land grid has multiple vegetation types plus bare ground.
2. Energy and mass balances.
3. For each vegetation-covered area, on the ground, one mean SWE, one SCF. Canopy interception and canopy snow cover.

Nature

Remote Sensing

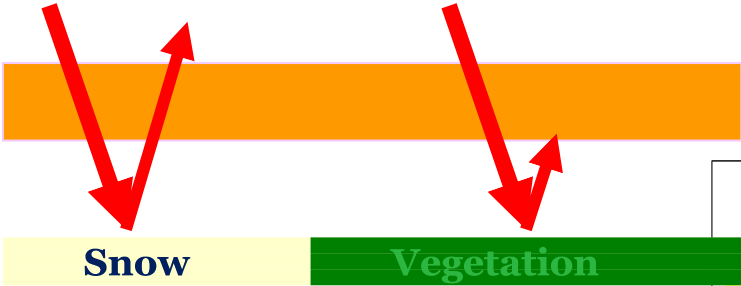
1. Pixels.
2. Integrated signals from multi-sources (e.g., snow, soil, water, vegetation), depending on many factors (e.g., view angle, aerosols, cloud cover, etc).
3. Each pixel, MODIS provides one SCF. AMSR provides one SWE.

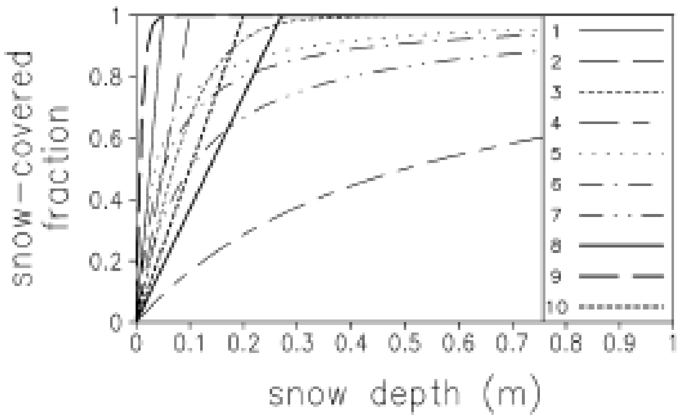


Snow Cover Fraction and Air Temperature

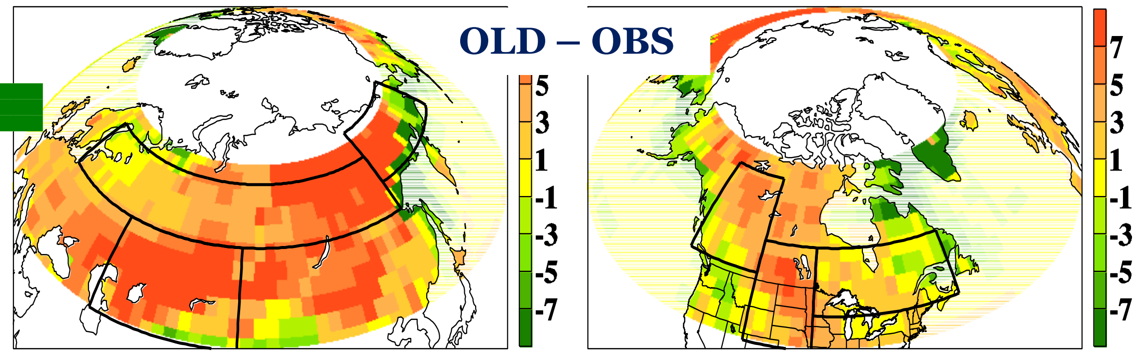
Smaller Snow Cover → Warmer Surface

$$SCF = \mathrm{anh}\left[\frac{h_{sno}}{2.5 z_{0g} (\rho_{sno} / \rho_{new})^{\alpha}}\right]$$

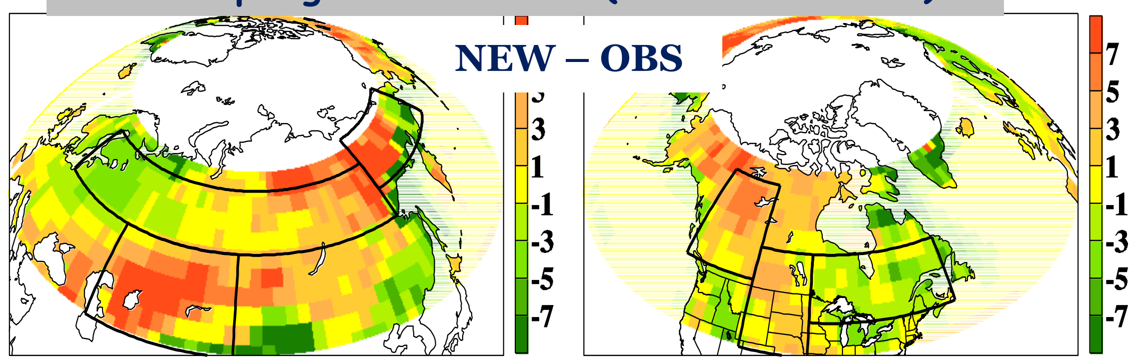




Liston (2004)
JCL



The new scheme reduces the warm bias in winter and spring in NCAR GCM (i.e. CAM2/CLM2).



* *(Z.-L. Yang, U.Texas – Austin)*

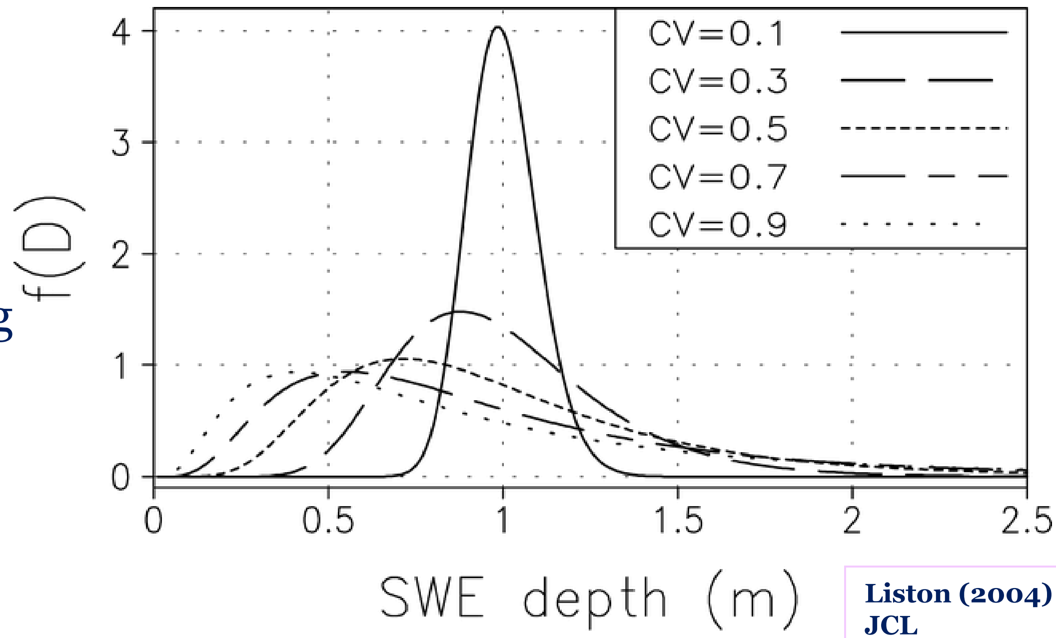
Theory of Sub-grid Snow Cover

Liston (2004), "Representing Subgrid Snow Cover Heterogeneities in Regional and Global Models". *Journal of Climate*.

The snow distribution during the accumulation phase can be represented using a lognormal distribution function, with the mean of snow water equivalent and the coefficient of variation as two parameters.

The snow distribution during the melting phase can be analyzed by assuming a spatially homogenous melting rate applied to the snow accumulation distribution.

CV – Coefficient of Variation

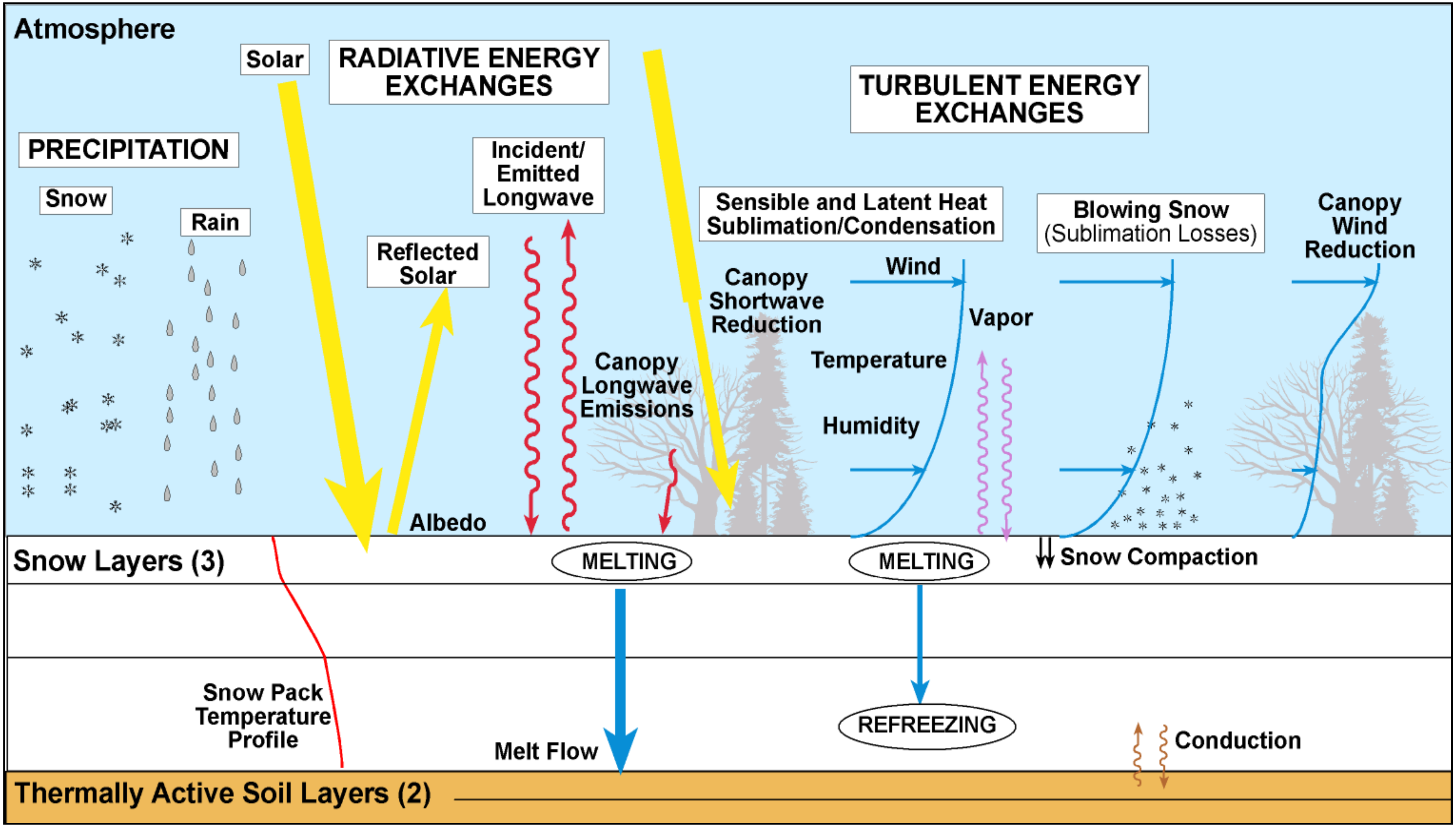


Liston (2004)
JCL

* (Z.-L. Yang, U.Texas – Austin)

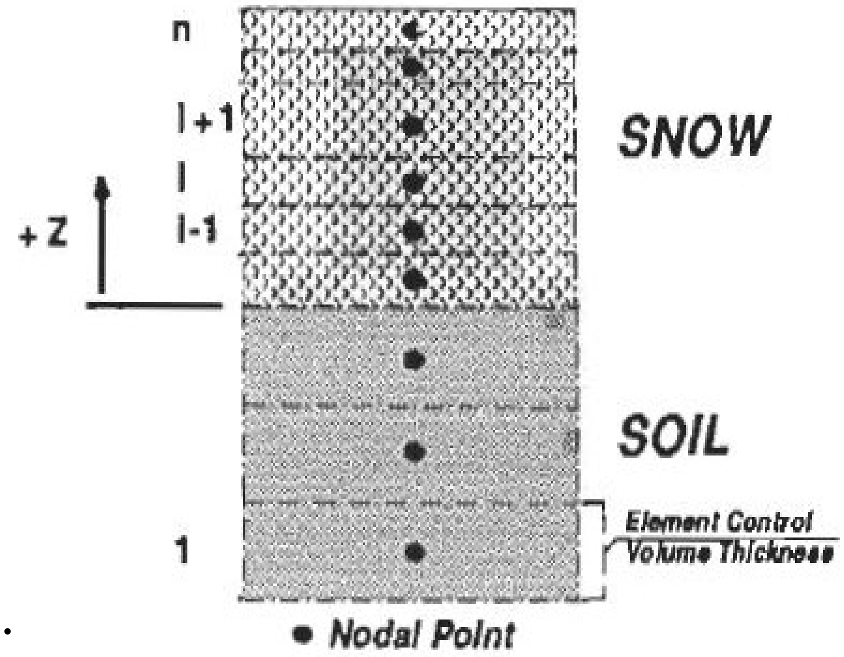
Snow Model Physics – In Operations

Multi-layer Energy- and Mass-Balance Model

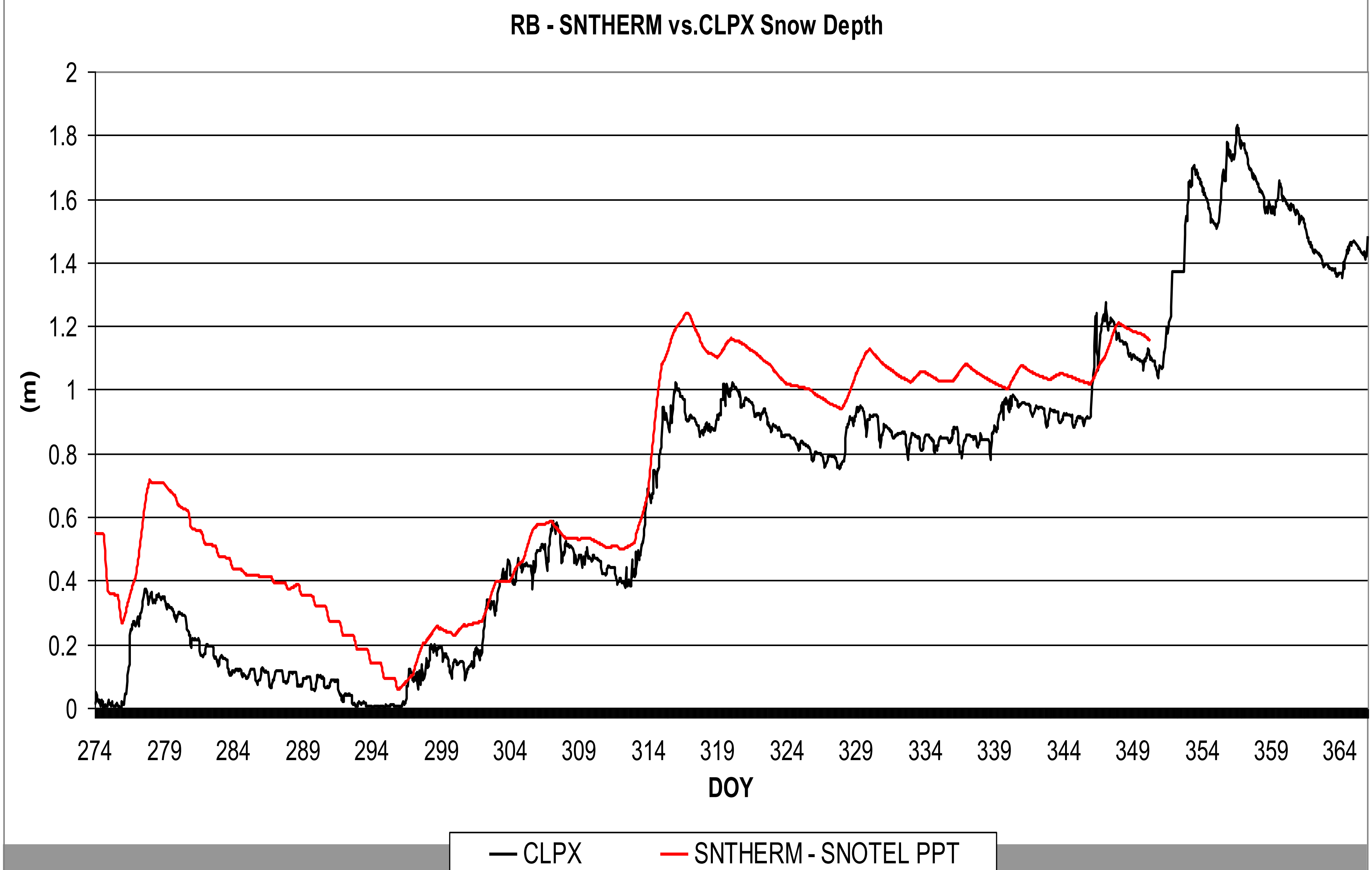


SNTHERM (SNow THERmal Model):
One of the more complicated snow schemes of today …

- SNTHERM numerical scheme divides both soil and snow layers in to finite element increments known as "nodes". The model can maintain around 23 nodes within the snow pack layer.
- Each node is characterized by its own temperature, water content, grain size, and thickness.
- For inputs, SNTHERM requires typical meteorological forcing (e.g.):
  - radiation fluxes,
  - liquid water precipitation
  - air temperature
- Certain model parameters (e.g.):
  - Met. station height
  - basic soil type
  - snow grain material characteristics.



SNTHERM Run - Rabbit Ears: Buffalo Pass (CLPX)



An Evaluation of Snow Model Complexity at Three CLPX Sites

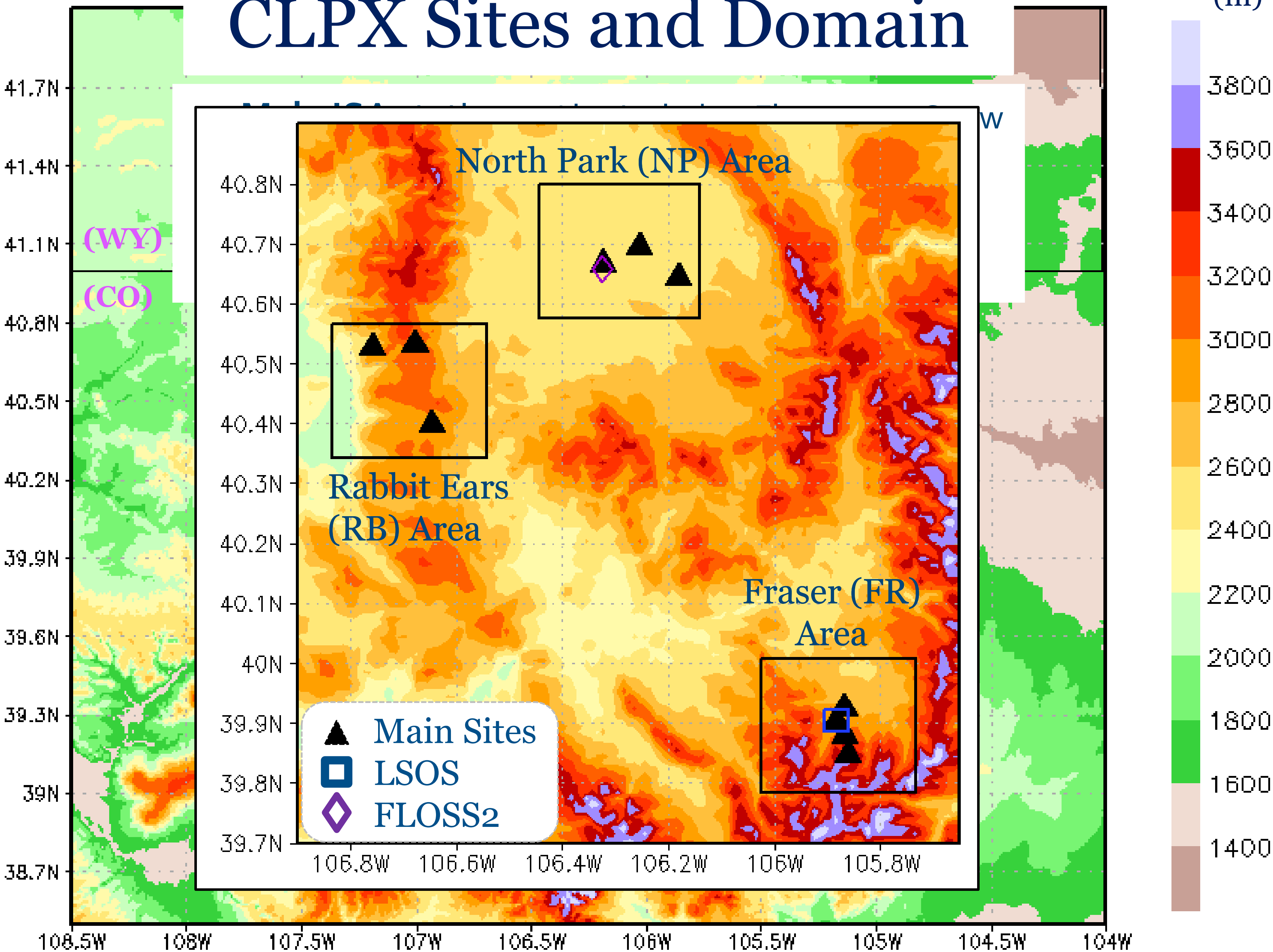
Results from the article:

Xia Feng, Alok Sahoo, Kristi Arsenault, Paul Houser, Yan Luo, and Tara Troy, 2008: The Impact of Snow Model Complexity at Three CLPX Sites. *Journal of Hydrometeorology*.

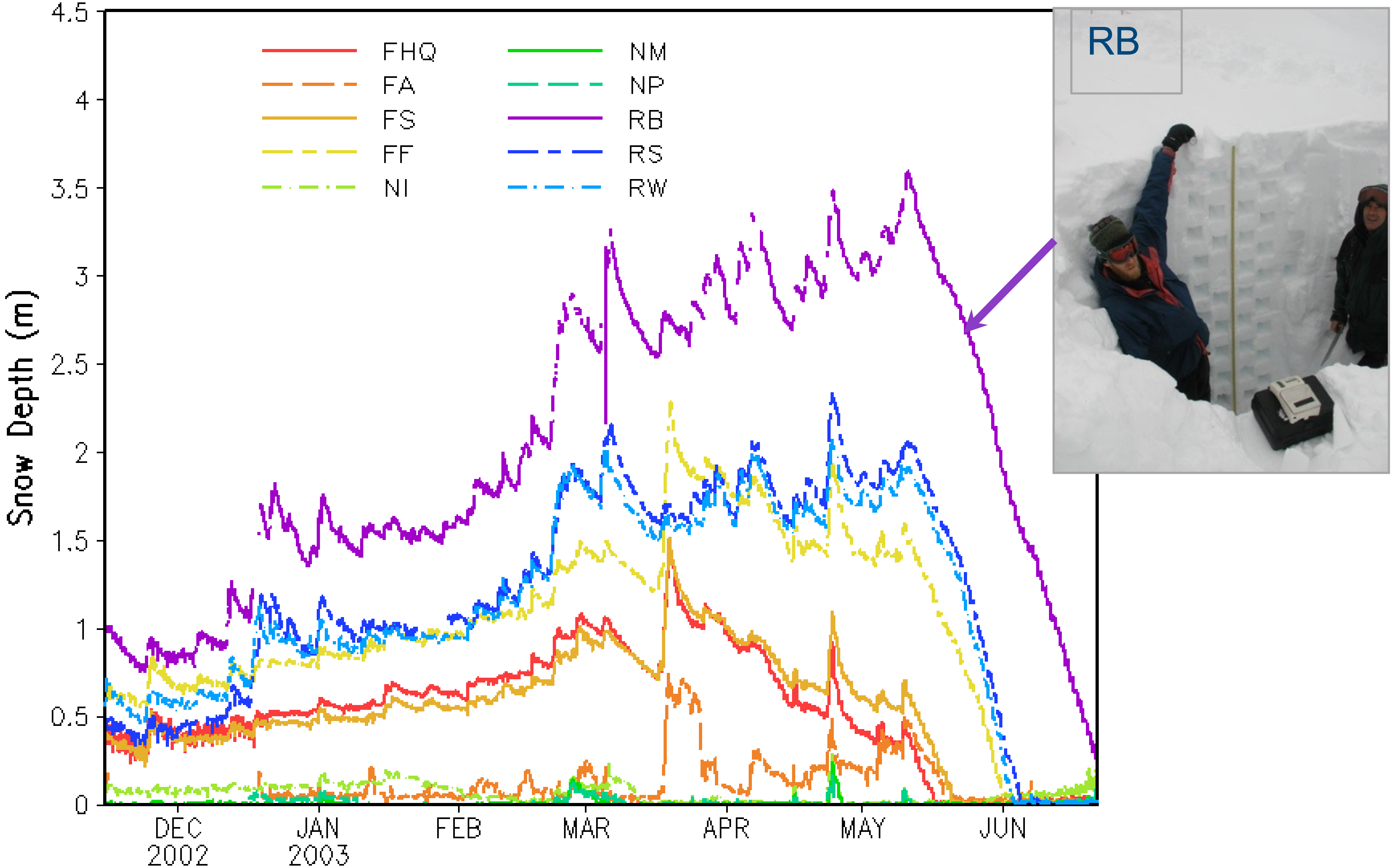
Overview:

- A comparison between five land surface models of varying complexity in terms of the snowpack physics at three different Cold Land Processes Experiment (CLPX) instrument sites in Colorado

CLPX Sites and Domain



Snow Depth Variability Among ISA Sites



Upper right picture from: *http://www.nohrsc.nws.gov/~cline/clp/field_exp/clpx_02/update_020224.html*

Models Used in Comparison

1. **SSiB**: COLA's Simplified Version of the Simple Biosphere Model (Xue et al. 1991)

2. **Noah (2.7.1)**: NCEP's Noah Land Surface Model (Ek et al. 2003)

3. **VIC**: Variable Infiltration Capacity Macroscale Hydrologic Model (Liang, 1994)

   - Solves the full energy and water balance on a grid mesh basis;

4. **CLM3**: Community Land Model version 3 (Dai et al 2003):

   - Solves snow cover variability with nested grid

5. **SNTHERM**: U.S. Army Cold Regions Research and Engineering Laboratory Model (Jordan, 1991)

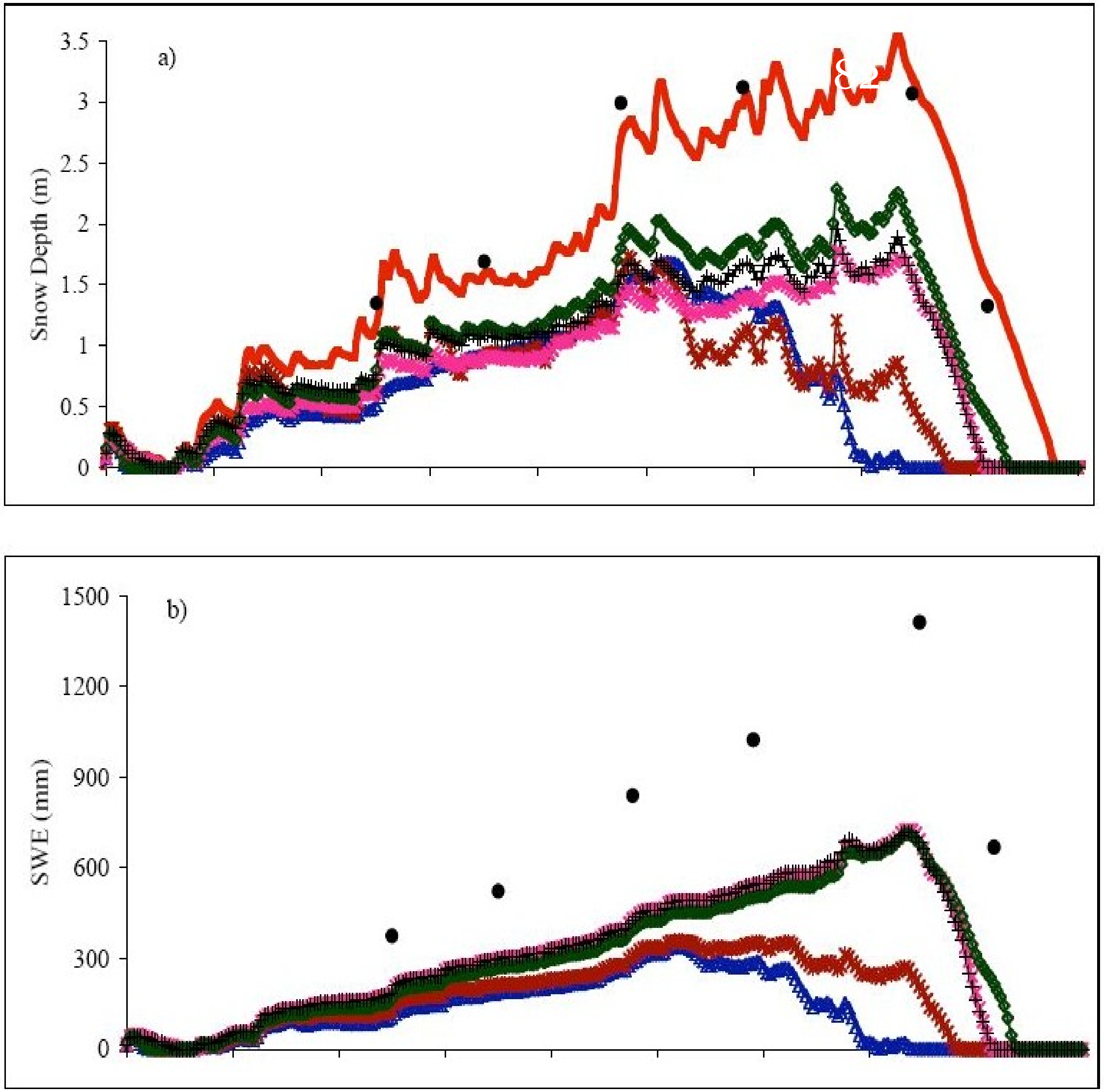
   - Simulates multiphase water and energy transfer processes in snow layers based on mixture theory.

Cold Land Processes Experiment Sites (Main ISA Sites)

1) Rabbit Ears MSA – Buffalo Pass Site (RB)
2) Frasier MSA – Alpine Site (FA)
3) Frasier MSA – Headquarters Site (FHQ)

Site	Latitude and longitude (N,W)	Soil Temperature (°C) (5cm, 20cm, 50cm)	Elevation (m)	Soil Type	Vegetation Type
RB	(40.53 °,106.68 °)	7.772, 6.297, 6.977	3200	Loam	Grassland
FA	(39,85 °,105.86 °)	6.807, 6.648, 3.014	3585	Sandy loam	Grassland
FHQ	(39.9 ° , 105.88 °)	-0.815, 0.109, 1.117	2760	Clay loam	Evergreen forest

RB: Snow Depth and SWE



Observations:

Snow Depth Obs = Red Line
Snow Pit Data – Black Dots

Models:

SSiB = Blue triangle

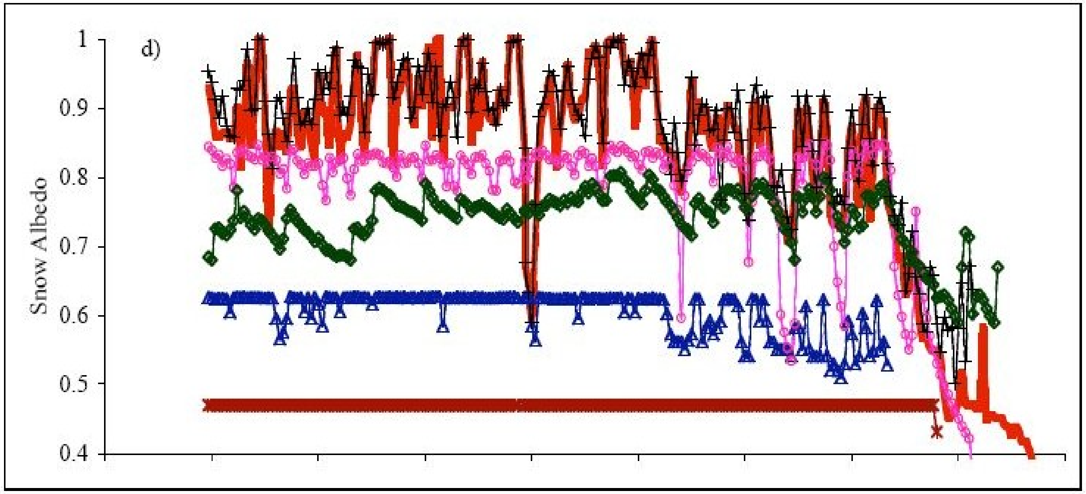
Noah = Brown star

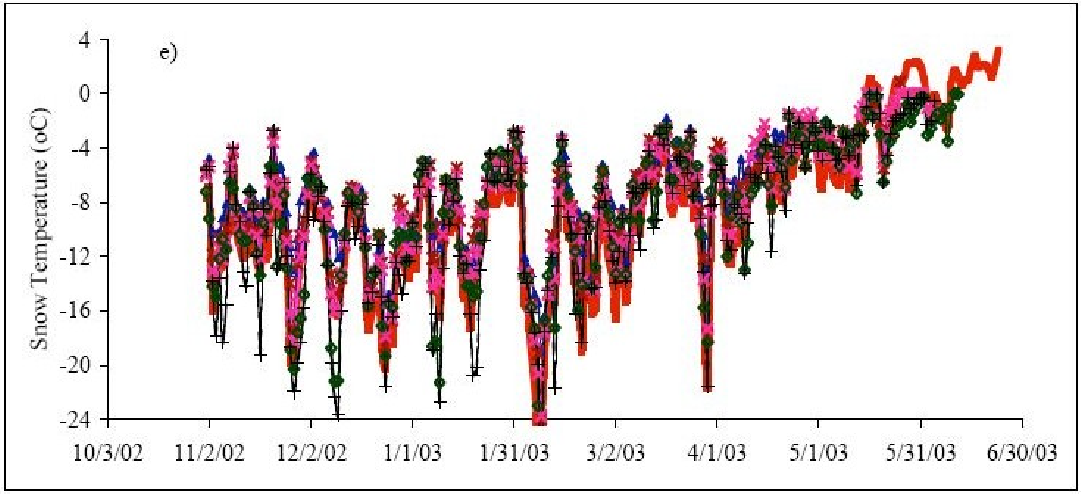
VIC = Pink circle

CLM3 = Green diamond

SNTHERM = Black plus

RB: Albedo and Snow Temperature





Observations:

Snow Depth Obs = Red Line
Snow Pit Data – Black Dots

Models:

SSiB = Blue triangle

Noah = Brown star

VIC = Pink circle

CLM3 = Green diamond

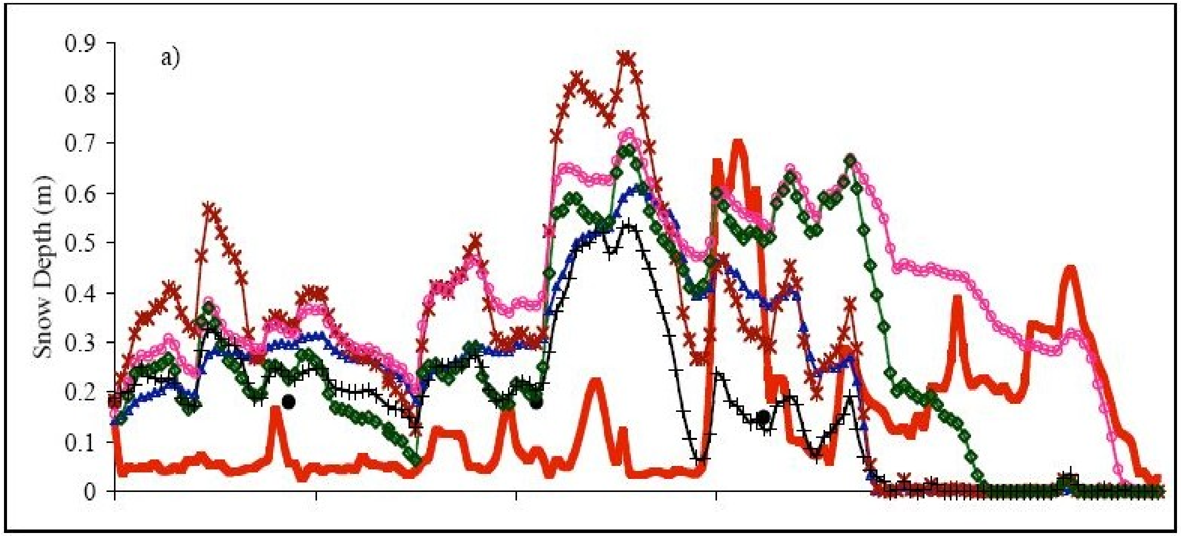
SNTHERM = Black plus

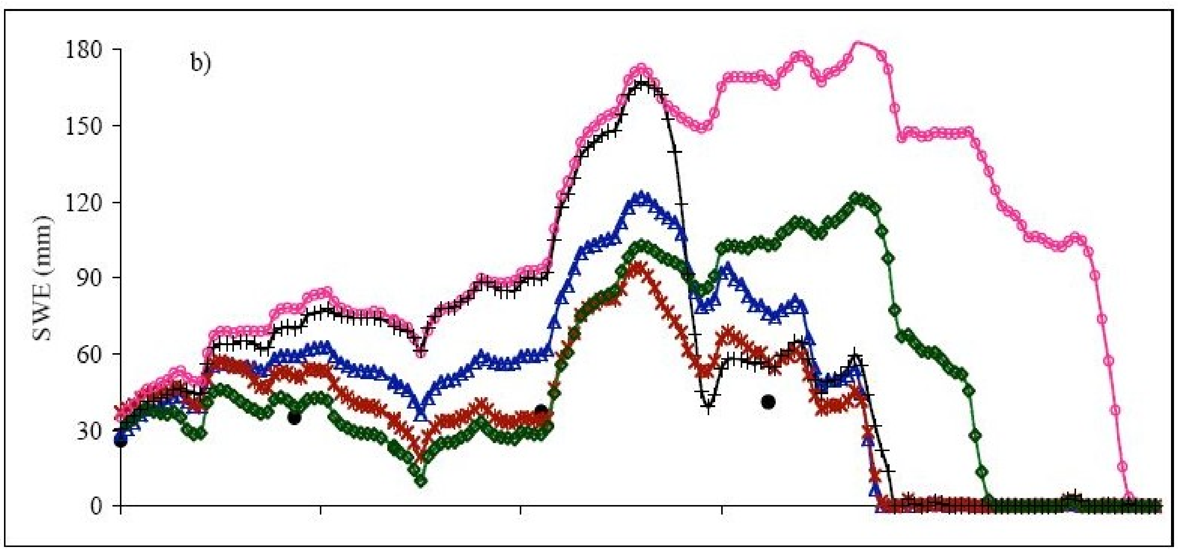
CLPX Site: Frasier – Alpine

The instrument heights for air temperature and relative humidity above the ground surface are 3 m in the Fraser. Wind speed measurement is taken from 10m.

Picture - ftp://sidads.colorado.edu/pub/DATASETS/CLP/data/ground_data/nsidc0172_met_main/photos/iop3/alpine

FA: Snow Depth and SWE





Observations:

Snow Depth Obs = Red Line
Snow Pit Data – Black Dots

Models:

SSiB = Blue triangle

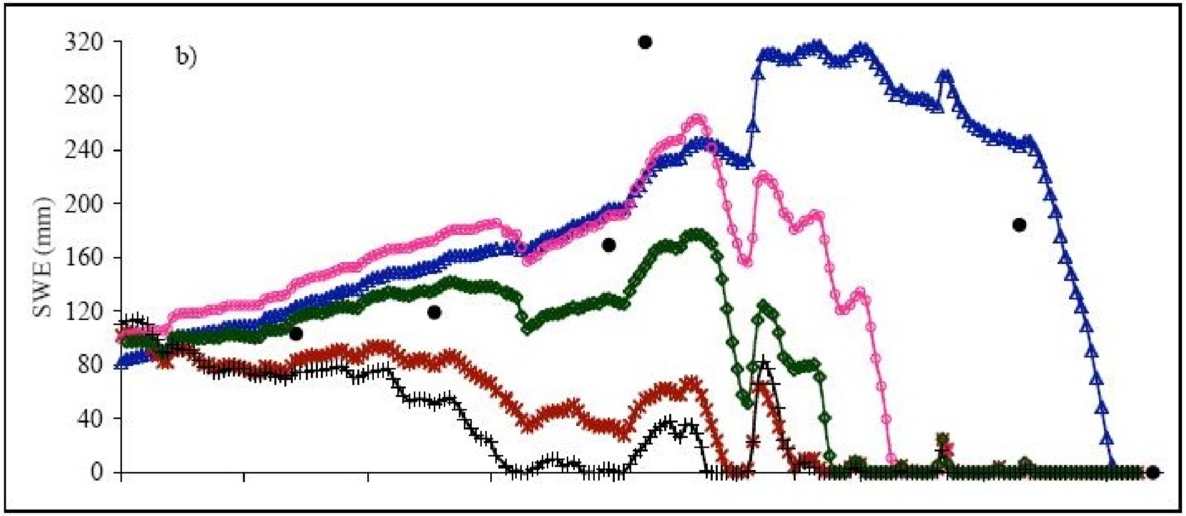
Noah = Brown star

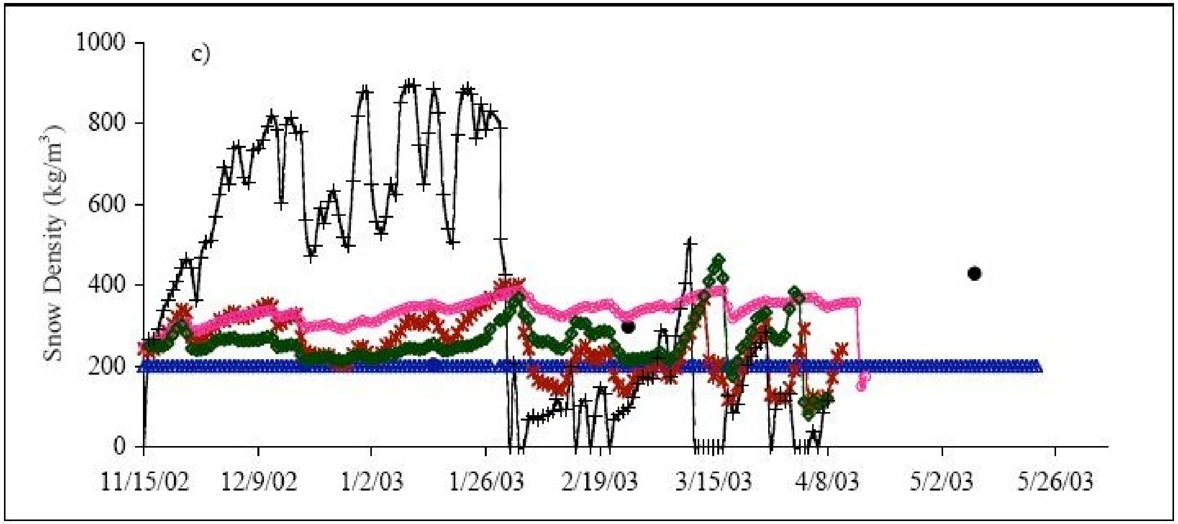
VIC = Pink circle

CLM3 = Green diamond

SNTHERM = Black plus

FHQ: SWE and Snow Density





Observations:

Snow Pit Data – Black Dots

Models:

SSiB = Blue triangle

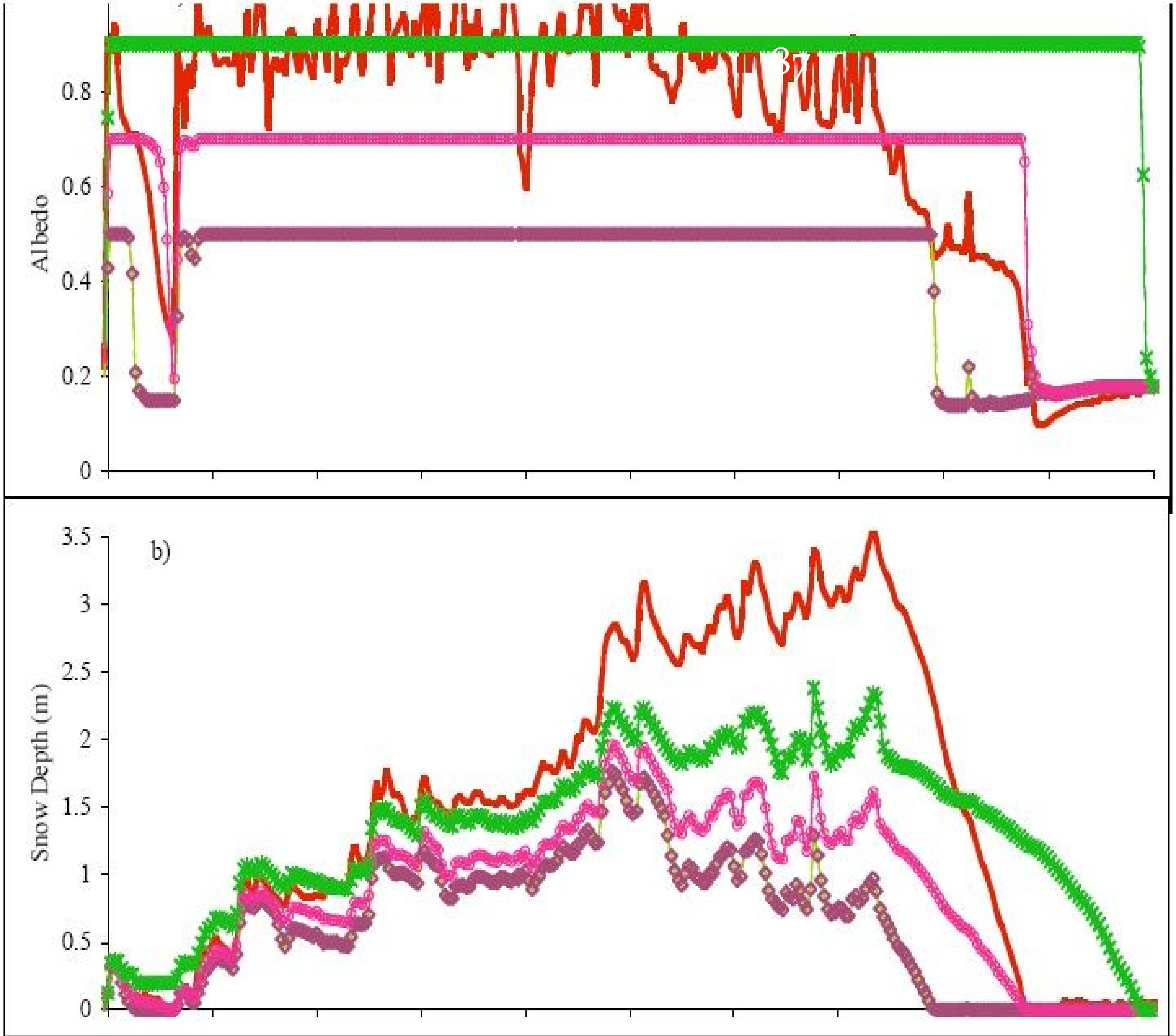
Noah = Brown star

VIC = Pink circle

CLM3 = Green diamond

SNTHERM = Black plus

Noah: Special Albedo Experiments



RB Site:
Snow Albedo

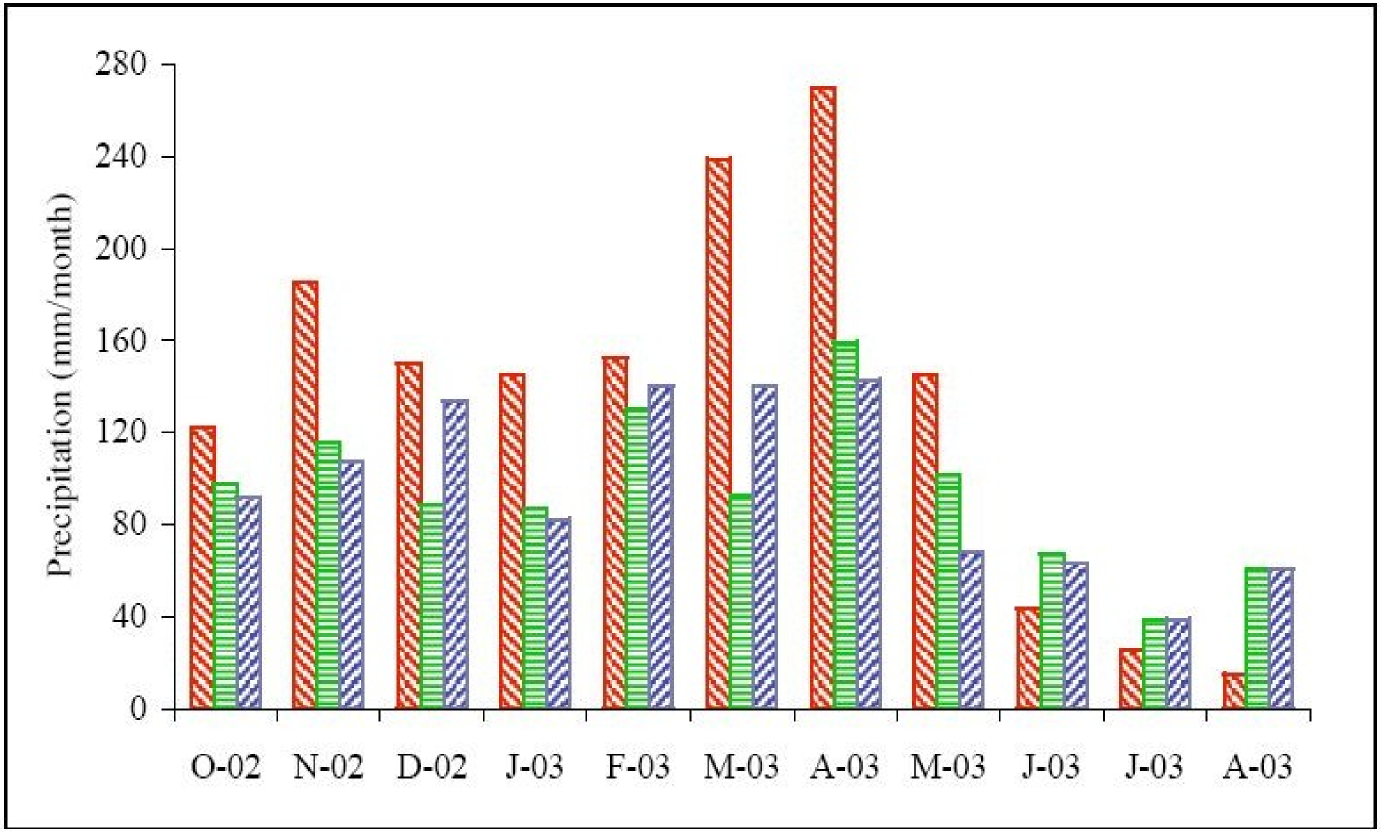
<u>0.5</u> = Purple

<u>0.7</u> = Pink

<u>0.9</u> = Green

<u>Obs</u> = Red

Precipitation Comparison and Experiments



RB Site:
Precipitation

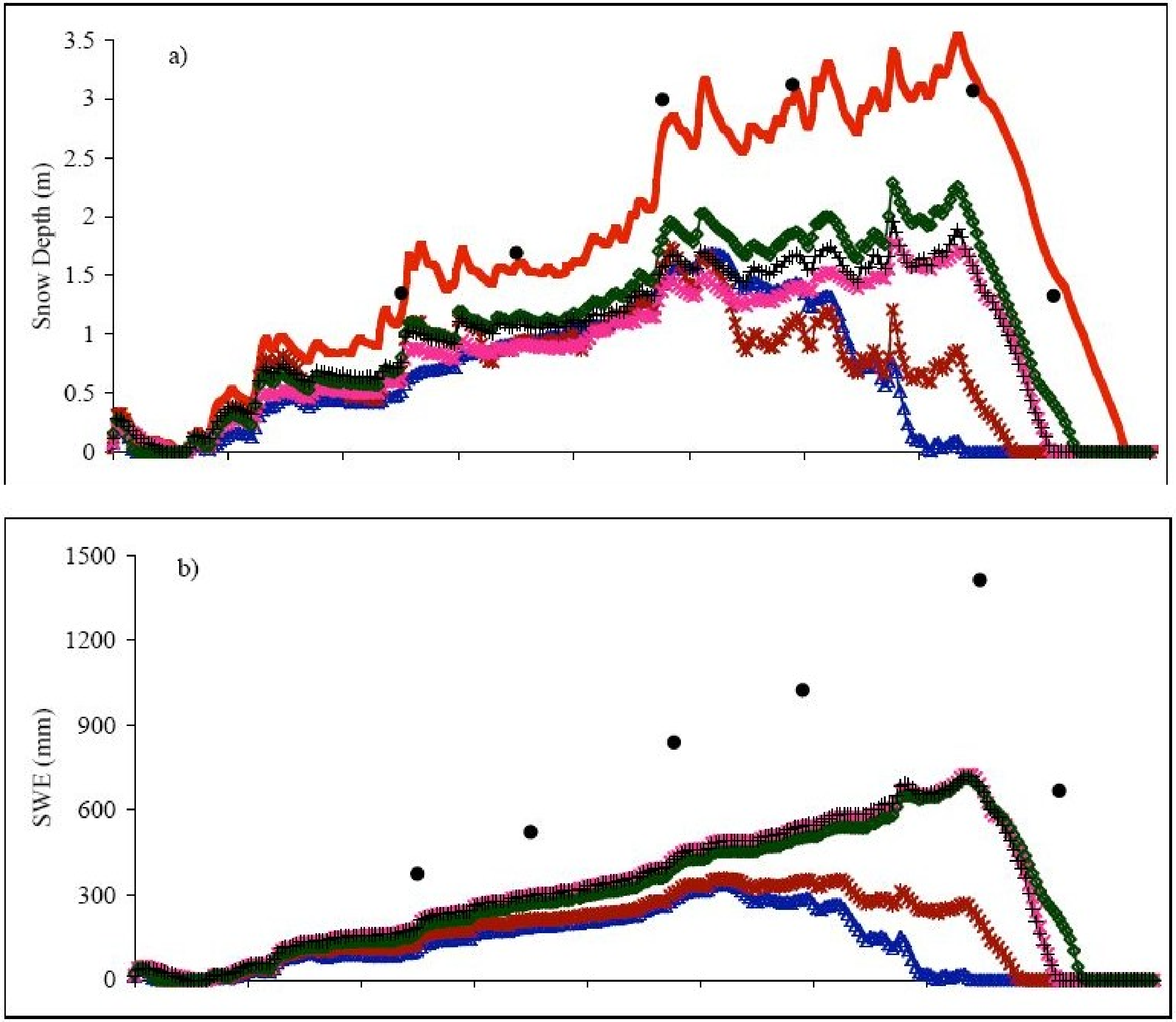
Daily Gage = Red

LDAS = Green

PSD = Blue

FIG. 11. Comparison of monthly precipitation (mm) from daily gauge measurement (left), LDAS (middle) and PSD (right) at RB during October 3 2002 to 60 June 2003.

RB: Snow Depth and SWE (LDAS-Only)



Observations:

Snow Depth Obs = Red Line
Snow Pit Data – Black Dots

Models:

SSiB = Blue triangle

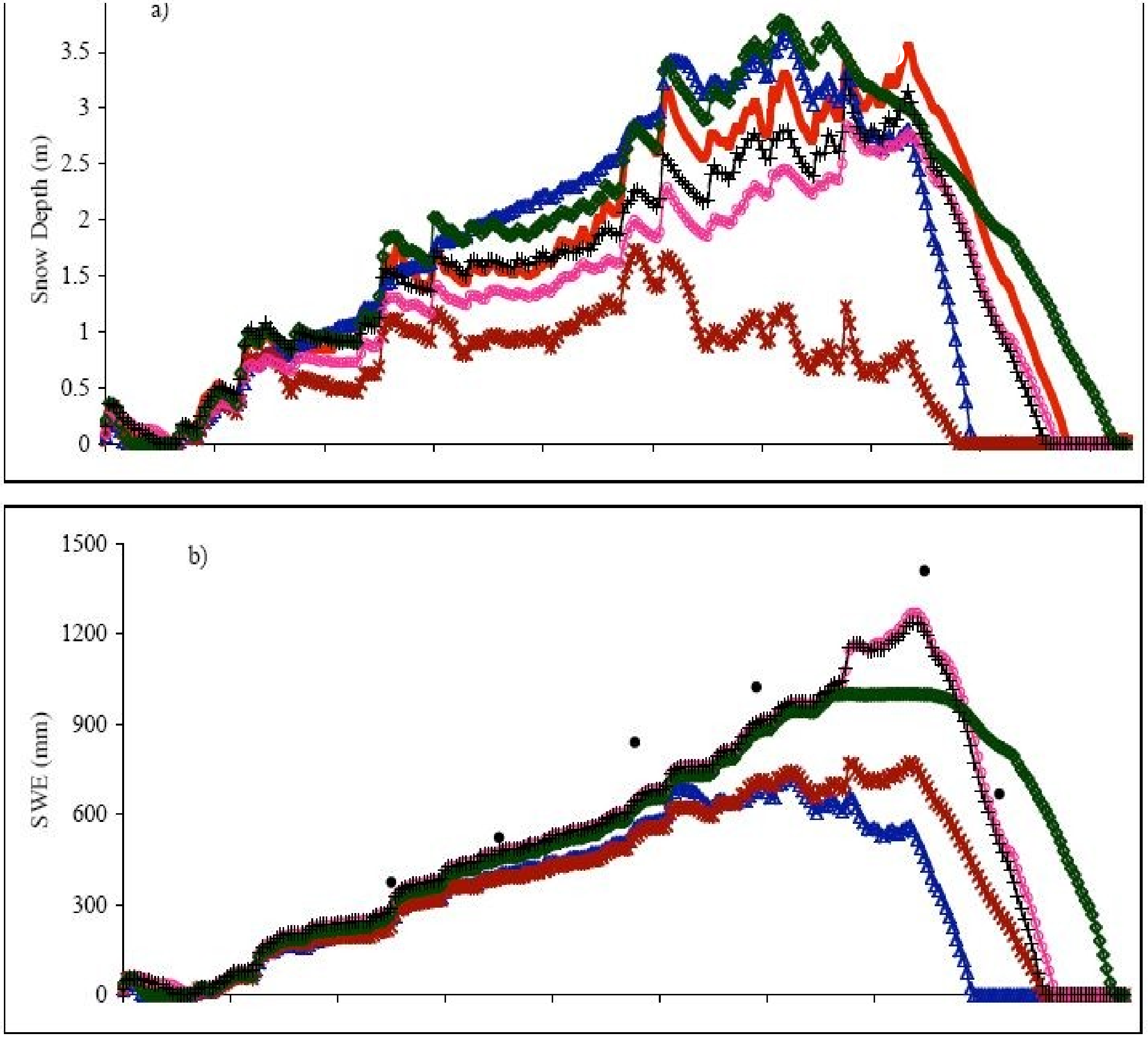
Noah = Brown star

VIC = Pink circle

CLM3 = Green diamond

SNTHERM = Black plus

LDAS-OBS: Snow Depth and SWE



Observations:

Snow Depth Obs = Red Line

Snow Pit Data – Black Dots

Models:

SSiB = Blue triangle

Noah = Brown star

VIC = Pink circle

CLM3 = Green diamond

SNTHERM = Black plus

Summary of Results

These models simulate the snow accumulation and snowpack ablation with varying skill when forced with the same meteorological observations, initial conditions, similar soil and vegetation parameters.

The simple snow schemes, such as SSiB and Noah capture snow accumulation at RB, however, both of them show inaccuracy in the simulation of SWE amount and the snowmelt timing.

VIC, CLM3 and SNTHERM produce similar snow depth, SWE and the snowmelt timing. However, they show substantial discrepancy in snow ablation through snow sublimation and snow melting due to different internal snow physics treatment.

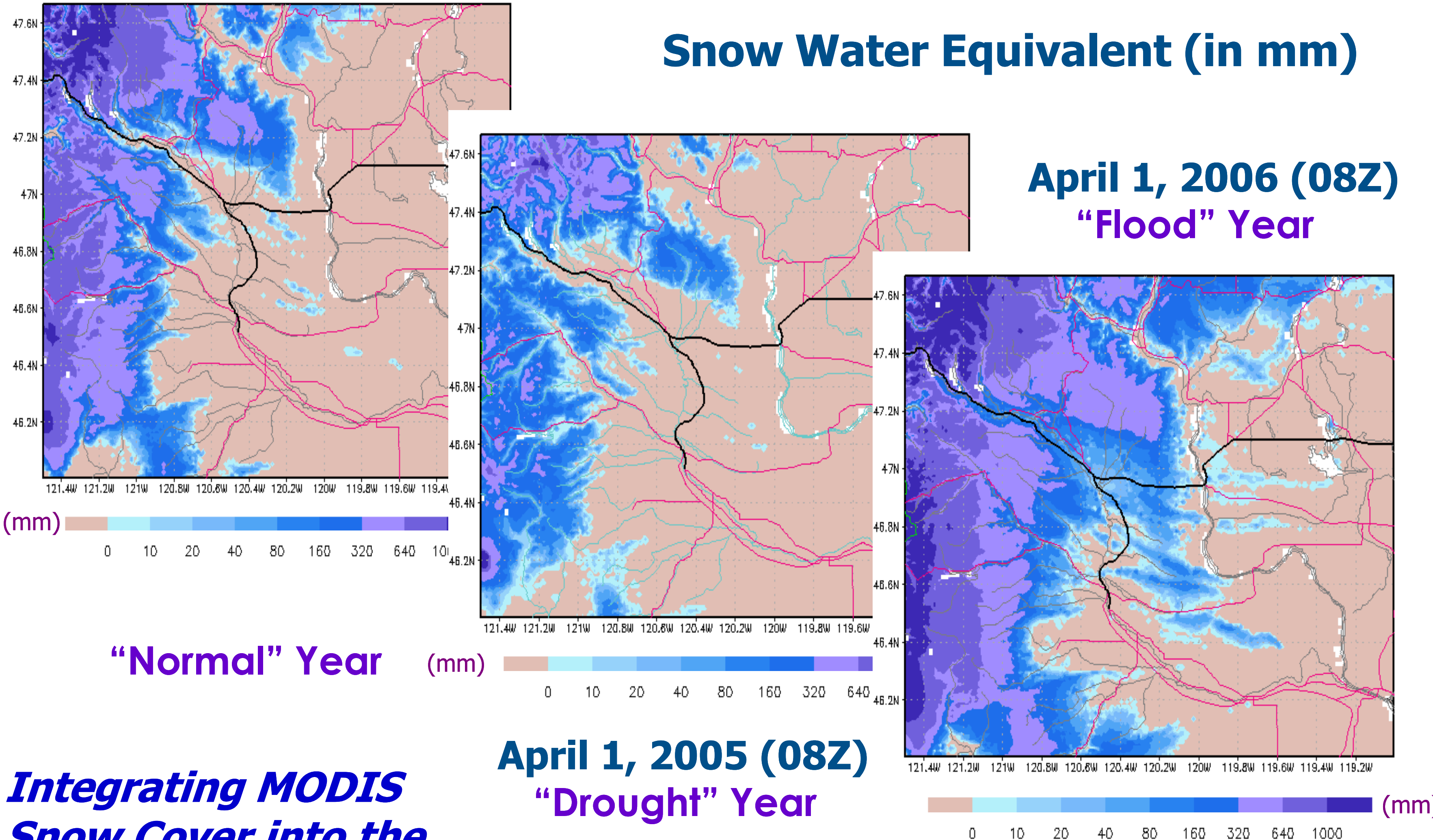
SNOW DATA ASSIMILATION

Snow Data Assimilation

- Much interest exists in improving hydrological predictions in complex terrain regions and global climate models using snow measurements.
- The assimilation of snow observations in land surface models is a promising approach to enhance runoff timing and discharges, mainly during critical melt periods.
- Also, improving weather and climate forecasts with assimilating observed snow data into coupled land-atmospheric models is another major area of research

Modeling Snow at Higher Resolutions

Snow Water Equivalent (in mm)



"Normal" Year

April 1, 2005 (08Z)
"Drought" Year

April 1, 2006 (08Z)
"Flood" Year

Integrating MODIS Snow Cover into the CLM → 3-Year Comparison for the <u>Yakima River Basin</u>

Different Data Assimilation (DA) Methods

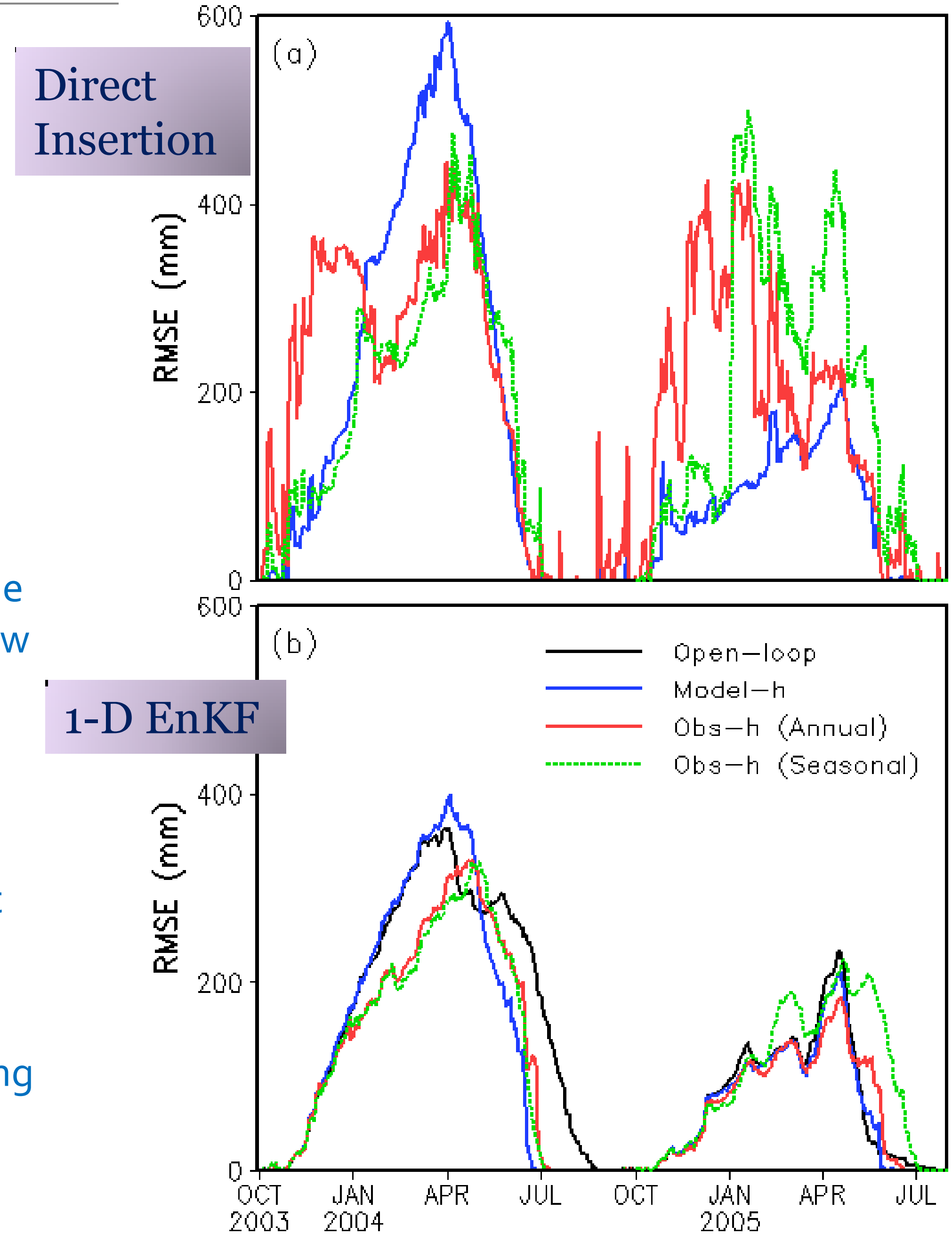
Assimilating MODIS SCF …

Direct Insertion (DI):

- Applying different snow depletion curves (SDCs) -- greatly increased the SWE errors, especially in the low snow year

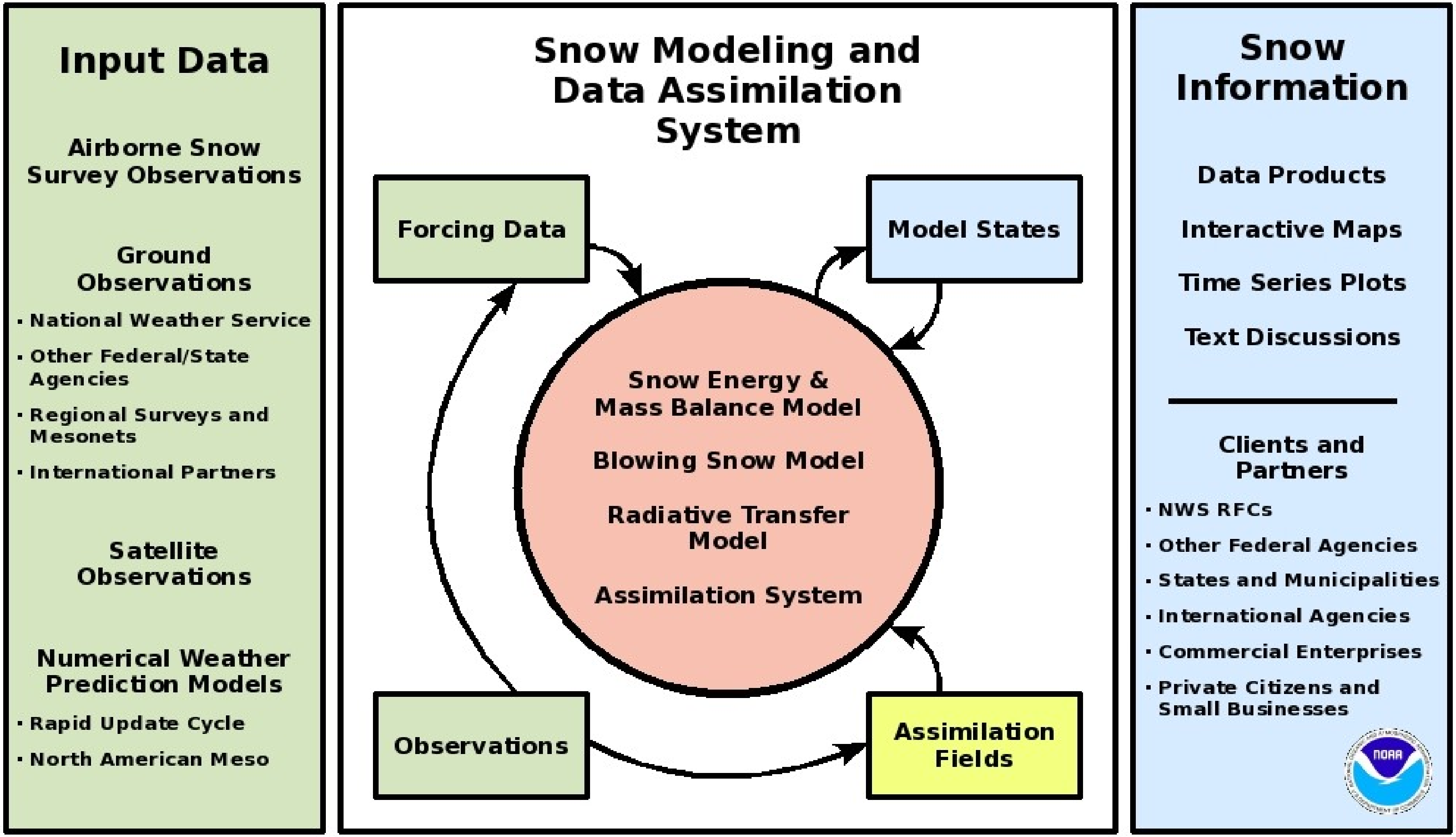
Ensemble Kalman Filter (EnKF**):**

- **Snow Depletion Curves,** which account for general relationships but not for interannual SCF-SWE variability
- Seasonal curves due better in applying the EnKF to reduce model SWE analyses

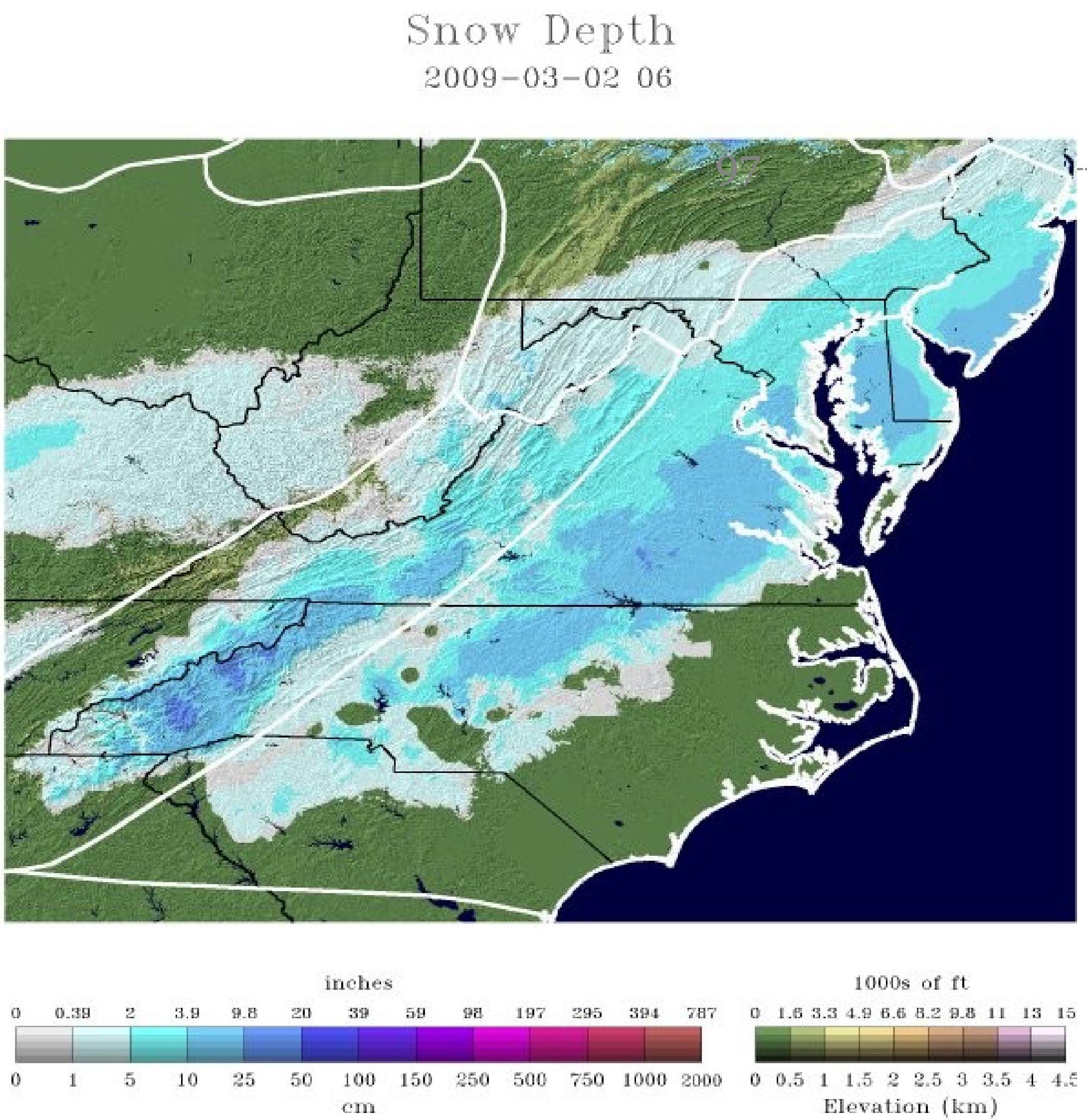


(Arsenault et al., 2010)

NOAA's - NOHRSC National Snow Analysis (NSA)



Example NSA Output



Snow Depth Map for March 2, 2009

Automated Model Discussion:
March 2, 2009

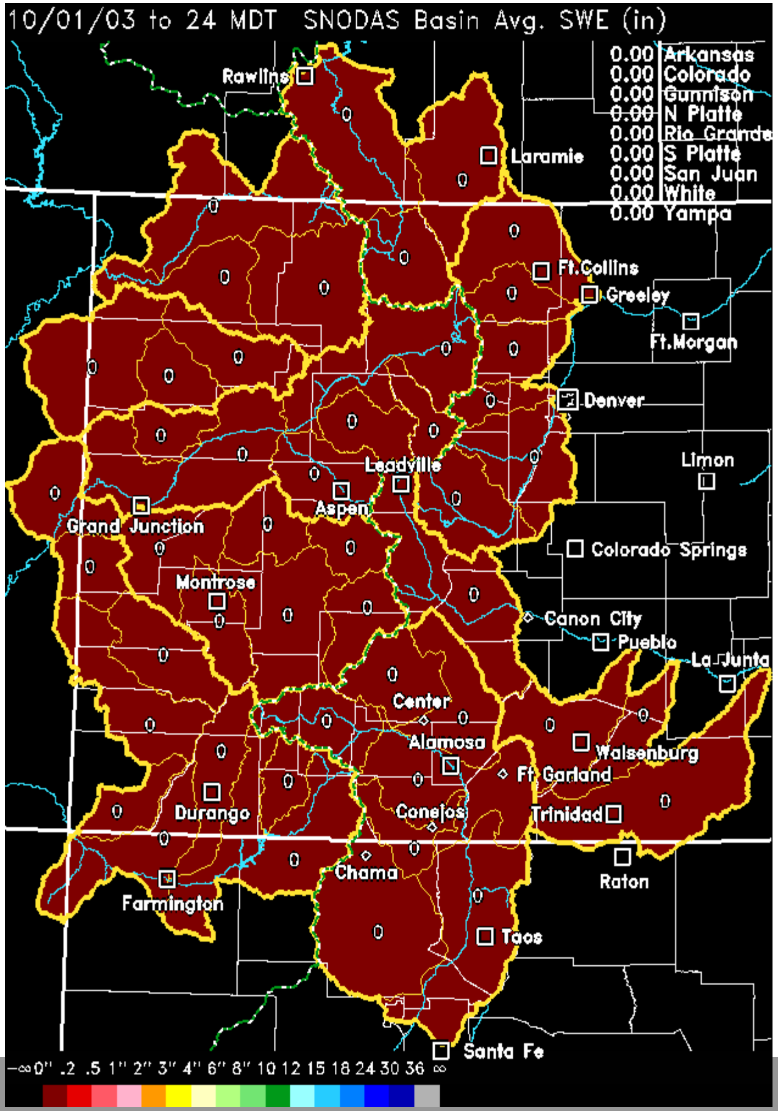
Area Covered By Snow:
59.5%

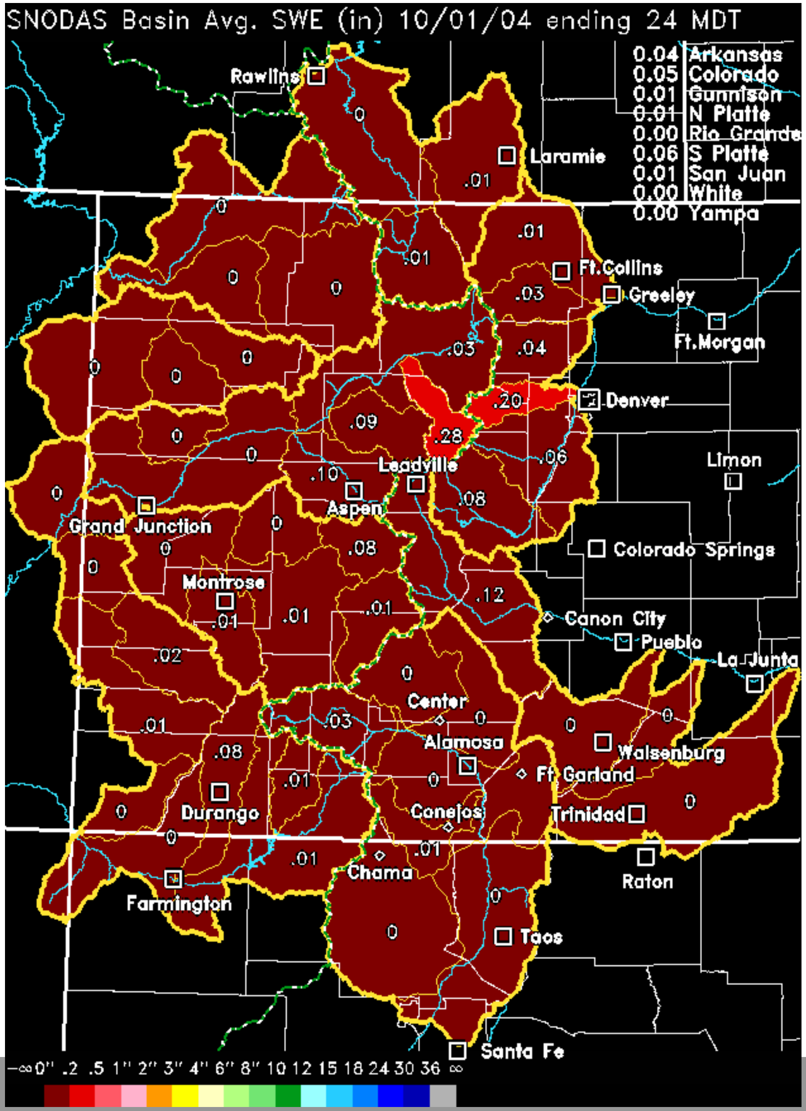
Area Covered Last Month: ***7.9%***

Snow Depth Average:
1.8 inches (for region)

Snow Water Equivalent Average: ***0.3 inches***

SNODAS Basin Average animations
2003-04 vs. 2004-05

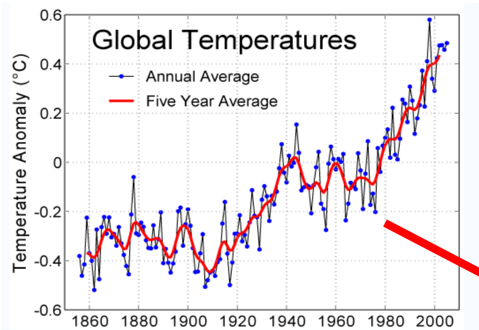




Snow Hydrology Lecture

CLIMATE CHANGE AND OTHER POTENTIAL ANTHROPOGENIC EFFECTS ON SNOW

Climate Change and an "Accelerated" Water Cycle ?



Atmospheric Moisture

Snow & Rain

Evaporation

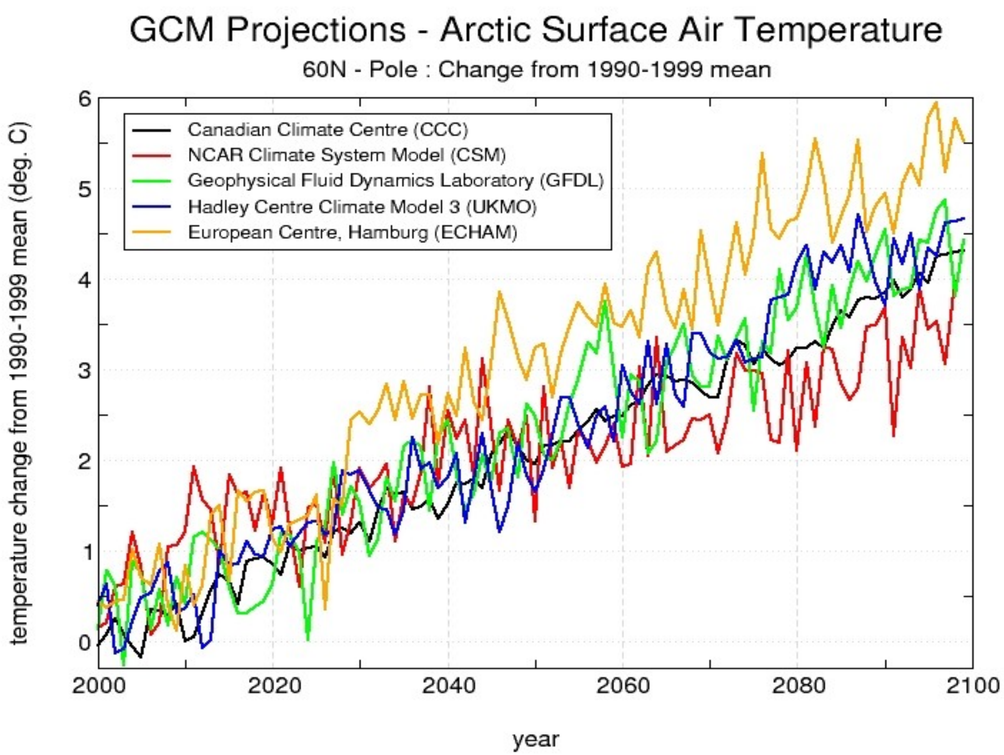
Soil & Surface Wetting

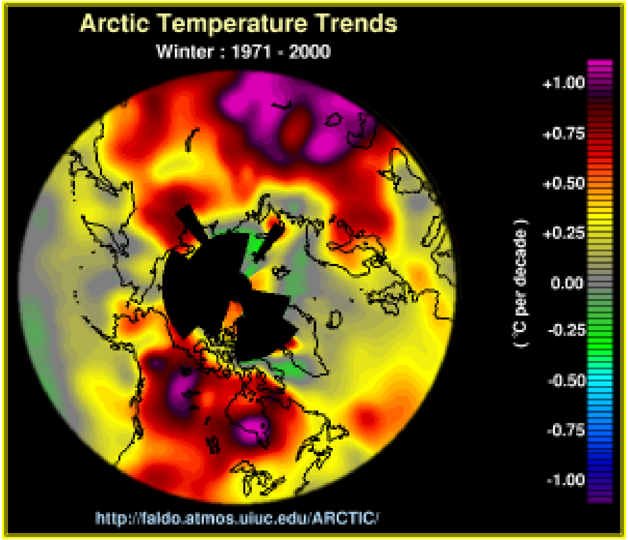
Runoff

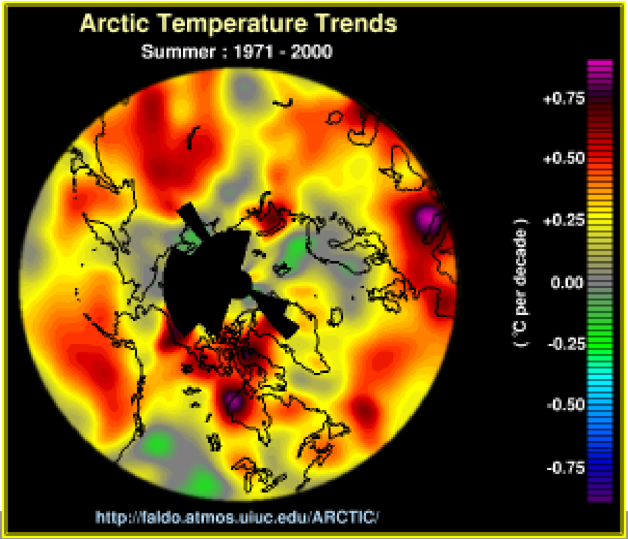
Potential Impacts of Climate Change on Snow-Atmosphere Relationships

- In a potentially warming climate, temperature changes could impact snow conditions which could then positively feedback further on the climate system.
- Different general circulation model (GCM) studies have demonstrated the sensitivity of the regional to global climate response to such changes in snow cover and albedo *(e.g., Levis et al., 2007; Euskirchen et al., 2007; Vavrus, 2007; and also several mentioned on the previous slide).*
- Observational studies *(e.g., Stone et al., 2002; Hamlet et al., 2005)* have shown that with warmer temperatures in polar regions or mountain areas, earlier onsets of snow melt may be occurring and contributing to shifts in springtime runoff *(e.g., Stewart et al., 2004).*
- In addition, studies like Feng and Hu (2007) show transitions to more rainfall versus snowfall events in different parts of the world (e.g., North America), which can also impact spring snowmelt.

Our best climate models project that the Arctic will become *warmer. And the Arctic is indeed warming*







http://zubov.atmos.uiuc.edu/ACIA/
http://zubov.atmos.uiuc.edu/ARCTIC/

Permafrost

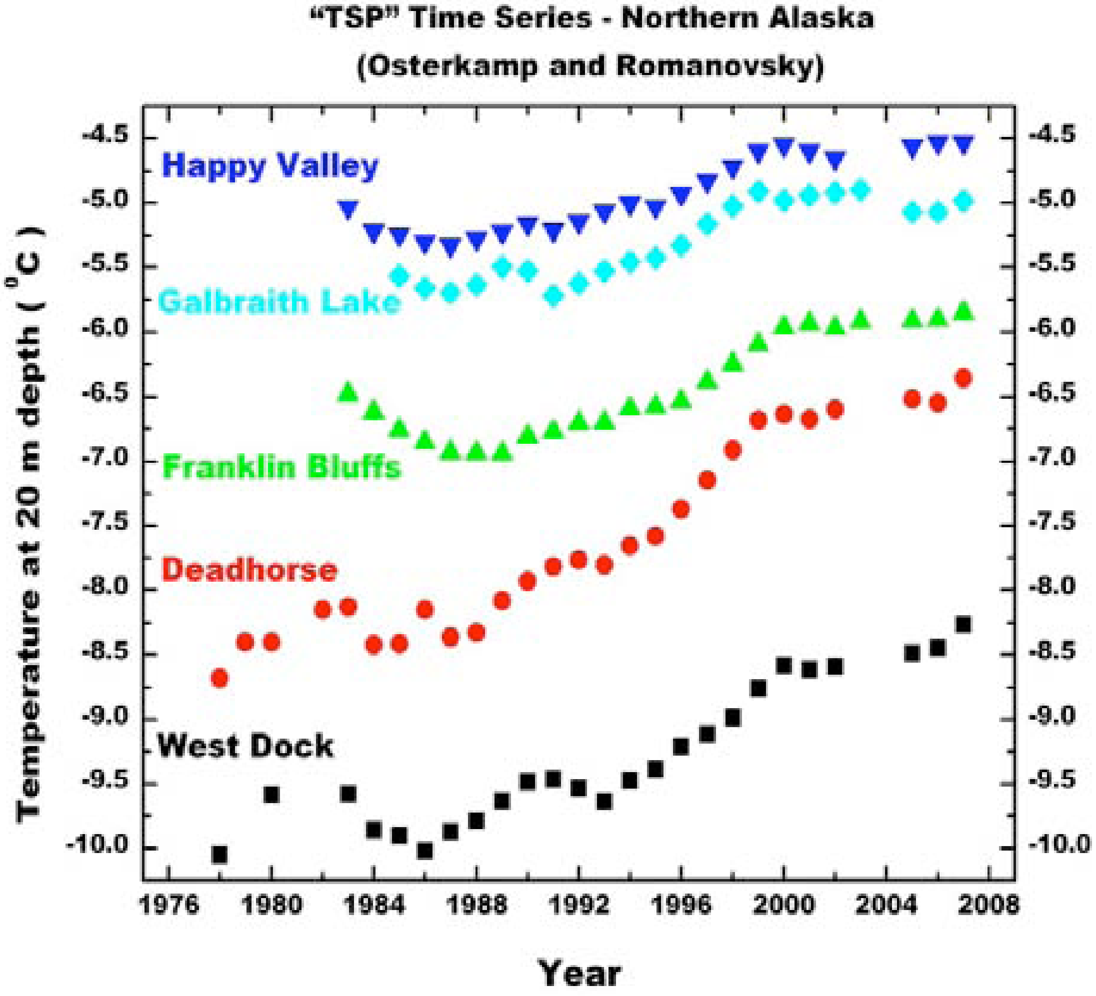
• The discontinuous permafrost region, currently within 1-2 degrees of thawing, will see most dramatic melt

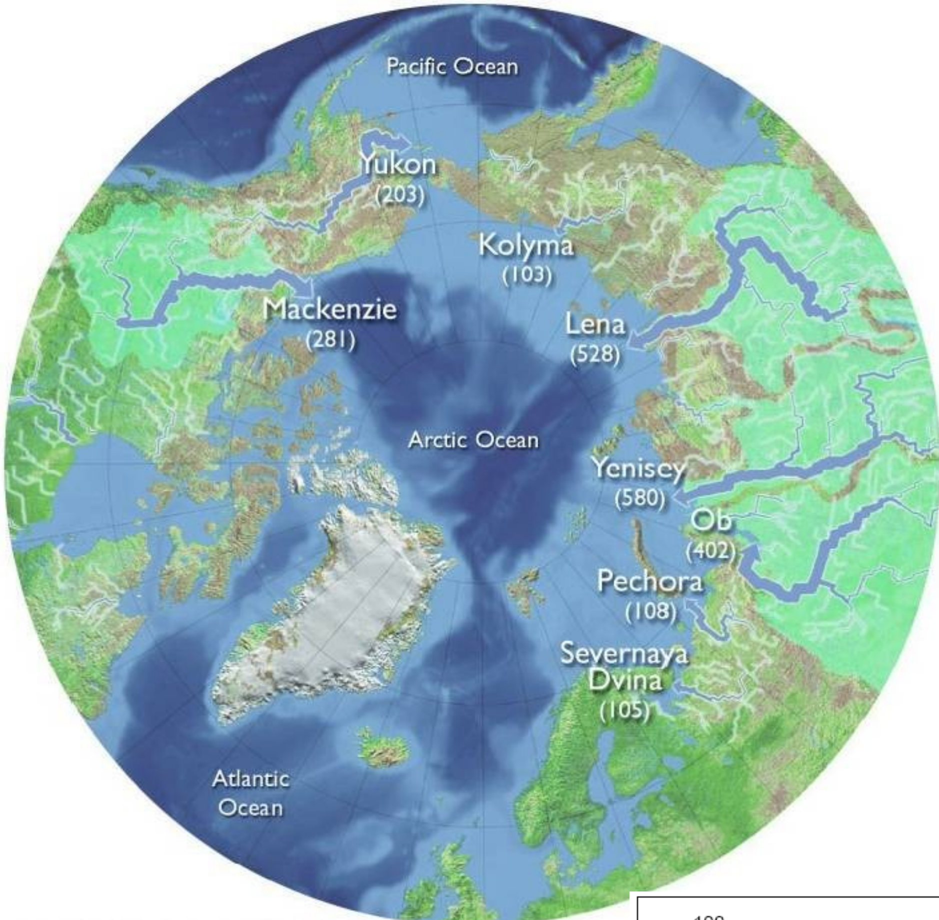
• Where ground ice contents are high, this permafrost degradation will have associated physical impacts.

• Biggest concern are soils with the potential for instability upon thaw (thaw settlement, creep or slope failure).
Such instabilities may have implications for the landscape, ecosystems, and infrastructure. (GSC 2002)

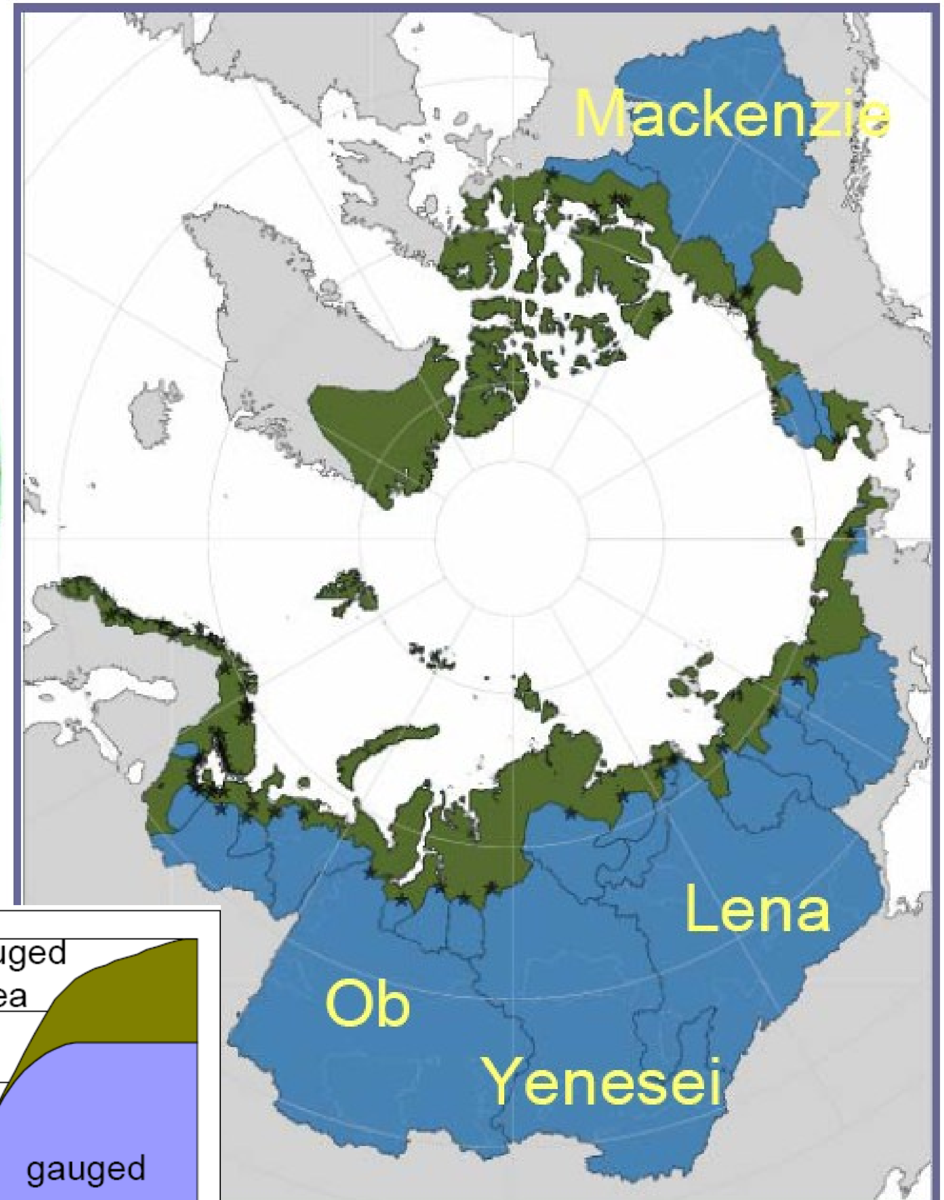
GRID Arendal UNEP

Changes since 1978 in permafrost temperatures at 20 m depth (updated from Osterkamp 2003) -- Northern Alaska (ARC 2008).

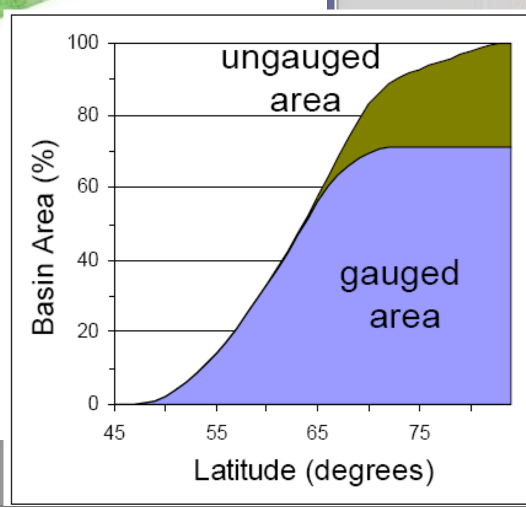




©2004, ACIA / Map ©Clifford Grabhorn

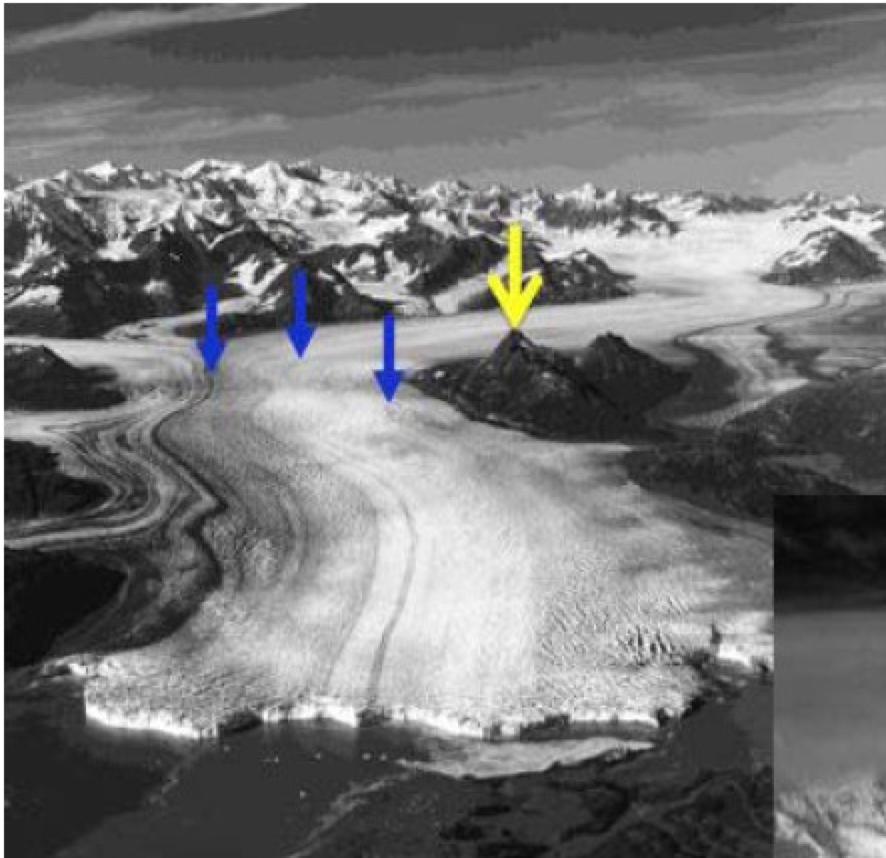


RUNOFF



GLACIERS

Columbia Glacier, Alaska

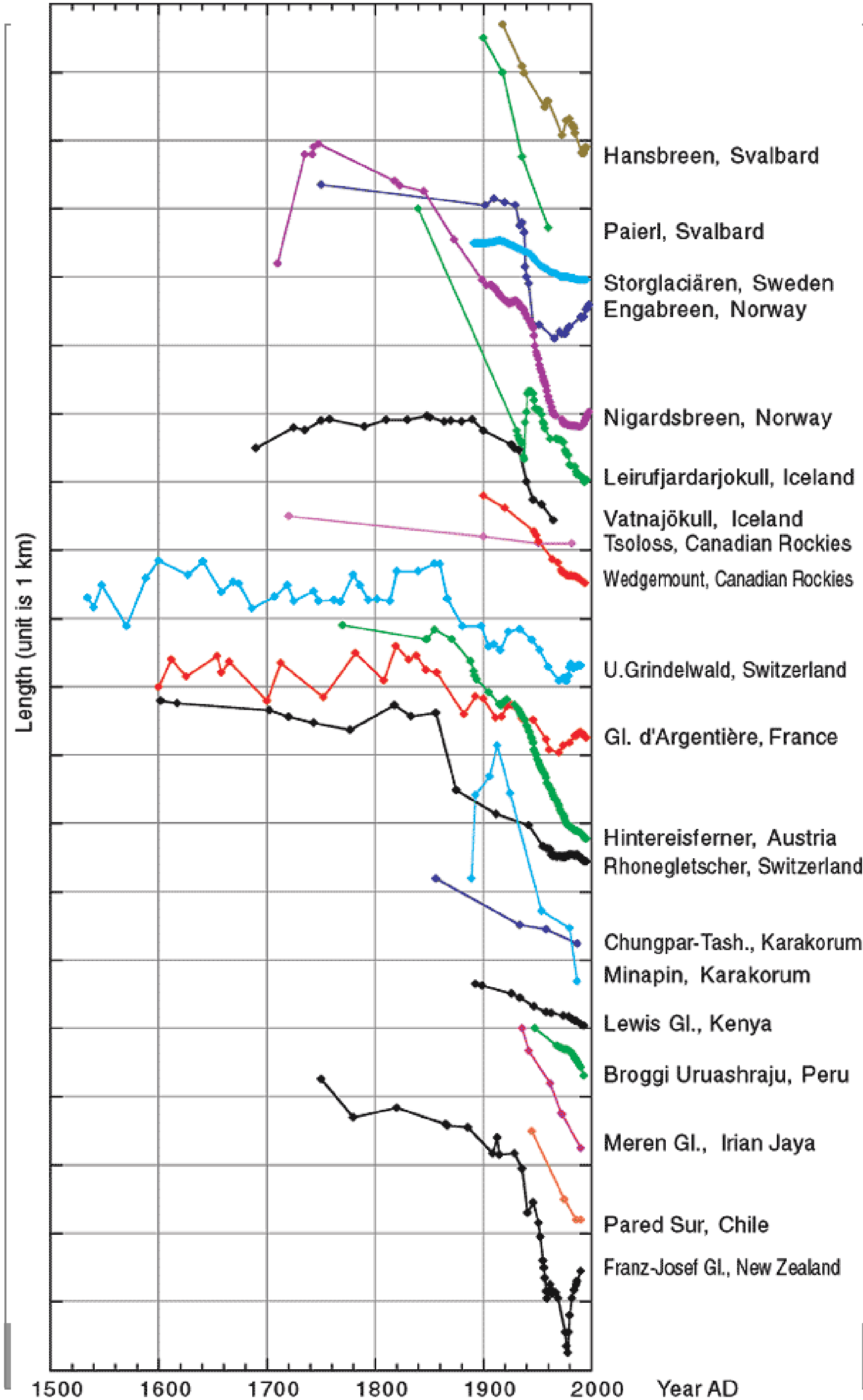


1980

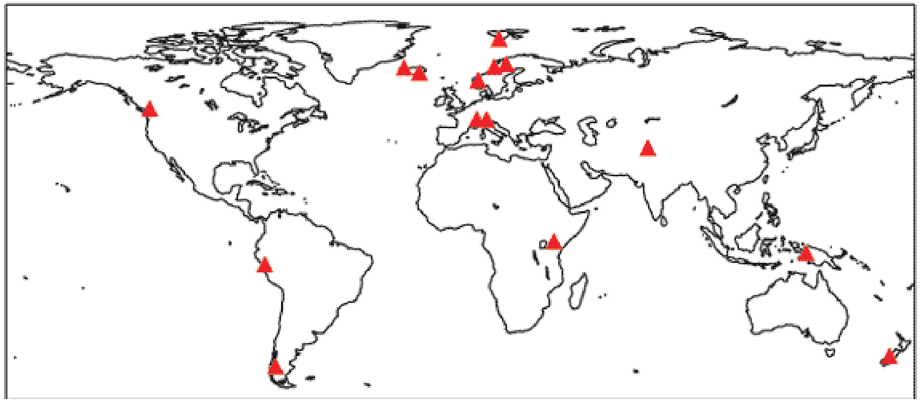
2005

Approx position 2005

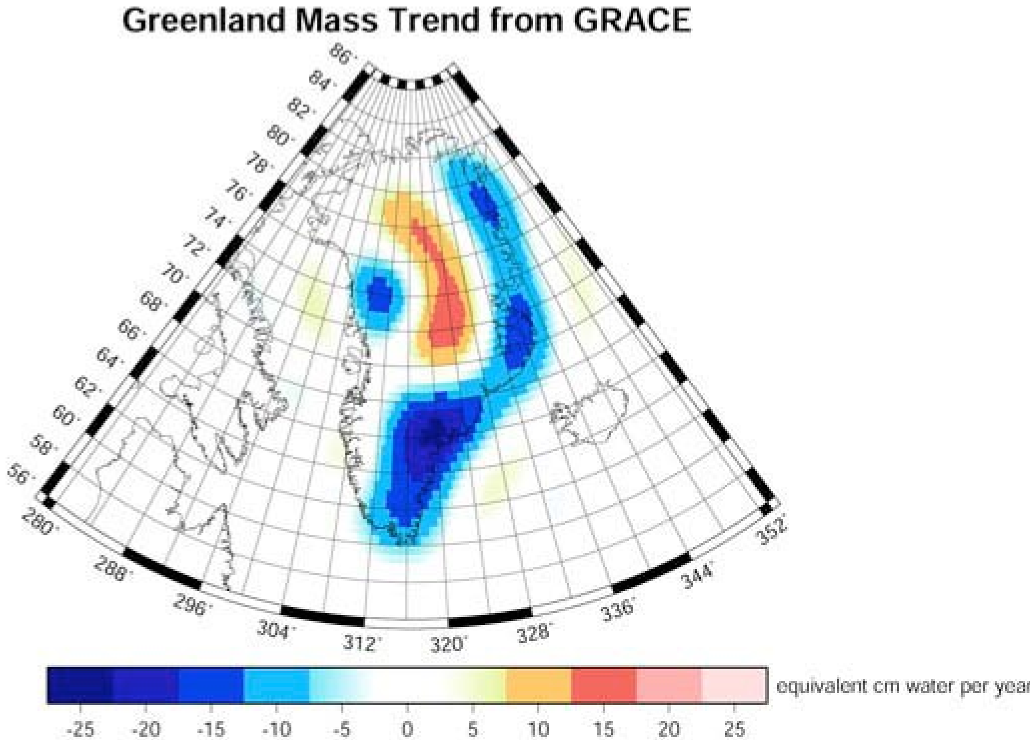
Common reference point



Historical retreat of non-polar glaciers



World Glacier Monitoring Service
www.geo.unizh.ch/wgms

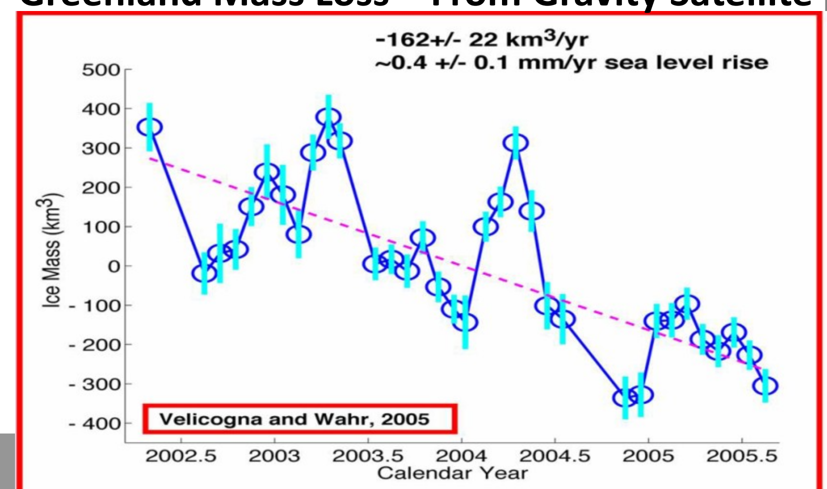


Melt descending into a moulin, a vertical shaft carrying water to ice sheet base.

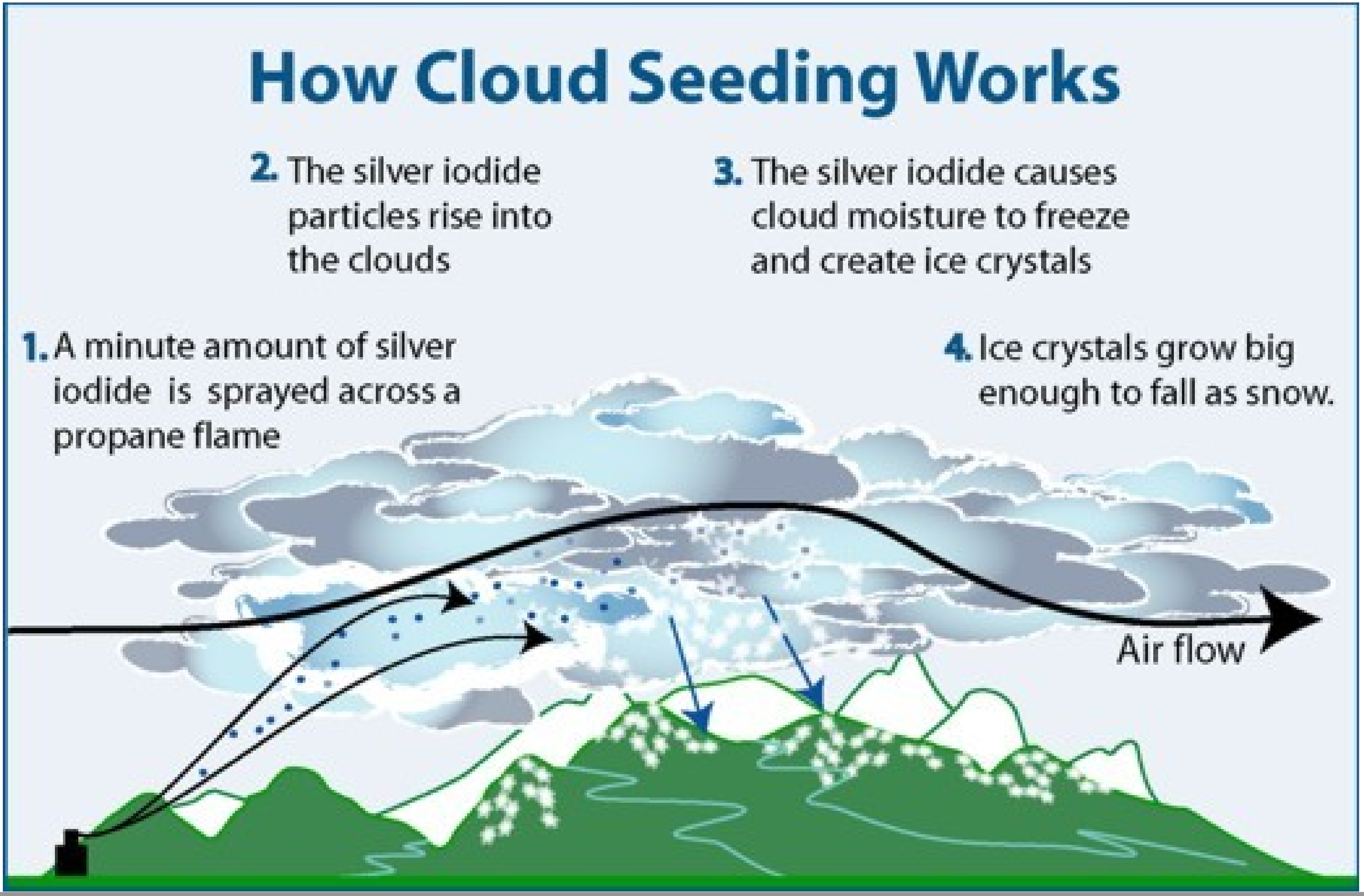
Source: Roger Braithwaite, University of Manchester (UK)

NASA satellite data has revealed regional changes in the weight of the Greenland ice sheet between 2003 and 2005. Low coastal regions (blue) lost three times as much ice per year from excess melting and icebergs than the high-elevation interior (orange/red) gained from excess snowfall Credit: Scott Luthcke, NASA Goddard

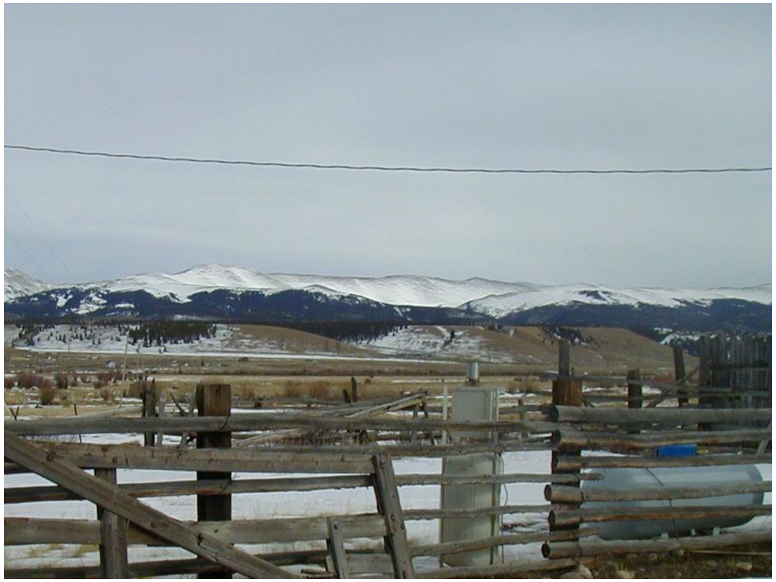
Greenland Mass Loss – From Gravity Satellite



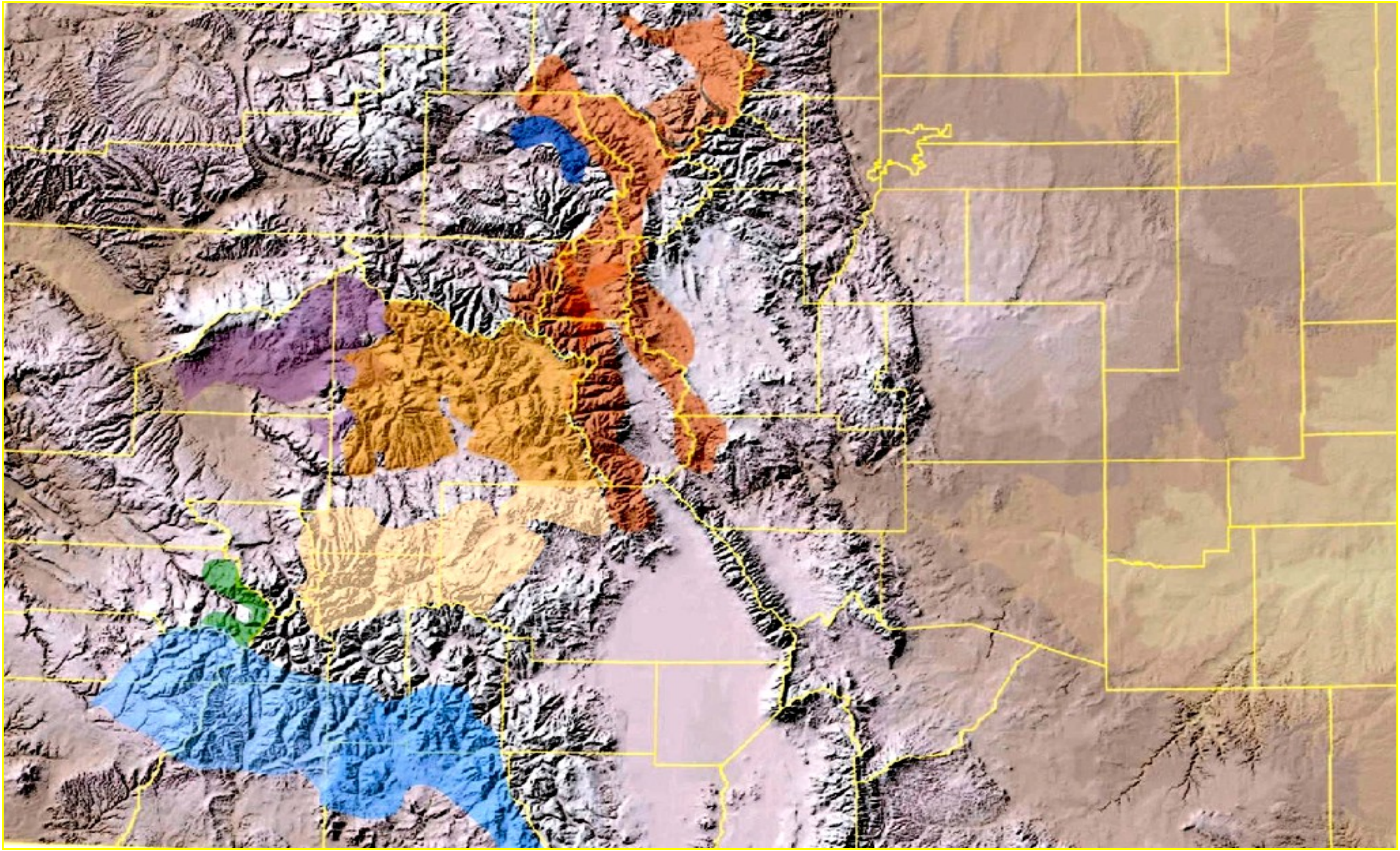
Snowpack Augmentation (Conceptual Model)



Example Silver Iodide Generators for the Denver Water Program



Colorado Wintertime Cloud Seeding Programs 2004-2005



Central Rockies Program (Denver Water + Arkansas Basin)

Grand Mesa Program

Telluride/Upper San Miguel Basin

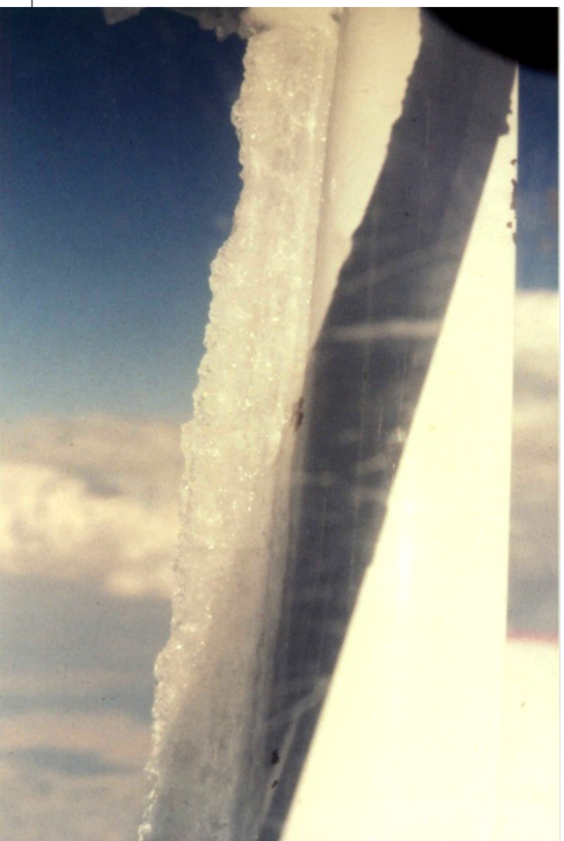
Vail/Beaver Creek Ski Resort

Gunnison Basin Program (expanded late 2003)

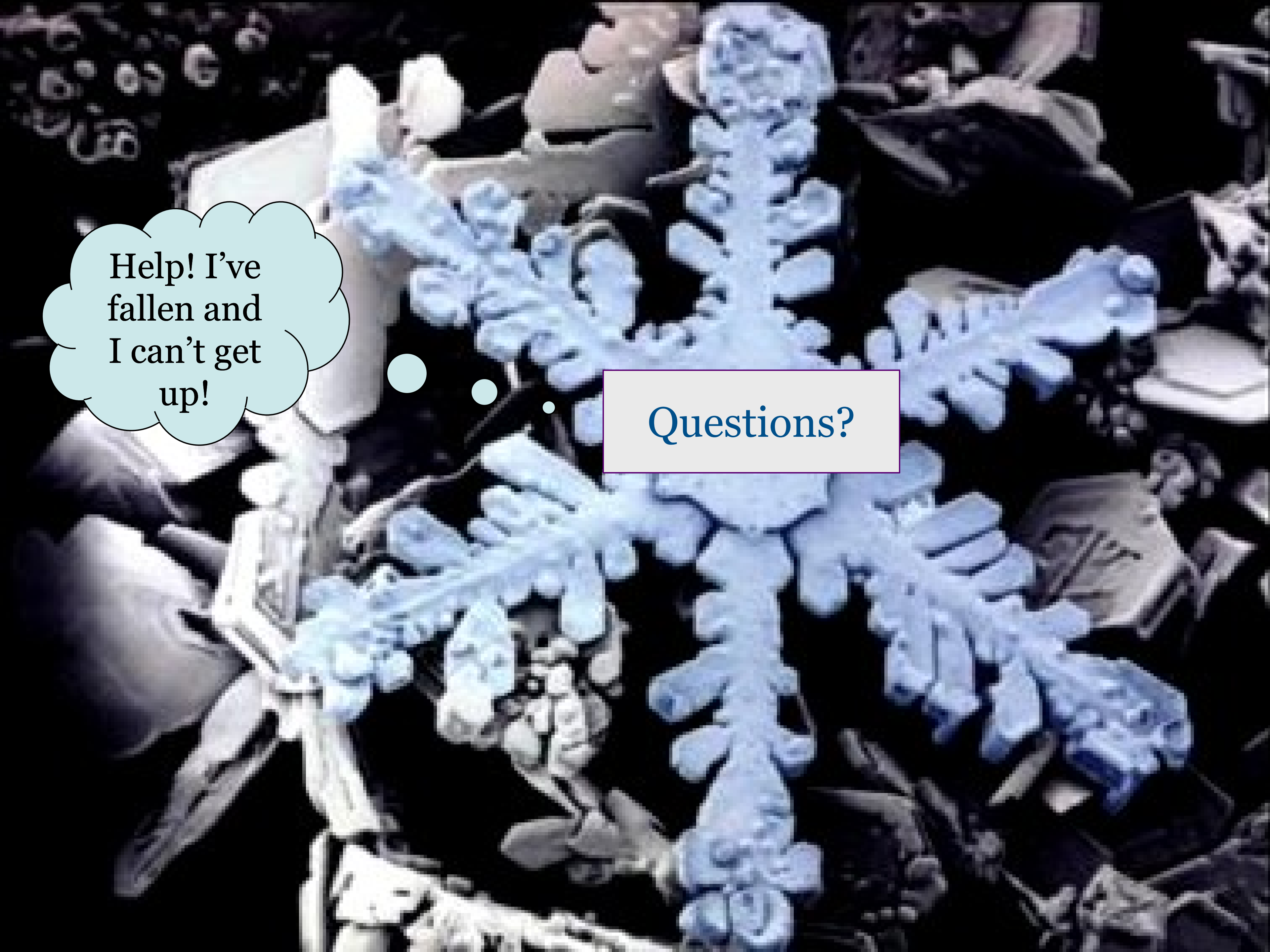
San Juan Mountains Program (expanded in 2002)

From http://cwcb.state.co.us/Weather_Modification/Permit_Program.htm

Supercooled Liquid Water (SLW)



- SLW is water droplets in a liquid state at temperatures below freezing
  - SLW also causes aircraft icing
- *SLW is the fuel* required for cloud seeding to work - droplets need a nucleus on which to freeze
- Cloud seeding provides those nuclei
- Result: more large ice particles, which fall to ground as snow


Help! I’ve fallen and I can’t get up!
Questions?