UNIVERSITY OF WASHINGTON

Department of Civil and Environmental Engineering

A Macroscale Glacier Model to Evaluate Climate Change Impacts in the Columbia River Basin

Joseph Hamman, Bart Nijssen,
Dennis P. Lettenmaier, Bibi Naz, and Jeremy Fyke.

September 9, 2014

5th Annual Pacific Northwest Climate Science Conference

University of Washington

Seattle, Washington

Predicting the Response of the Columbia River Basin to Climate Change

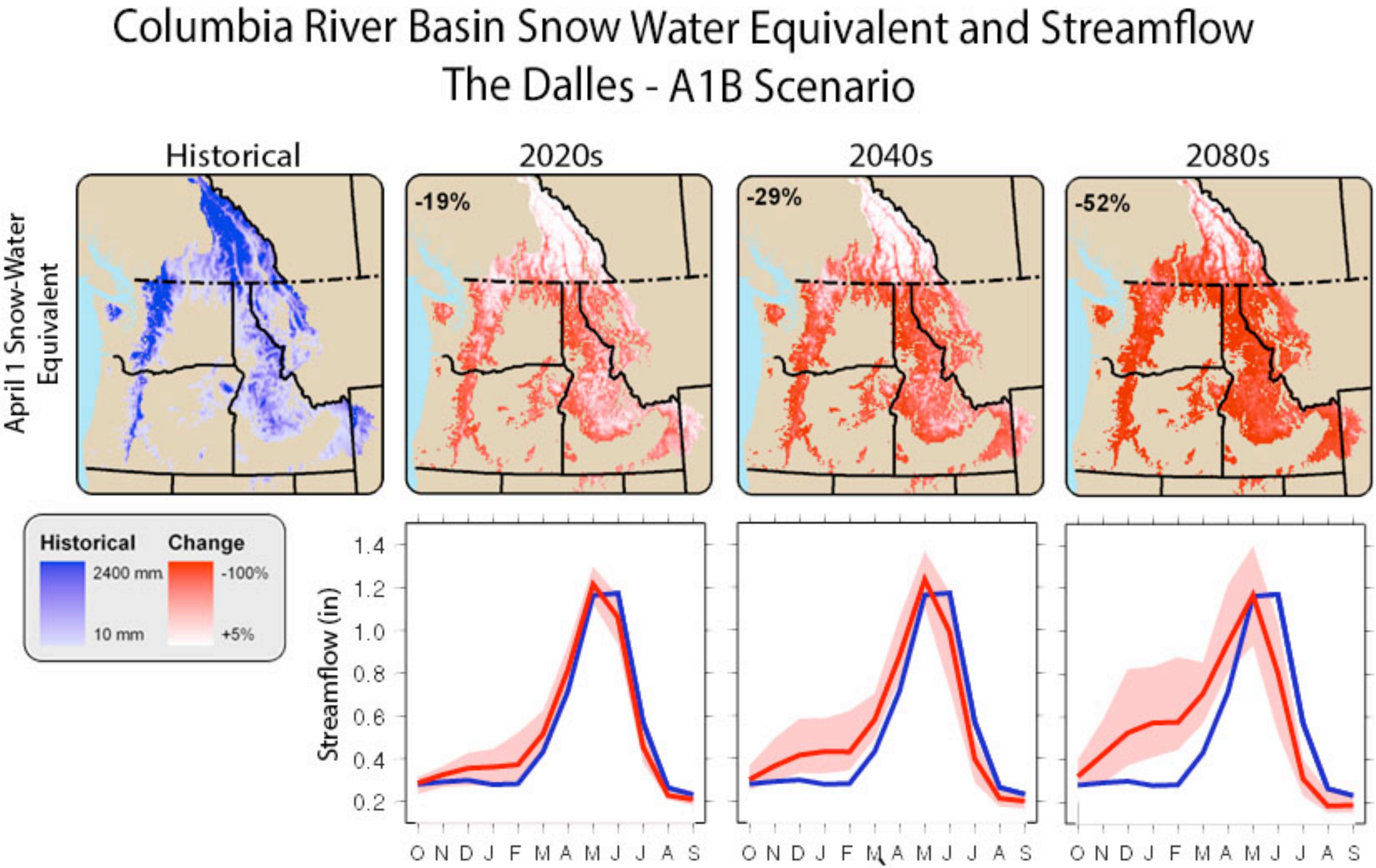
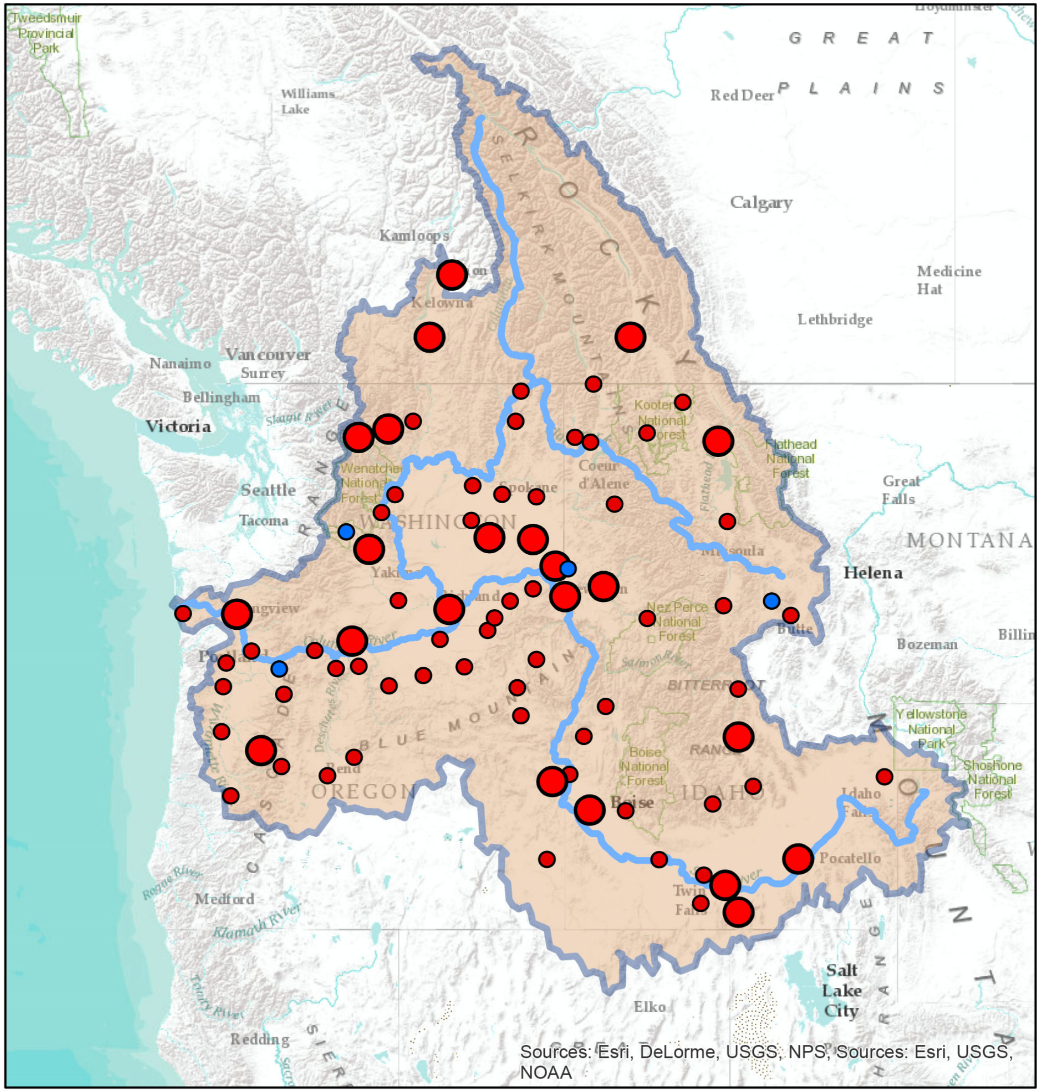


Figure adapted from Hamlet et al., 2010.

Predicting the Response of the Columbia River Basin to Climate Change

What's new in this study?

1. Latest CMIP5 climate change scenarios
2. Rapid evaluation of large number of climate change projections
3. Multiple downscaling methods which will fully exploit CMIP5 data at daily time step
4. Multiple hydrologic models
   - including a novel glacier representation in one of them



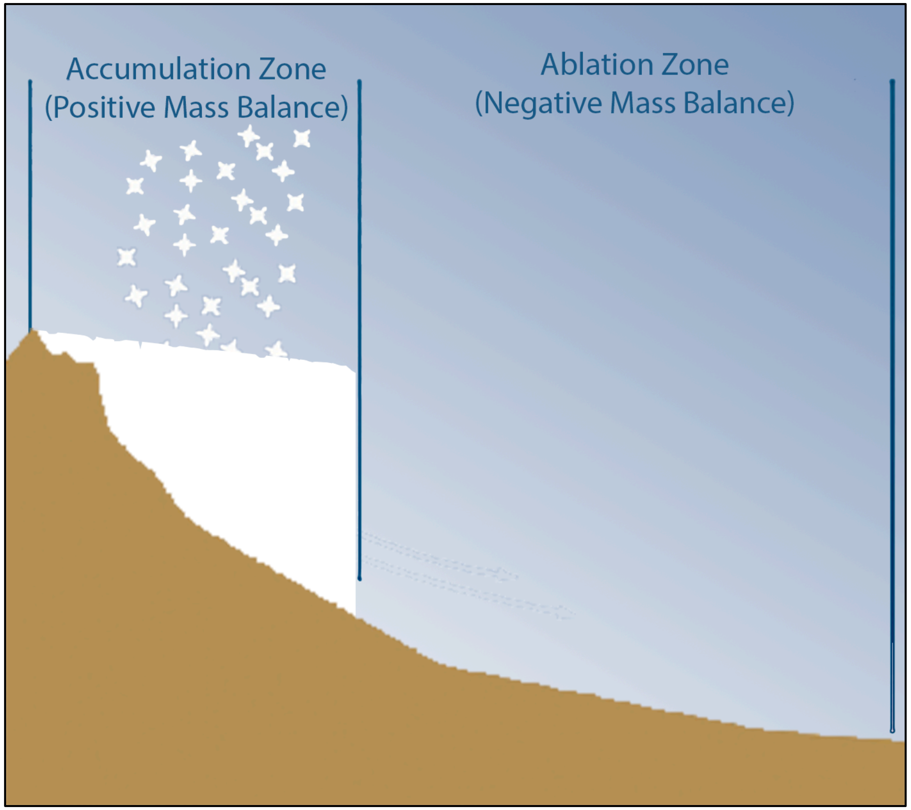
Observation Stations

Change in mean annual temperature between 1911 and 2010

- Greater than 2 deg F increase
- Up to 2 deg F increase
- Up to 1 deg F decrease

Why we need to consider glaciers in VIC

Glaciers redistribute ice from the accumulation zone to the ablation zone.



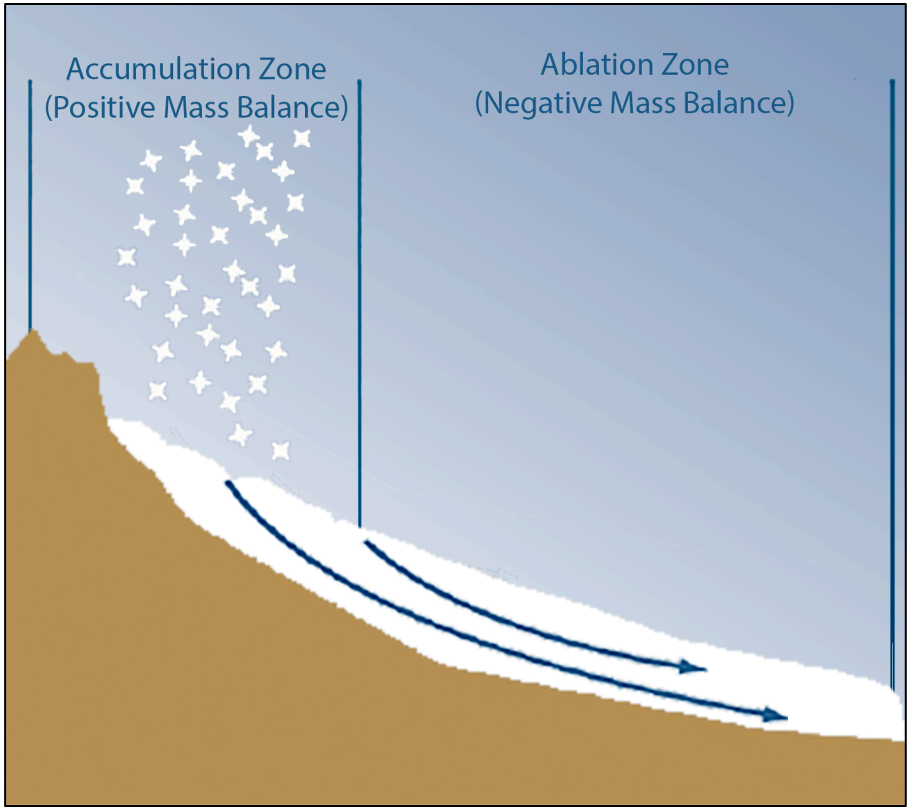
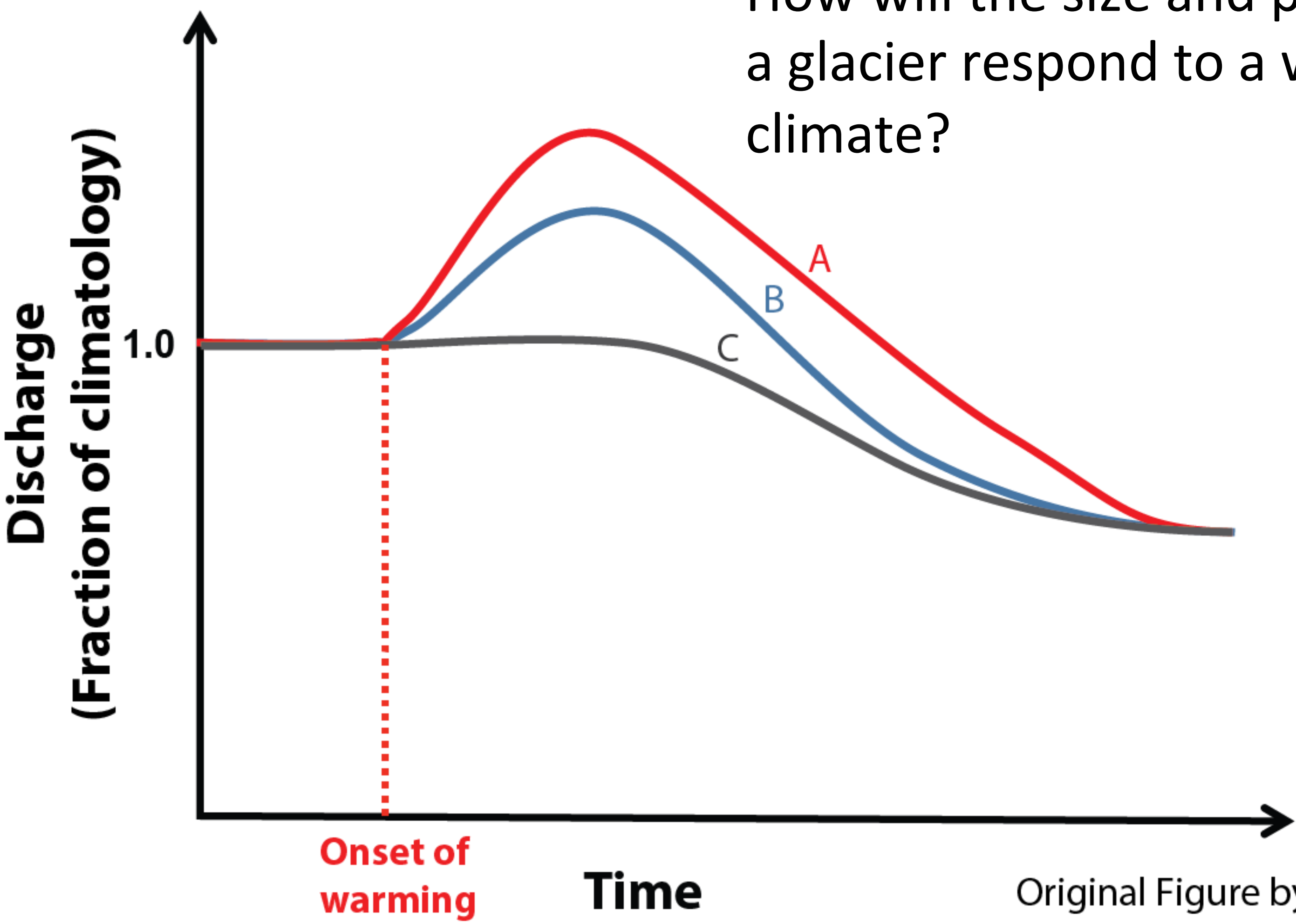


Figure adapted from USGS

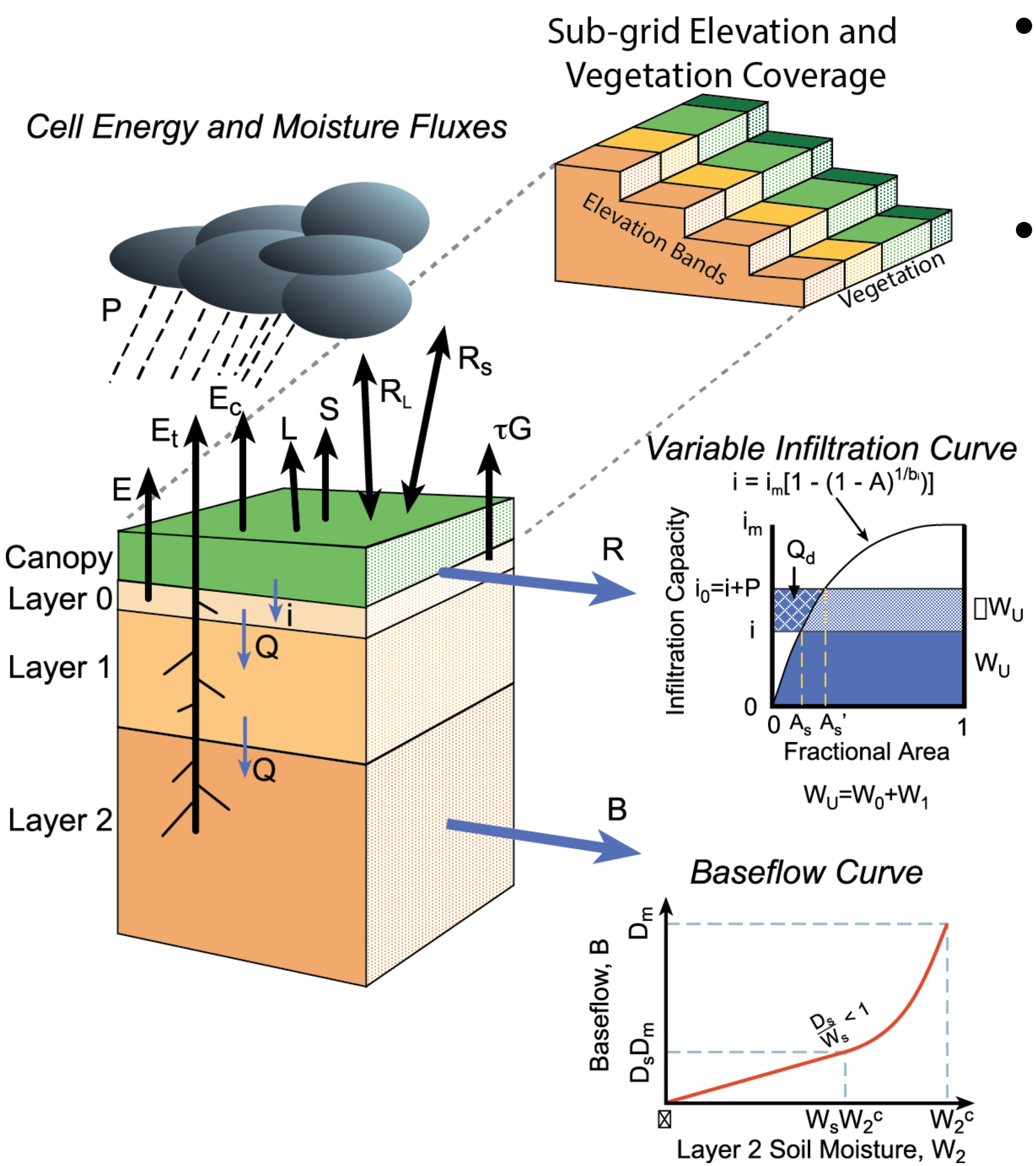
Hydrologic Response to Glacier Recession

How will the size and position of a glacier respond to a warming climate?



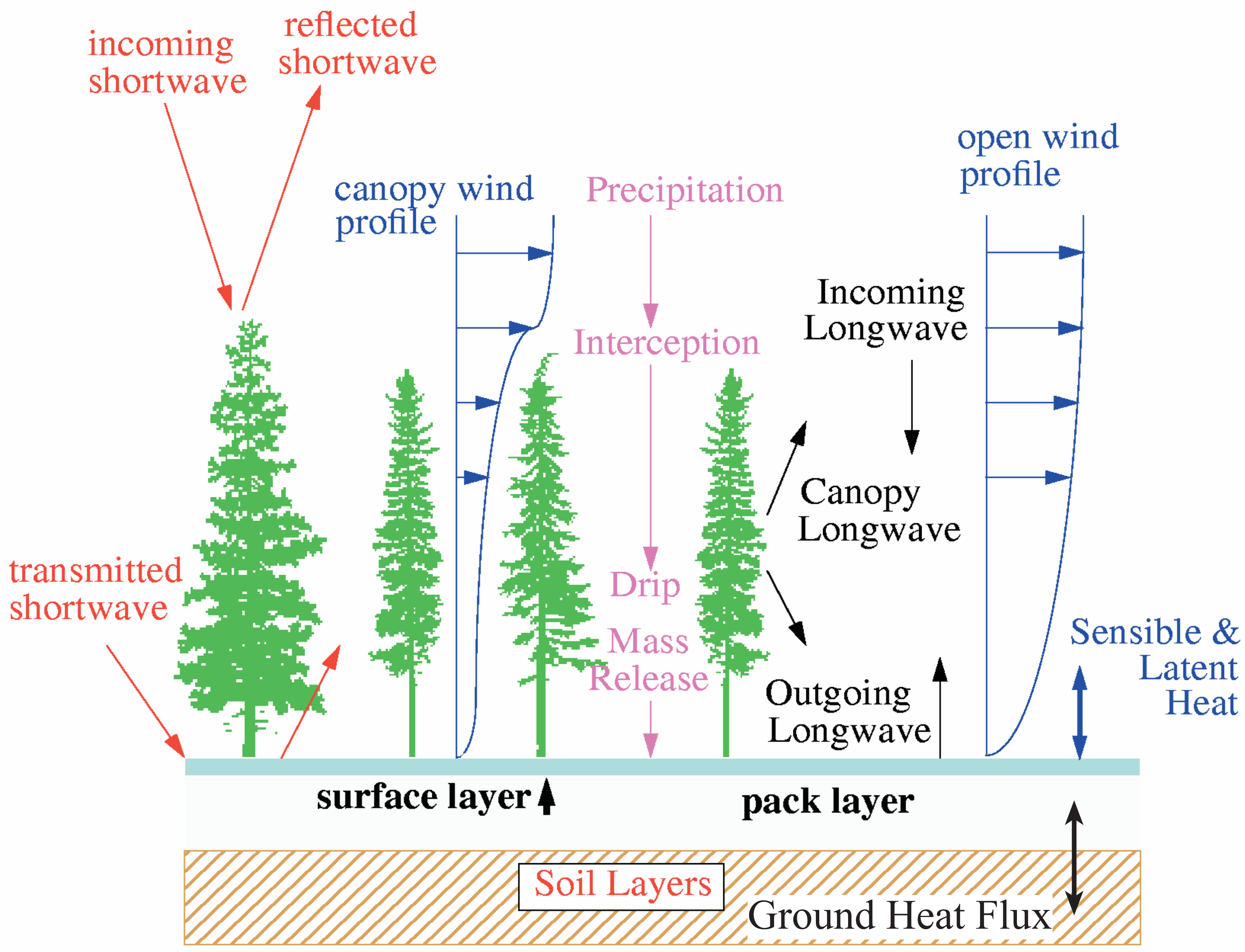
Original Figure by Chris Frans

The Variable Infiltration Capacity Model: Overview

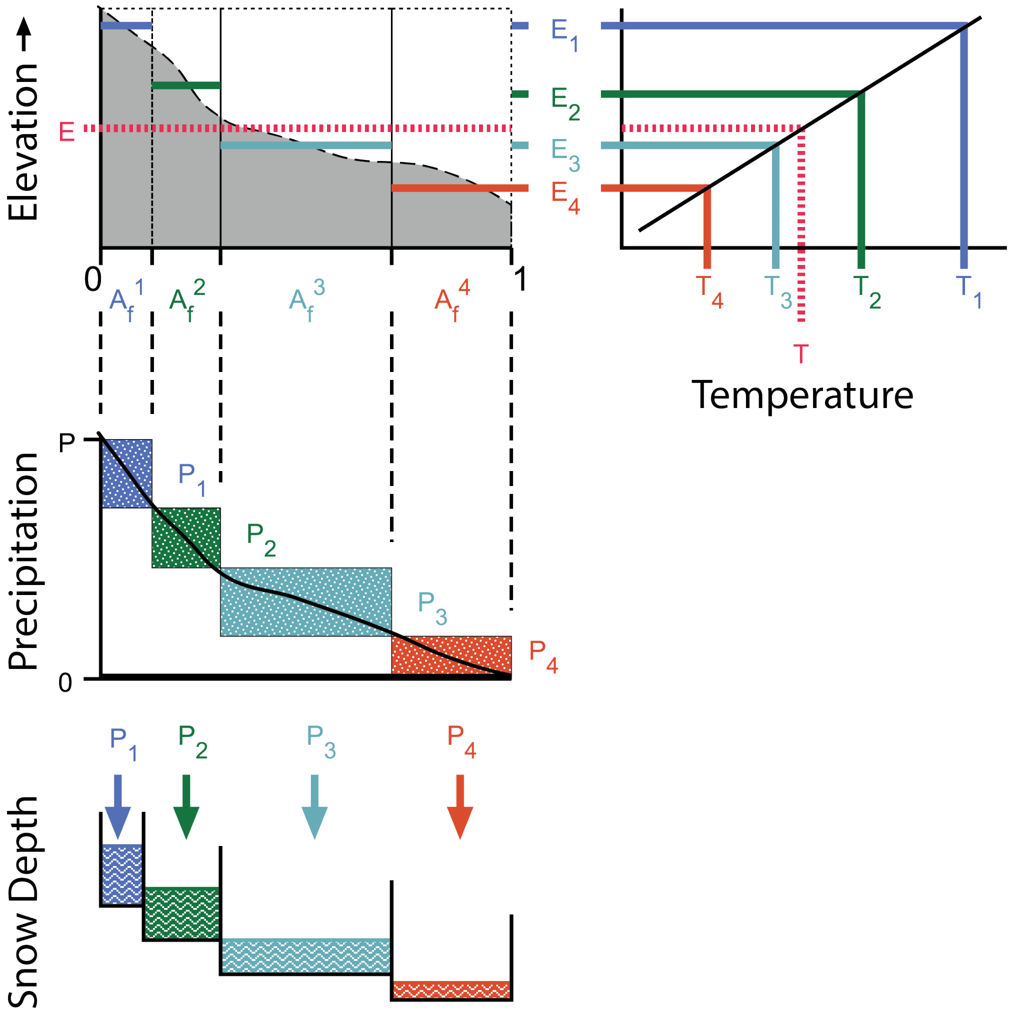


- Macro-scale semi-distributed hydrologic model (Liang et al., 1994).
- Key Features:
  - Large, <u>disconnected</u> grid cells (7km x 7km).
  - Represents sub-grid variability via statistical tiling scheme.
  - Nonlinear distribution of soil moisture, infiltration capacity, and baseflow recession.
  - Iterates to find surface temperature and close the energy balance.

The Variable Infiltration Capacity Model: Snow



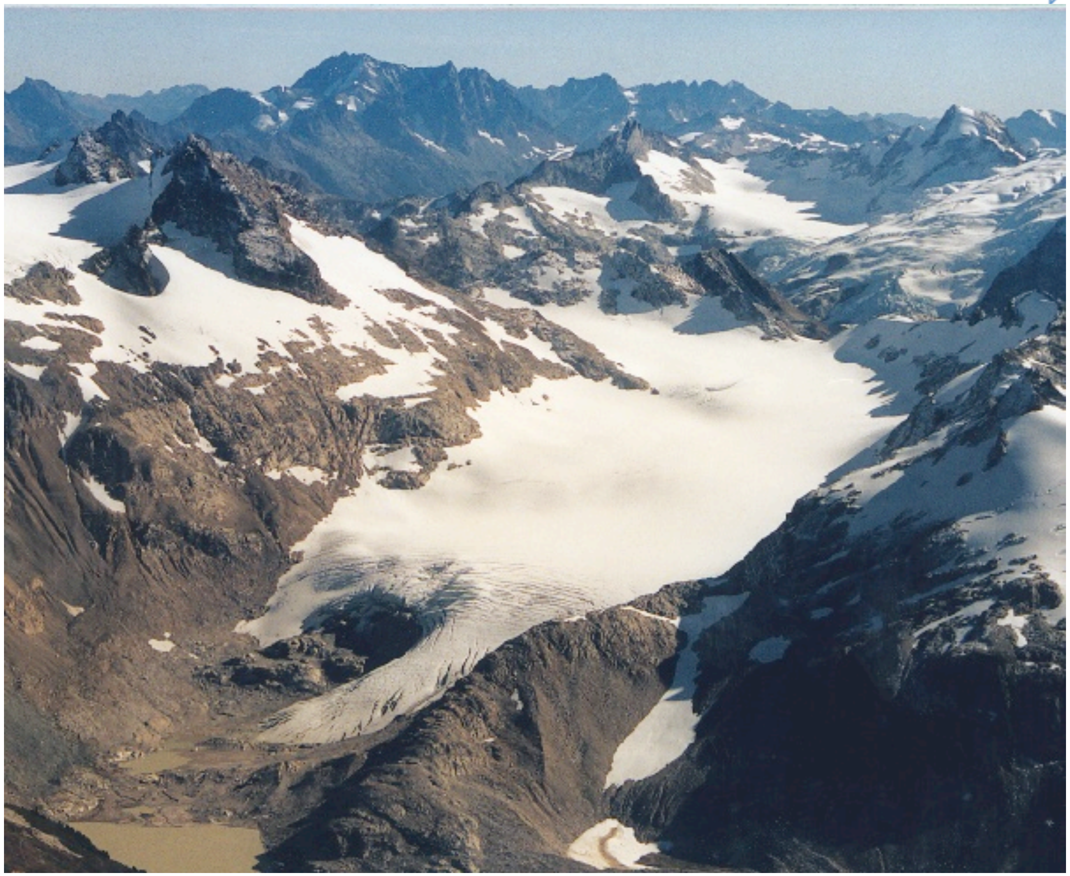
The Variable Infiltration Capacity Model: Topography



- Elevation bands are used to represent topographic subgrid variability.
- Elevation bands are not explicitly connected.
- Full water and energy balance is calculated for each band.

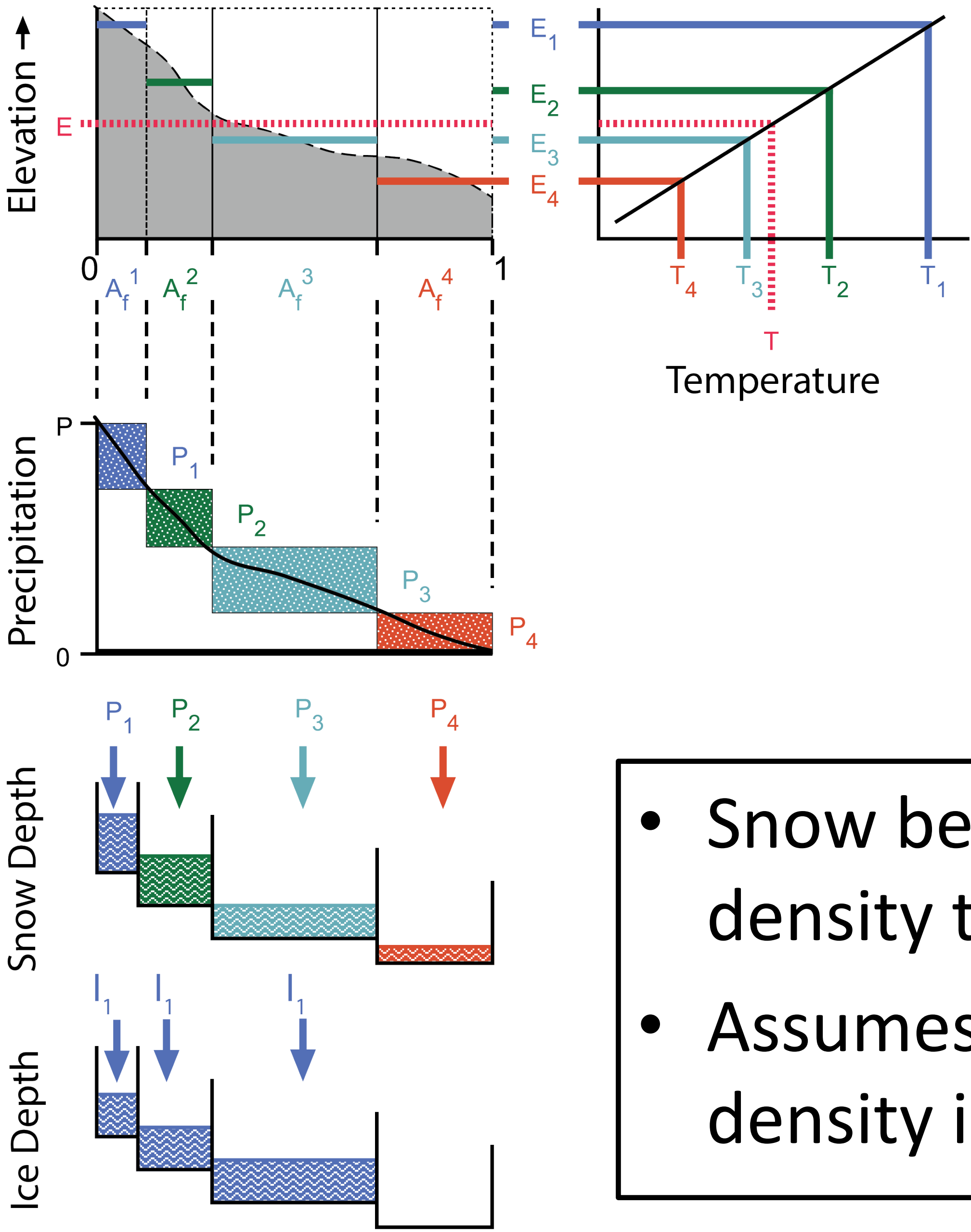
The VIC Glacier Model

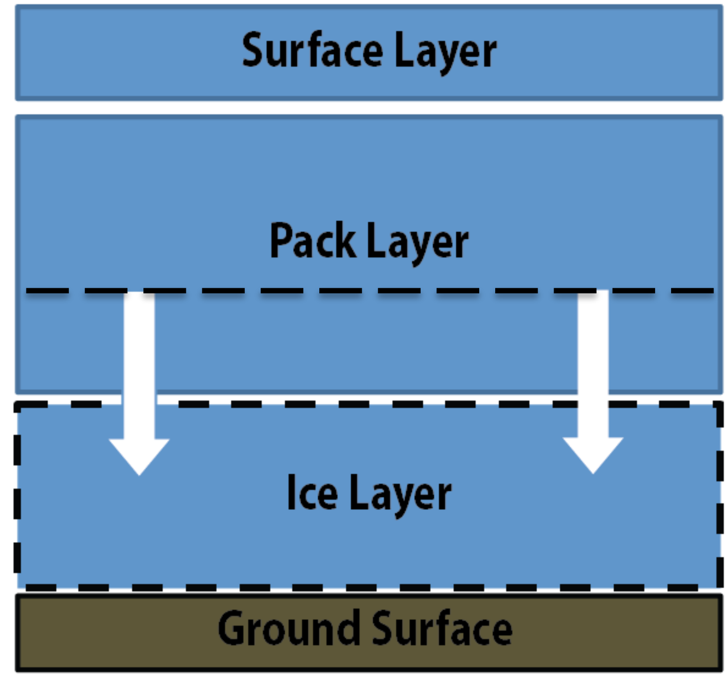
Accumulation → Redistribution → Ablation



VIC Glacier Model

Accumulation | Redistribution | Ablation

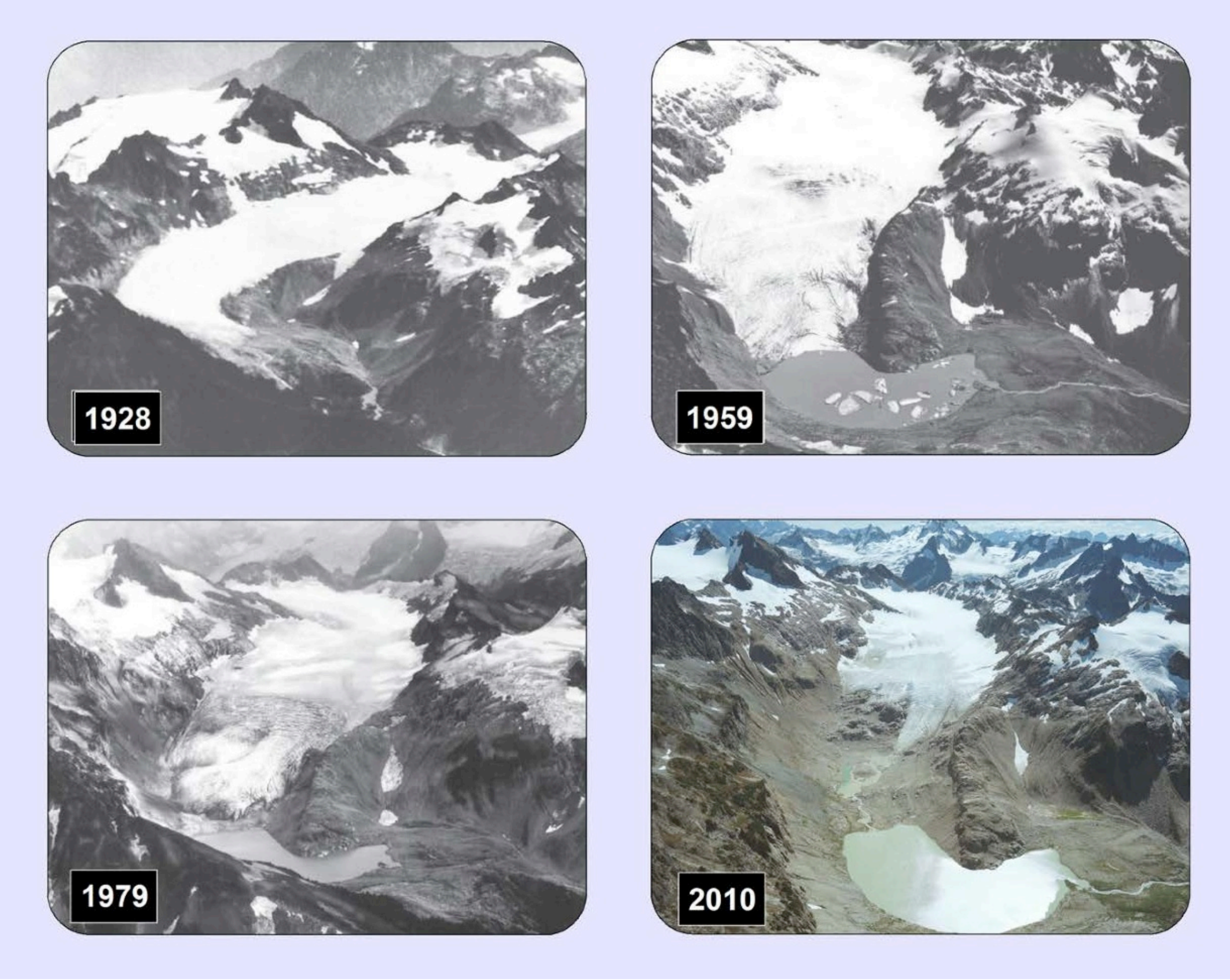




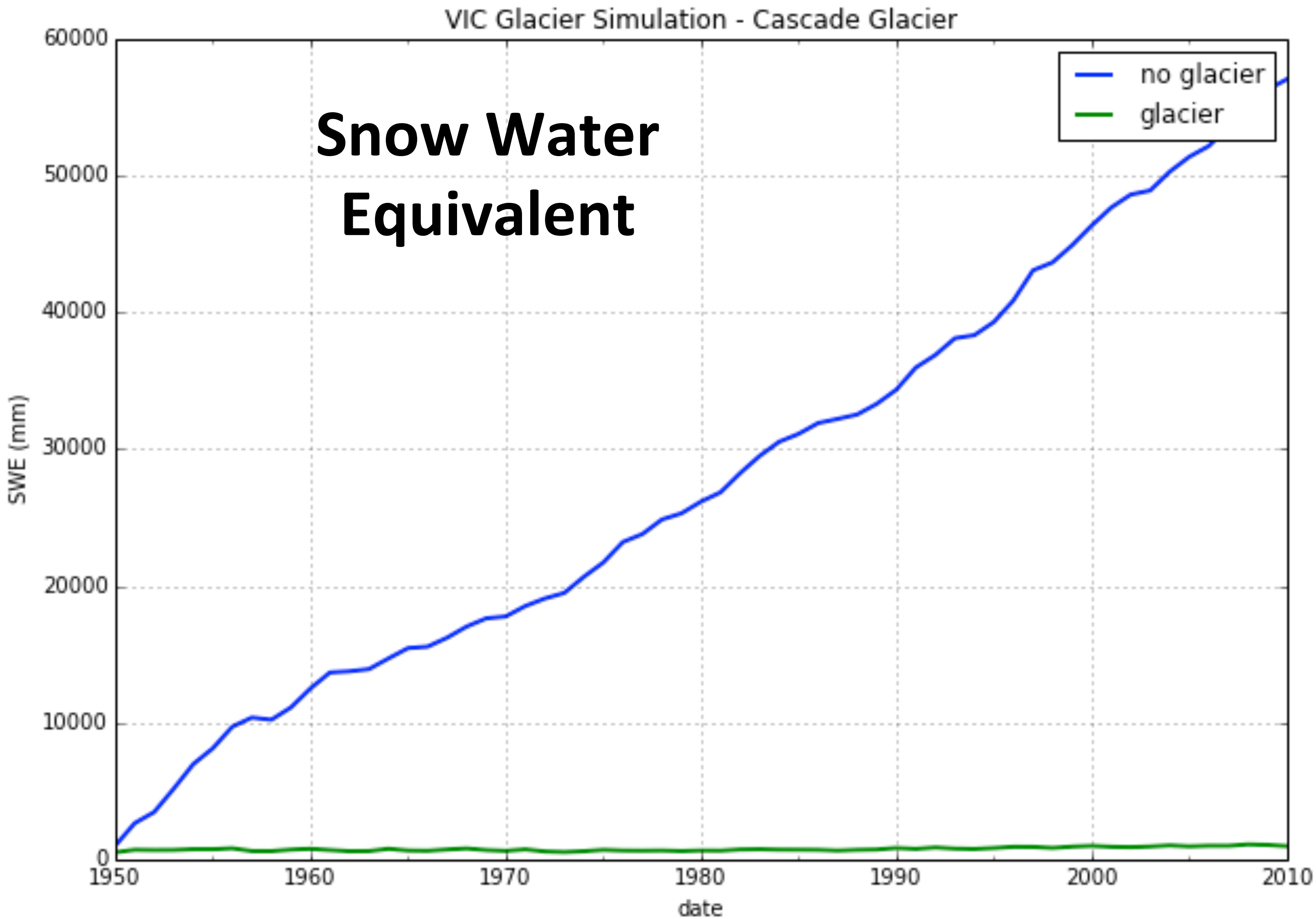
- Snow becomes ice based on density threshold (750 kg/m^3)
- Assumes a linear distribution of density in the snow pack layer.

Initial Results: Cascade Glacier Example

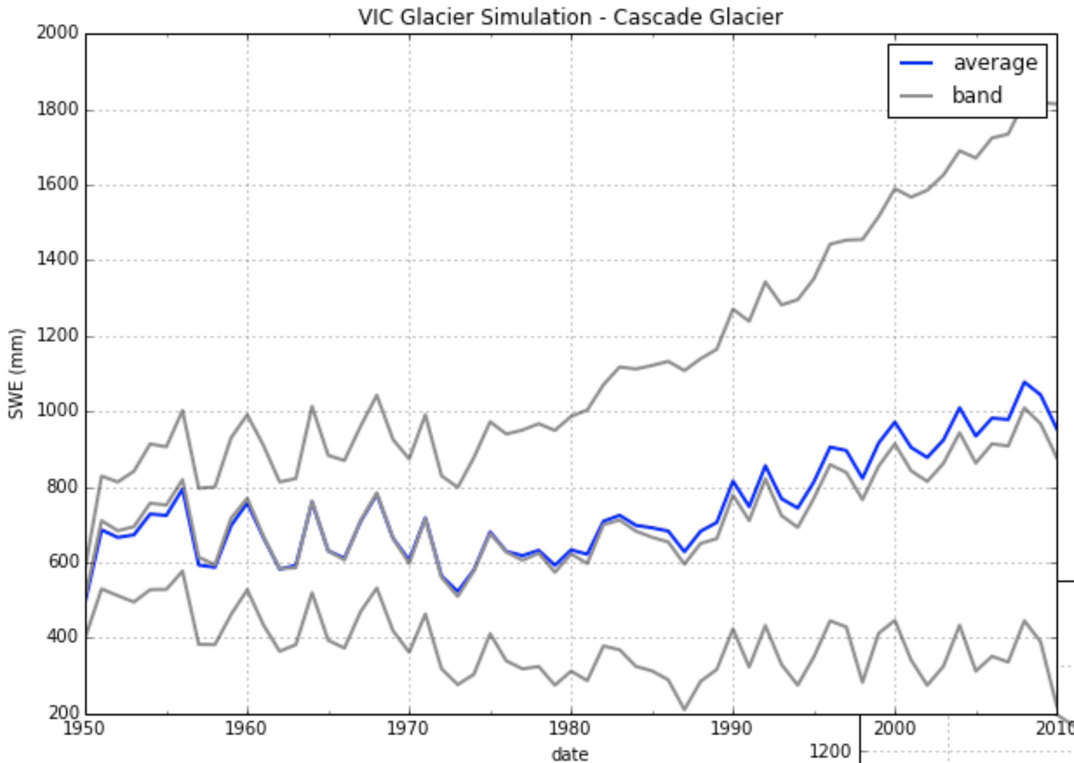
Source: ESRI, TeleAtlas, USGS



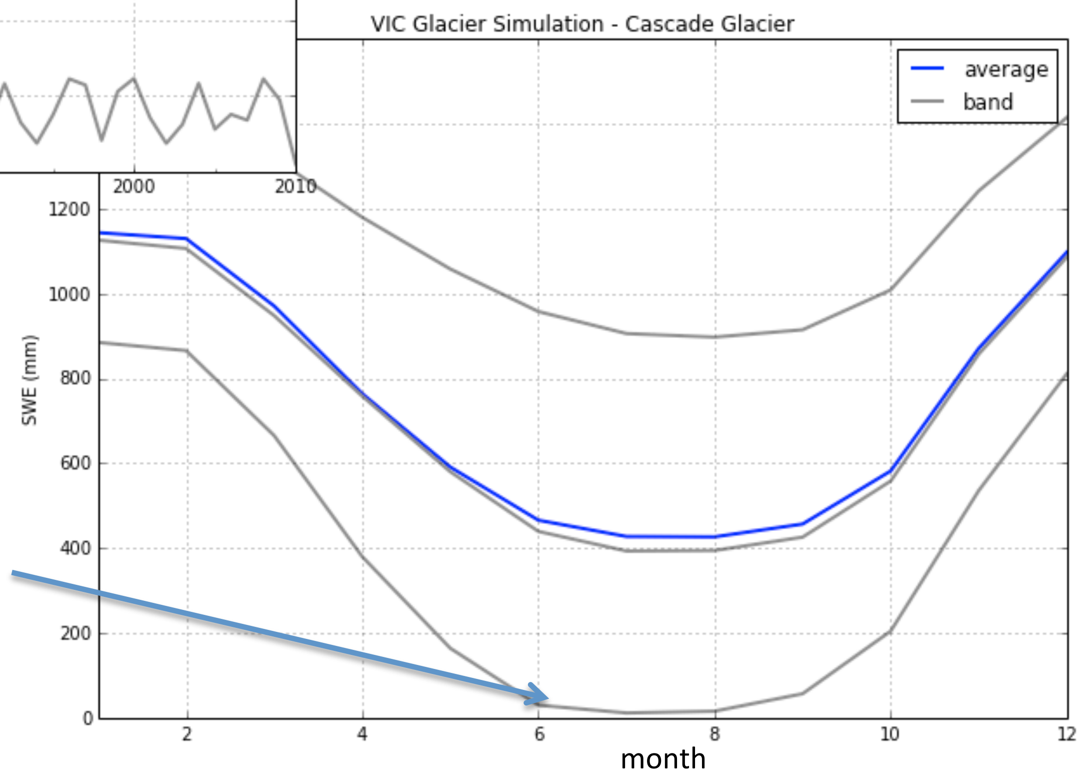
Initial Results: Cascade Glacier Example



Initial Results: Cascade Glacier Example



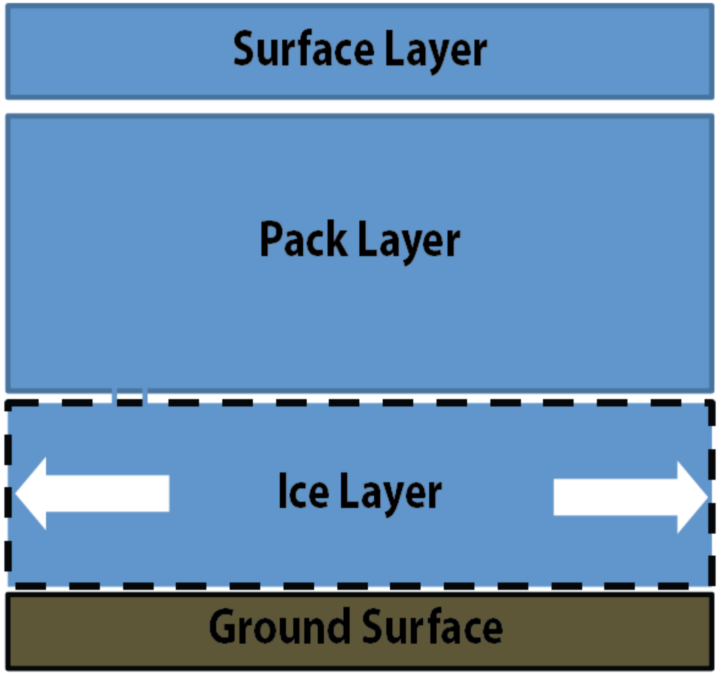
Snow Water Equivalent

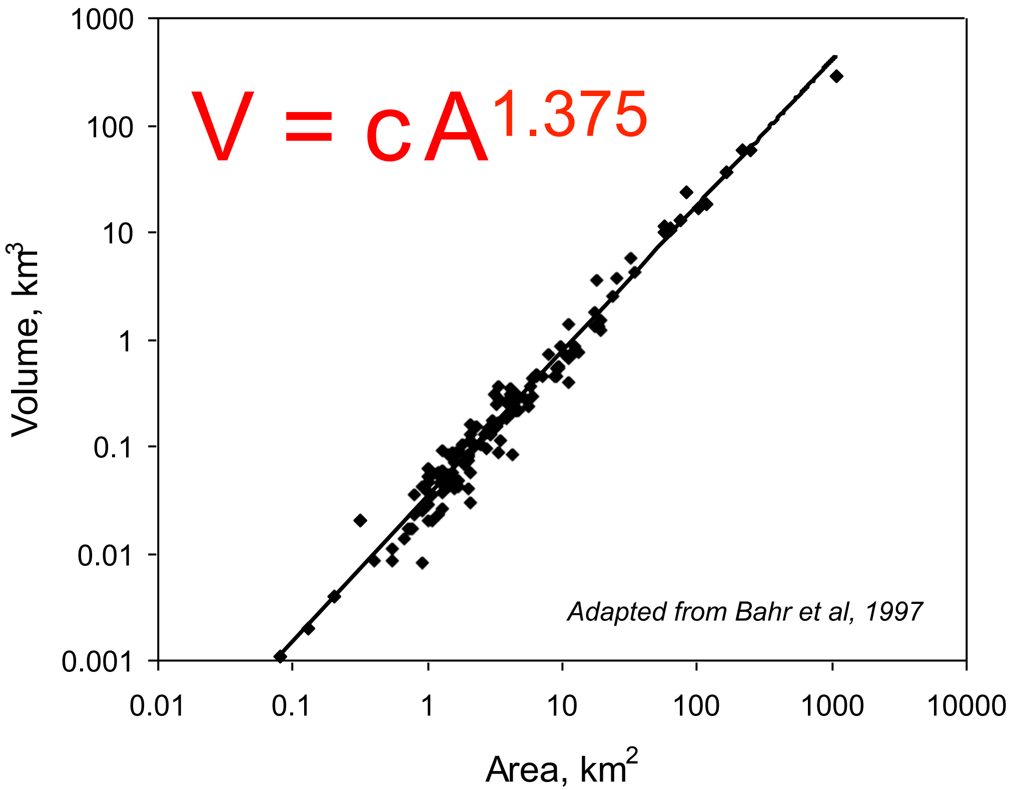


Lowest band is seasonally snow free, exposing glacier ice.

VIC Glacier Model

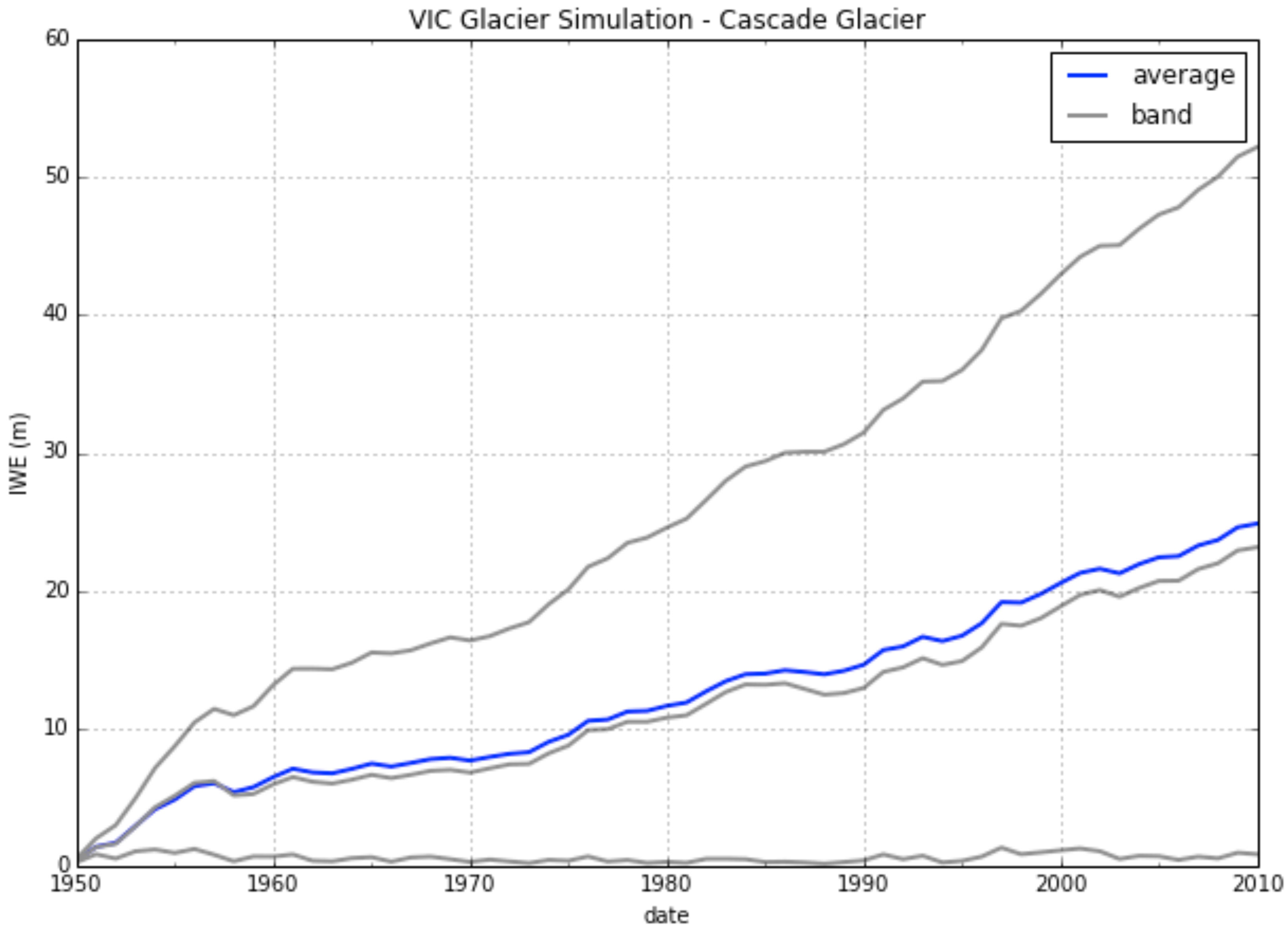
- Glacier dynamics are collapsed to a scaling relationship between ice volume (V) and ice area (A).





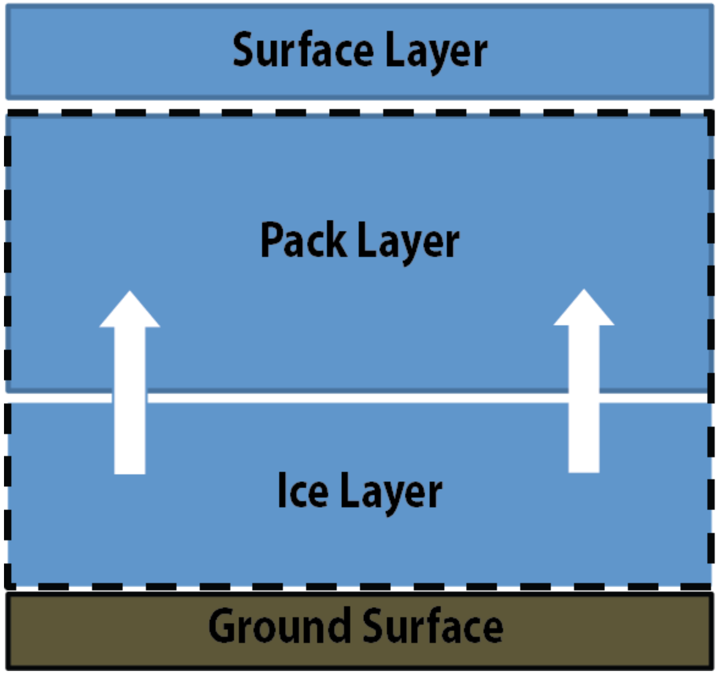
- Derived from dynamics and from observations.
- Valid in both steady state and non-steady state glaciers/climates

Initial Results: Cascade Glacier Example



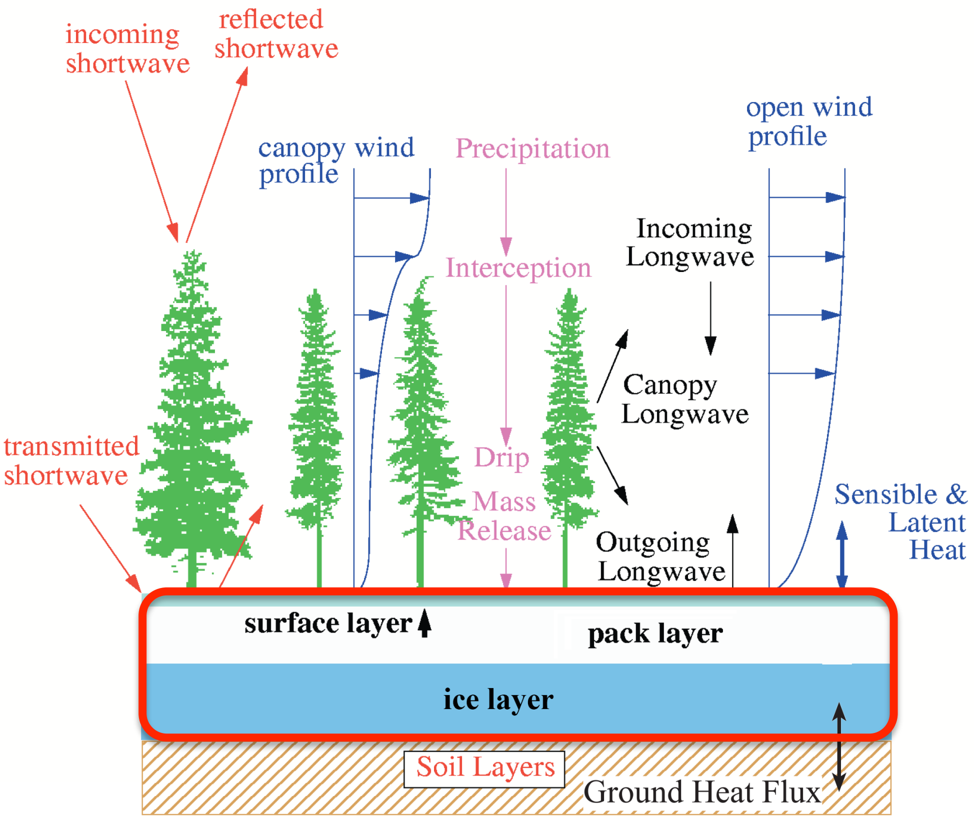
VIC Glacier Model

Accumulation | Redistribution | Ablation



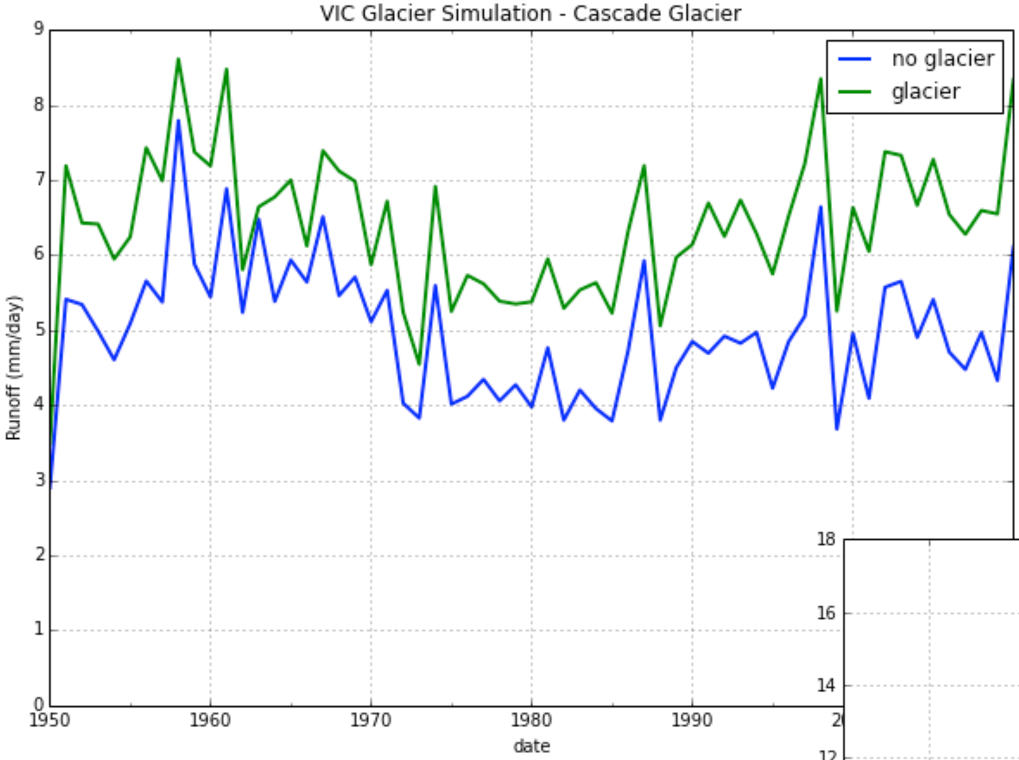
- Ice layer is combined with the snow pack layer for energy balance and snow melt computations.

VIC Snow Algorithm



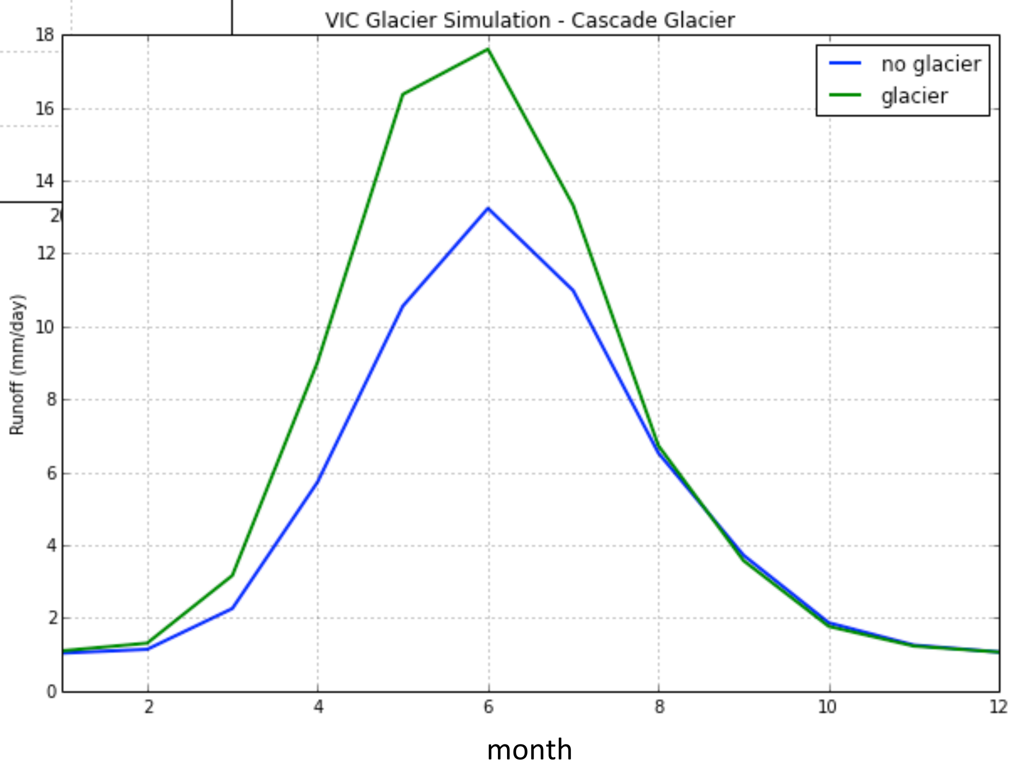
- Standard VIC snow algorithm is run using bulk pack layer.

Initial Results: Cascade Glacier Example

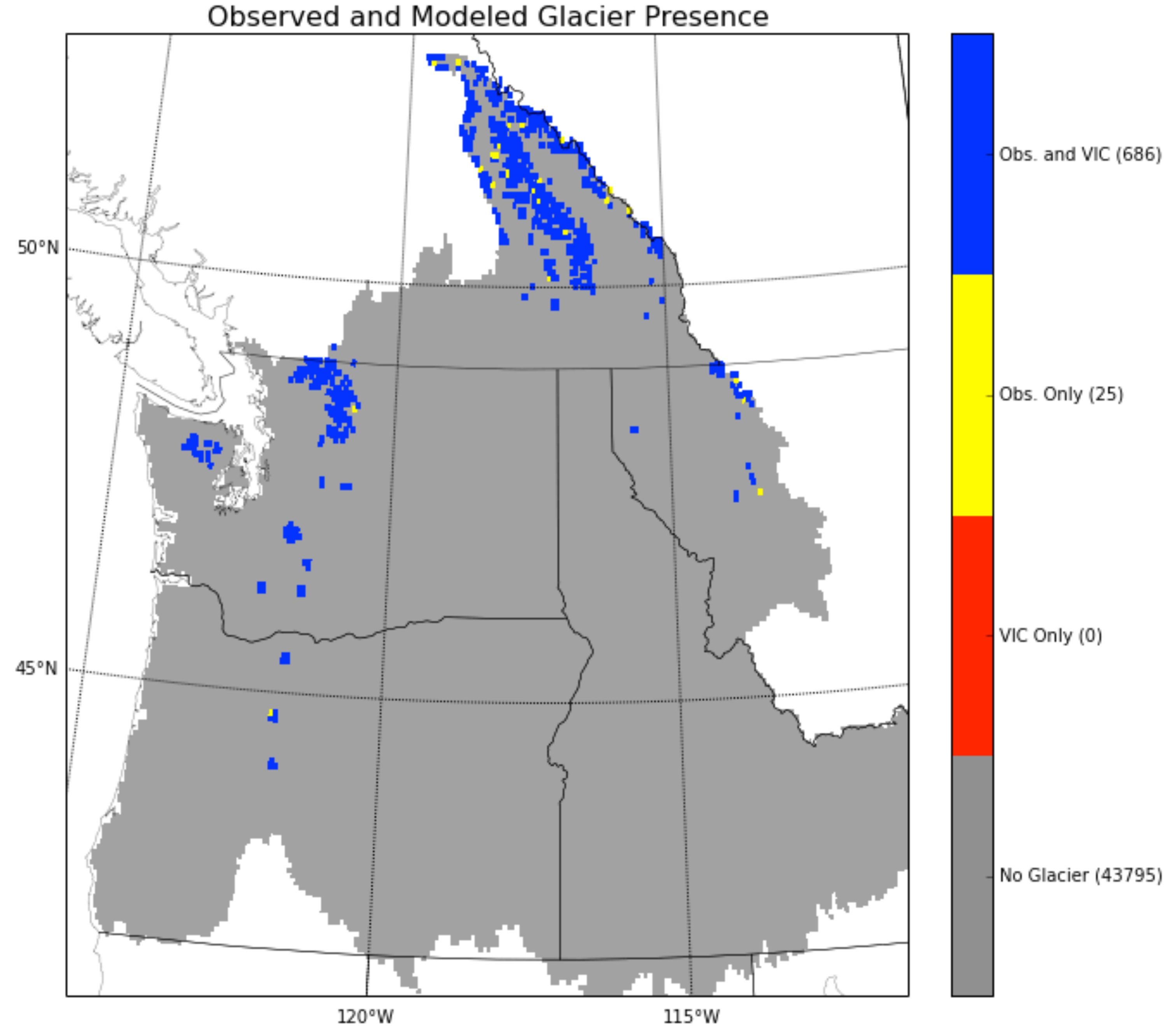


~25% Increase of annual runoff

Spring and summer months have largest increase in runoff



Glaciers in the PNW



A few last comments…

- Volume-Area scaling doesn't hold exactly when applied to an aggregate grid-cell rather than a single glacier.

- Scaling parameters may be tuned, calibrated, or estimated using observations.

- Requires better vertical resolution (more elevation bands) to adequately resolve accumulation/ablation line (ELA).

- Not directly applicable for glaciers larger than a single grid cell.

The End.

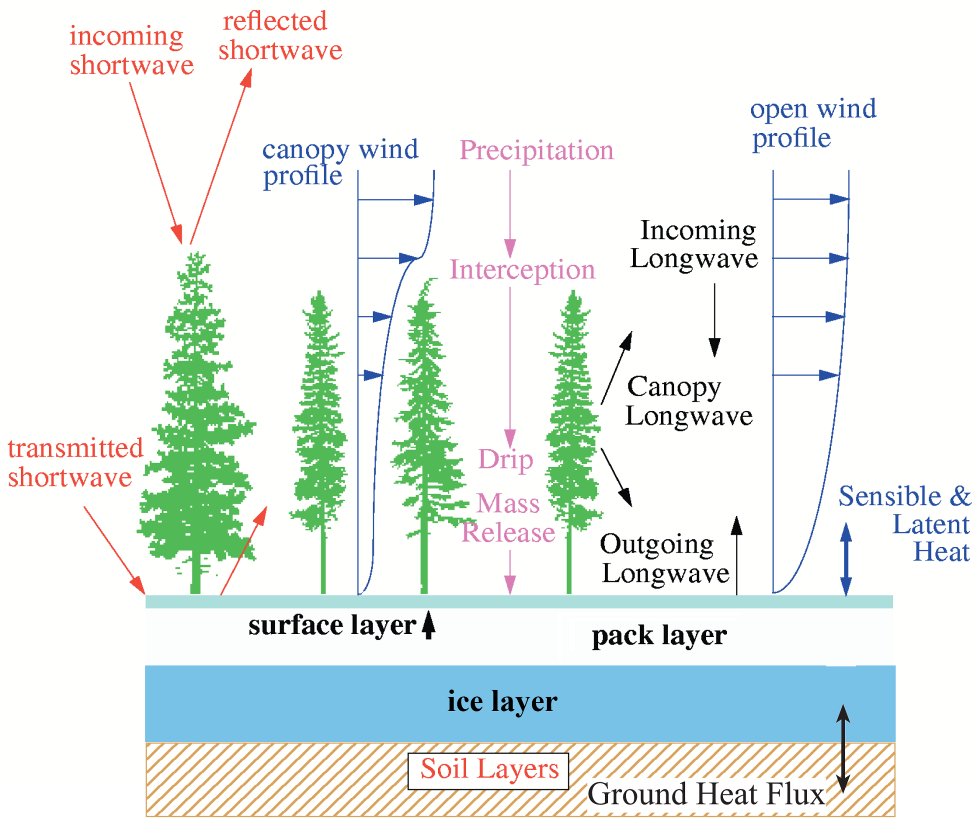
- Questions?

outline

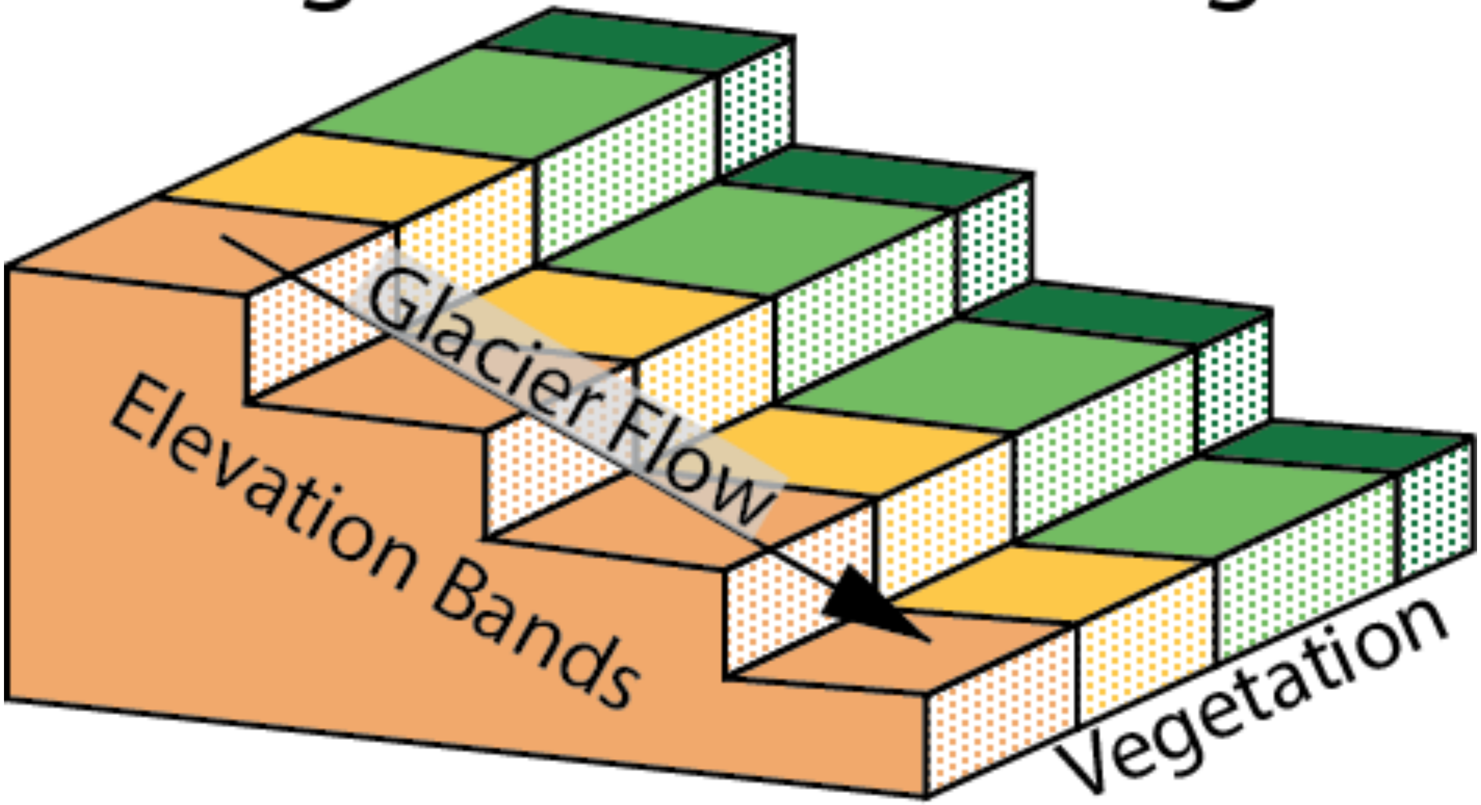
- Motivation:
  - 2860 Project (1 slide)
  - BPA 304 Project (3 hydrologic models, VIC glacier model) (1 slide)
  - Why we need to represent glacier model (1 slide)
- Description of VIC
  - VIC structure, snow model, elevation bands (2 slides)
  - Glacier model components (4 slides)
    - Include summary of Bahr et al’s work.
- Results
  - PNW glacier masks (simulated / remote sensing) (1 slide)
  - Cascade glacier results (5 slides)
- Next steps
  - Regionalization and/or calibration of scaling parameters (1 slide)
- Questions

Extras

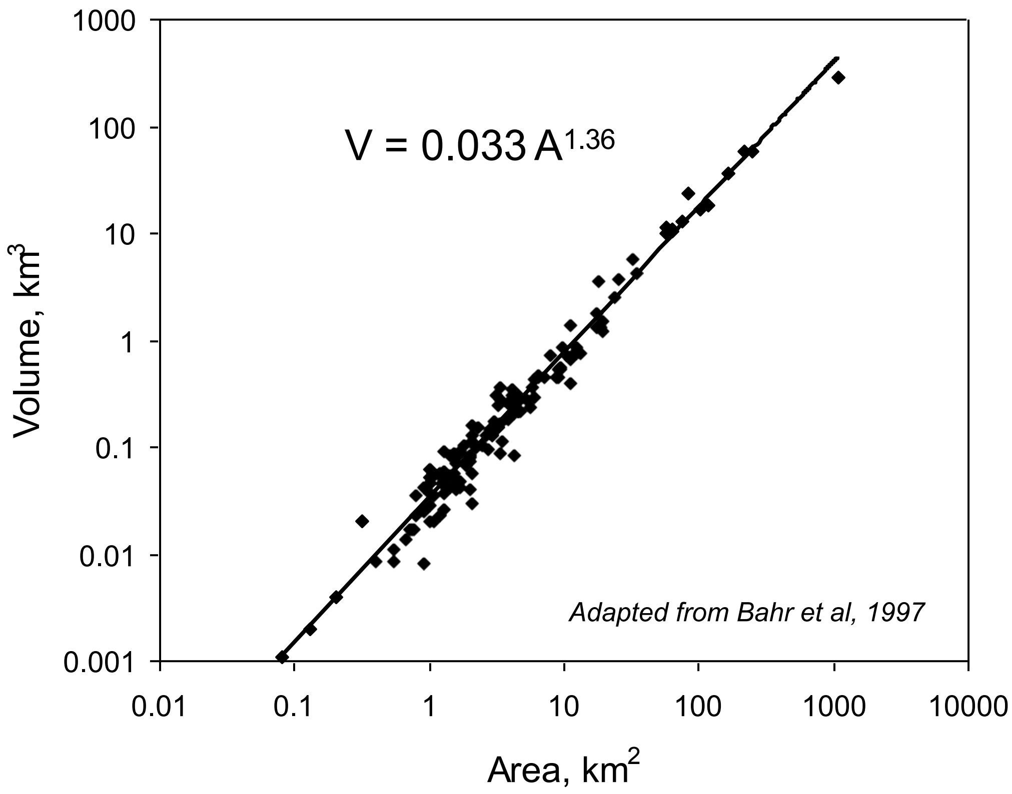
VIC Snow Algorithm



Sub-grid Elevation and Vegetation Coverage



$$V = c A^{1.375}$$



Collapse complex glacier dynamics to scaling relationship between volume and area.

Derived mathematically from dynamics.

Derivations and modeling show scaling is valid in both steady state *and* non-steady state. i.e., scaling is valid in past, present, and future.

Empirically established from data.

Bahr et al, 1997

Slide taken from Bahr, 2011. CESM Land Ice Working Group Presentation: Scaling Techniques for Simultaneously Modeling Hundreds of Thousands of Glaciers and Ice Caps

Also Need Response-Time Scaling

Response-time scaling: $T = k\,A^{\beta}$

Relaxes exponentially towards new state with characteristic time T.

South Cascade Glacier, WA

Small area, fast response to climate changes

Columbia Glacier, AK (Photo: James Balog)

Large area, slow response to climate changes

Bahr et al, 1998; Pfeffer et al, 1998

Finally, Need Hypsometry

Aletsch Glacier, Switzerland

- Average shape of a glacier
  - Long.
  - Nearly linear.
    - More data/analysis forthcoming.
  - Constant width.
    - Width given by (what else),
    - $W = c_w A\alpha$

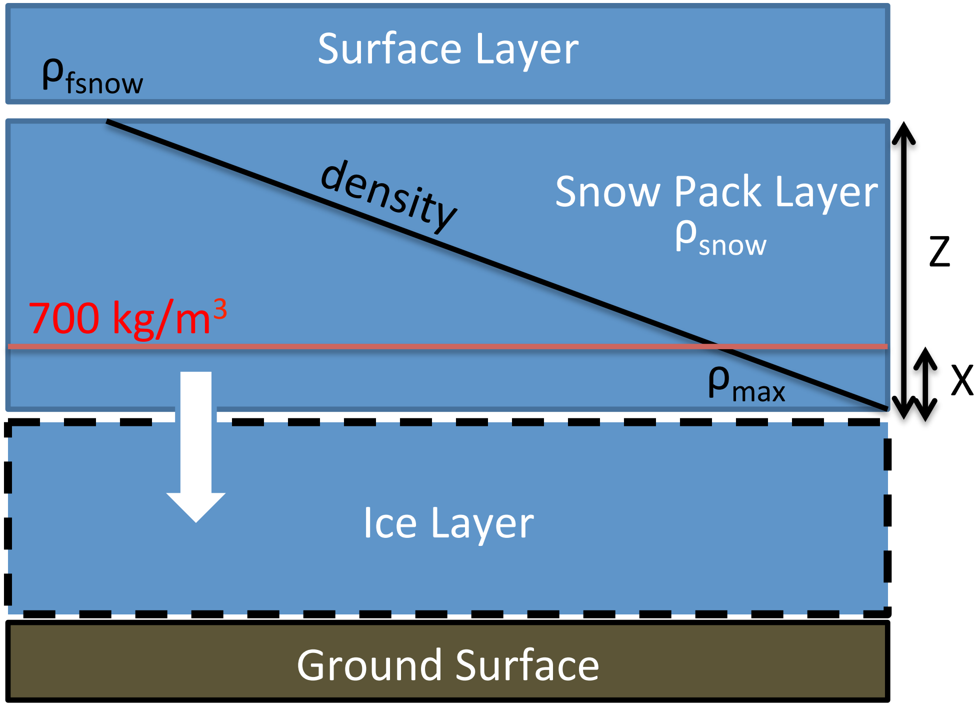
Vatnajokull Ice Cap, Iceland

- Average shape of an ice cap
  - Round.

Slide taken from Bahr, 2011. CESM Land Ice Working Group Presentation: Scaling Techniques for Simultaneously Modeling Hundreds of Thousands of Glaciers and Ice Caps

Ice with Density > 700kg/m³ becomes ice.

$$\rho_{max} = 2\rho_{snow} - \rho_{fsnow}$$



Depth of snow that becomes ice

$$X = Z - \frac{\rho_{thresh} - \rho_{fsnow}}{\rho_{slope}}$$

where $\rho_{slope} = \dfrac{\rho_{max} - \rho_{fsnow}}{Z}$

Update Snow Pack

$$\Delta SWE_{dens} = \int_{x}^{Z_{max}} \rho(z)dz \;= (Z - X)\cdot\left(\frac{(\rho_{max} + \rho_{thresh})}{2}\right)/\rho_w$$

$$\rho_{snow} = \frac{1}{Z}\int_0^z \rho(z)dz = \frac{1}{2}(\rho_{thresh} + \rho_{fsnow})$$