Simulating Areal Snowcover Depletion and Snowmelt Runoff in Alpine Terrain

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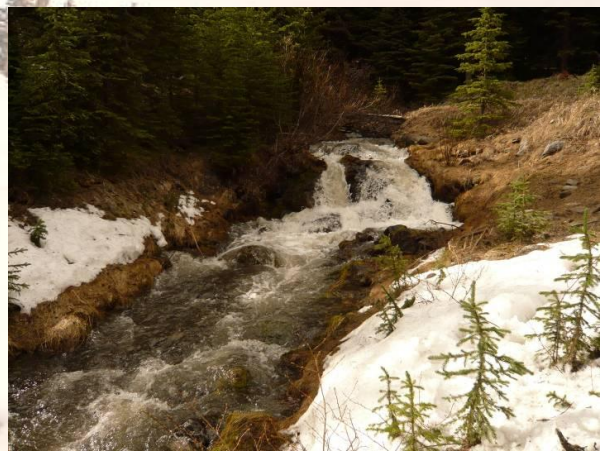


Background

- Snowmelt runoff from Rocky Mountains is an important water resource
- High uncertainty in the future hydrological response to climate and/or landcover change
- Important to be able to better understand and predict likely changes for future water management
  - Requires robust and physically based models for simulating snow processes

Variability of Alpine Snow Processes

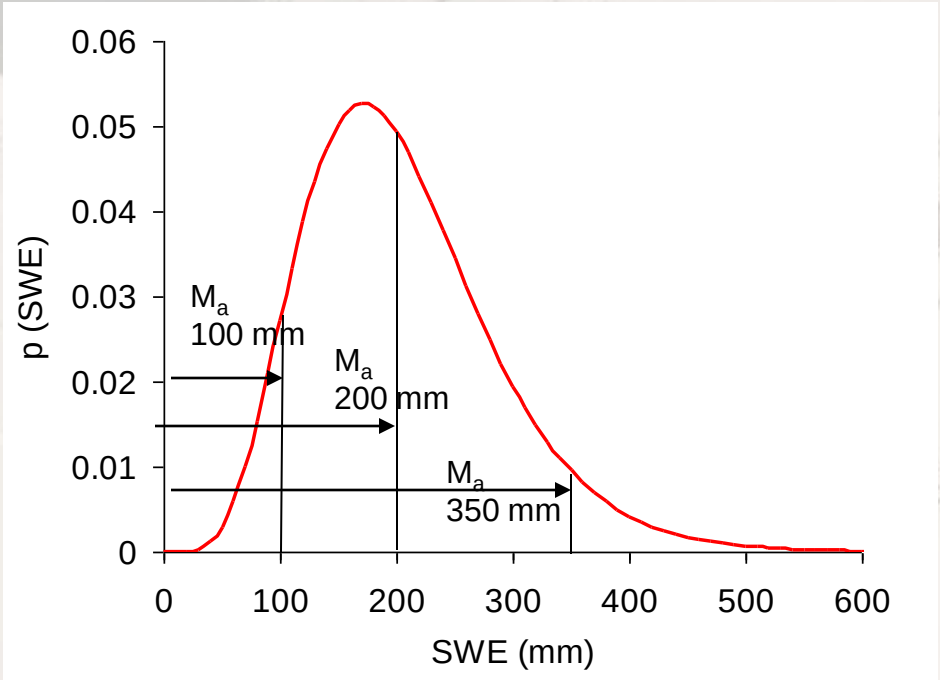
- Complexities in terrain and vegetation affect snow accumulation, redistribution, and melt
  - High spatial variability in snow water equivalent (SWE)
  - Large variation in energy for snowmelt during the spring
- Leads to a patchy snowcover as the spring progresses
- Significantly affects timing, rate, and magnitude of meltwater generation

Areal Snowcover Depletion (SCD)

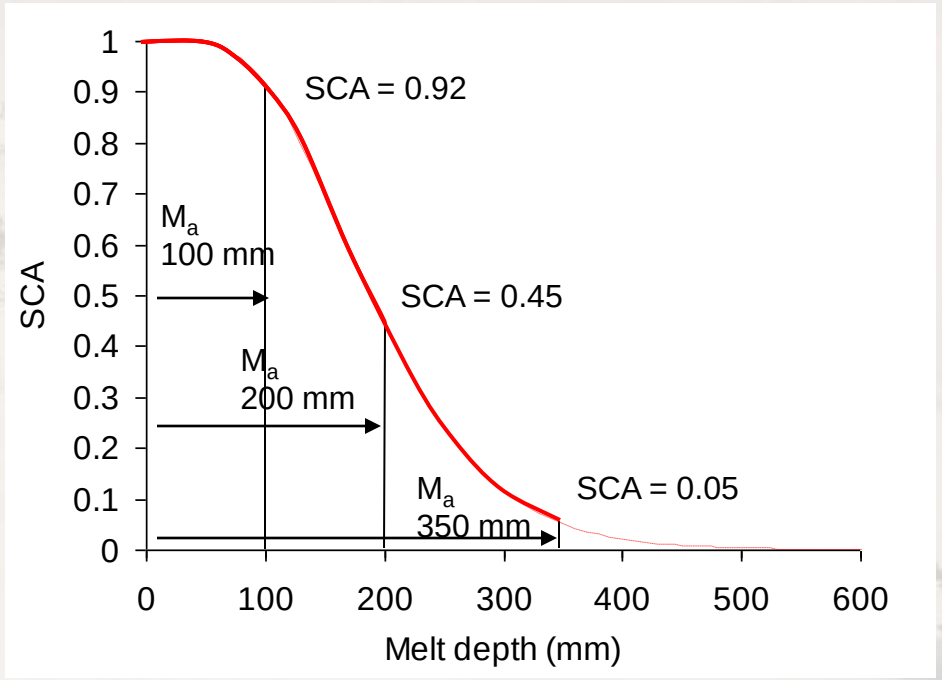
- Melt rate computations applied to a distribution of SWE yield snowcovered area (SCA) over time (SCD curve)

$$SCA = \int_{M_a}^{\infty} p(SWE)dSWE$$

Frequency distribution of SWE



Derived SCD curve



Problems with SCD Approach in Alpine Terrain

- The approach assumes uniform melt rate over the SWE distribution
  - Energy balance melt rate computations depend on snowpack state (e.g. depth, density, SWE, temperature, etc.)
  - Melt rates are not uniform in alpine terrain

- Further problems with new snowfall part way through melt

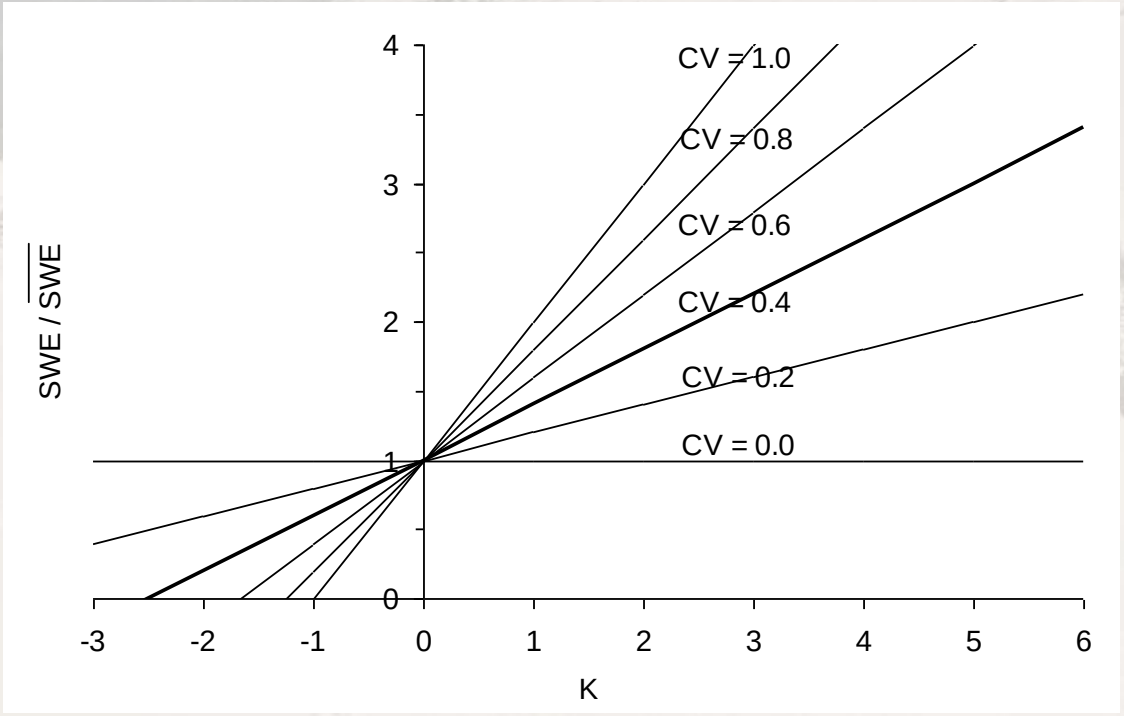
Study Objectives

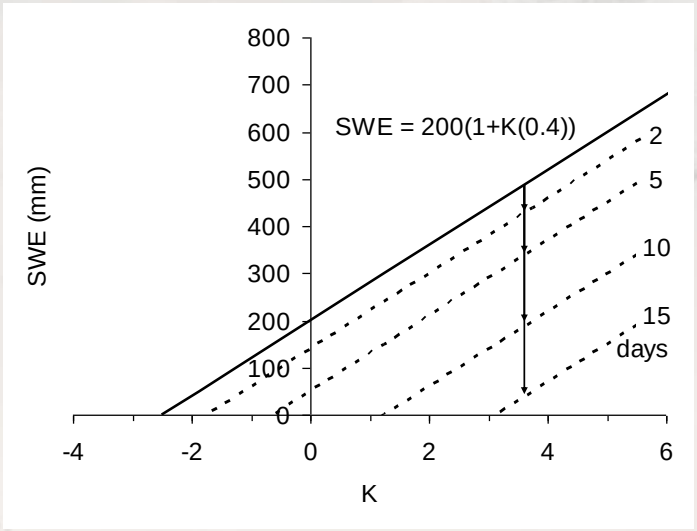
- Develop new theoretical framework for areal snowcover depletion (SCD) and meltwater generation
- Test framework using observations in alpine basin
- Determine how variability of SWE and snowmelt energy affect areal SCD and meltwater generation
- Incorporate framework within hydrological model and examine influence of variability on hydrograph

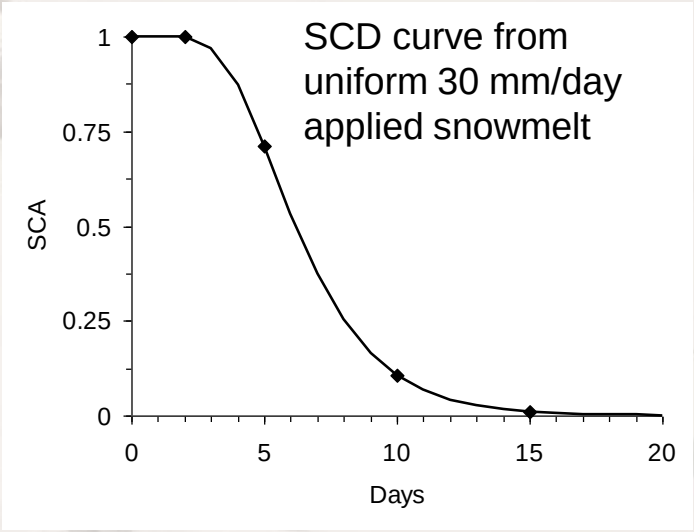
Development of Theoretical Framework

- Framework for areal SCD based on lognormal distribution

$$SWE = \overline{SWE}(1 + K \cdot CV)$$



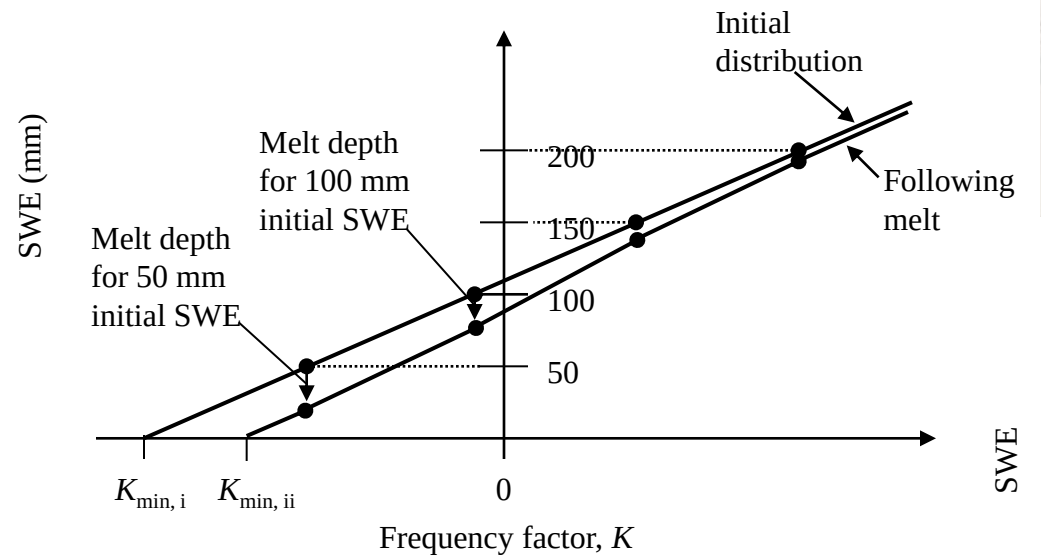




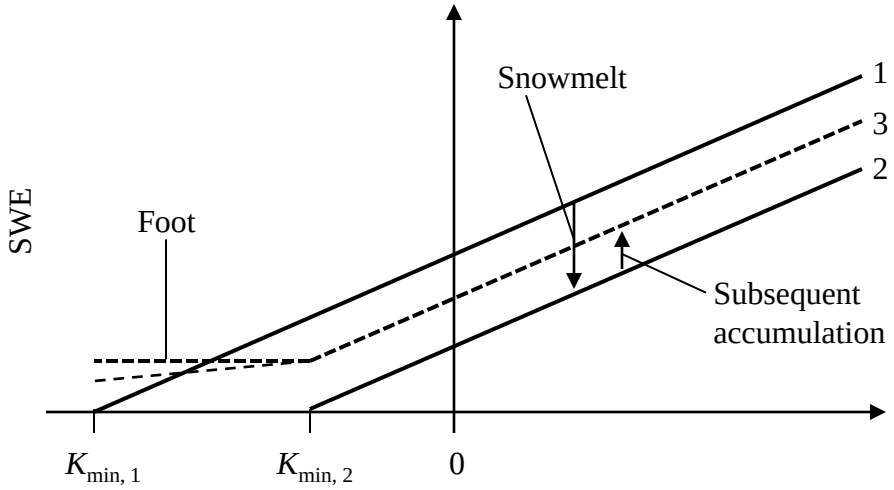
Development of Theoretical Framework

- Framework handles other important aspects of spatial snowmelt and new snowfall during spring

Line representing the distribution can be discretized

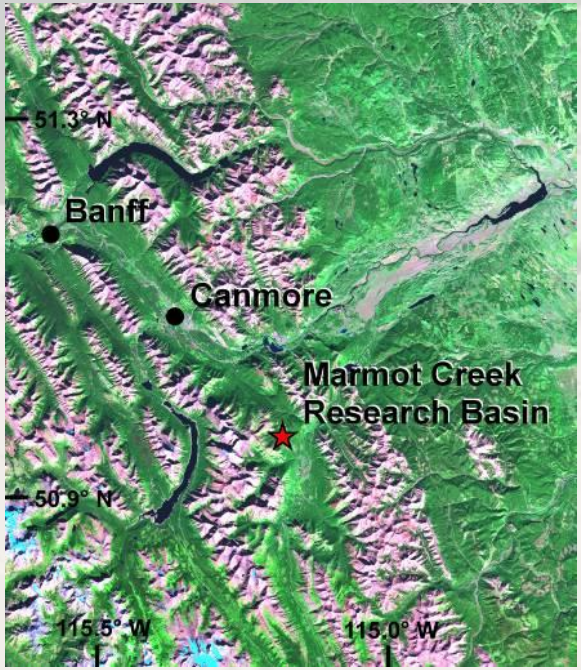


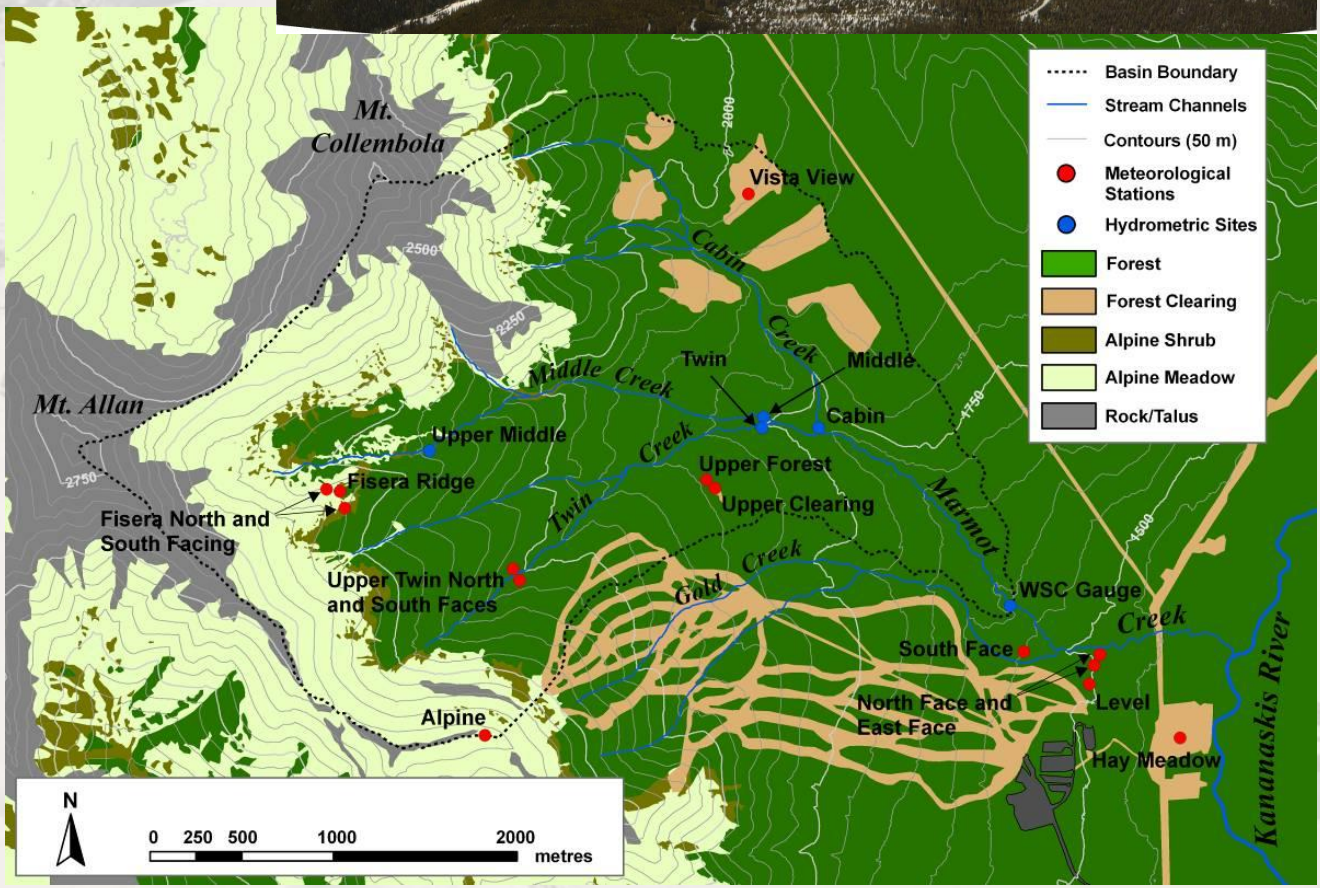
New snow added uniformly over remaining distribution



Field Study Site

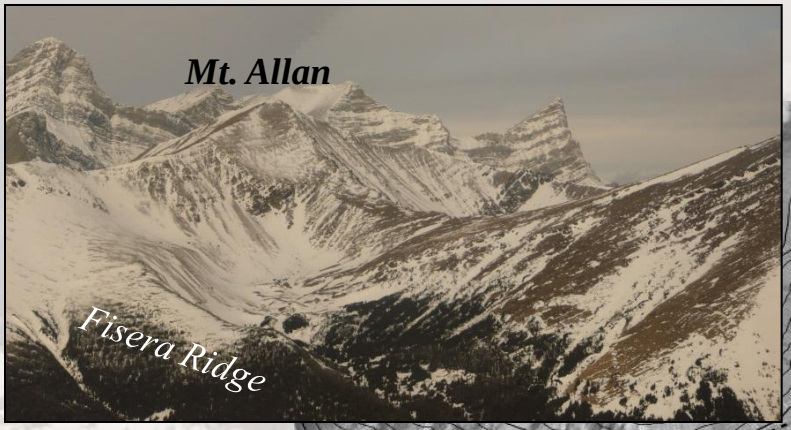
- Marmot Creek Research Basin, Kananaskis Country, Alberta

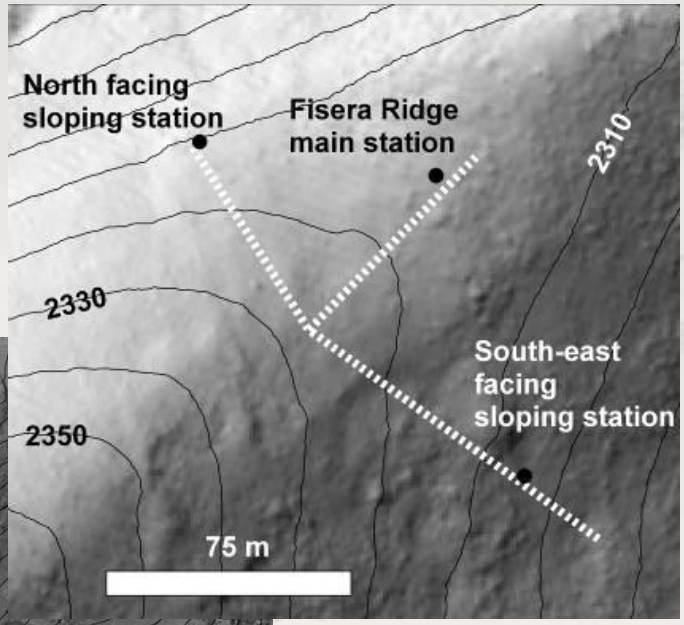


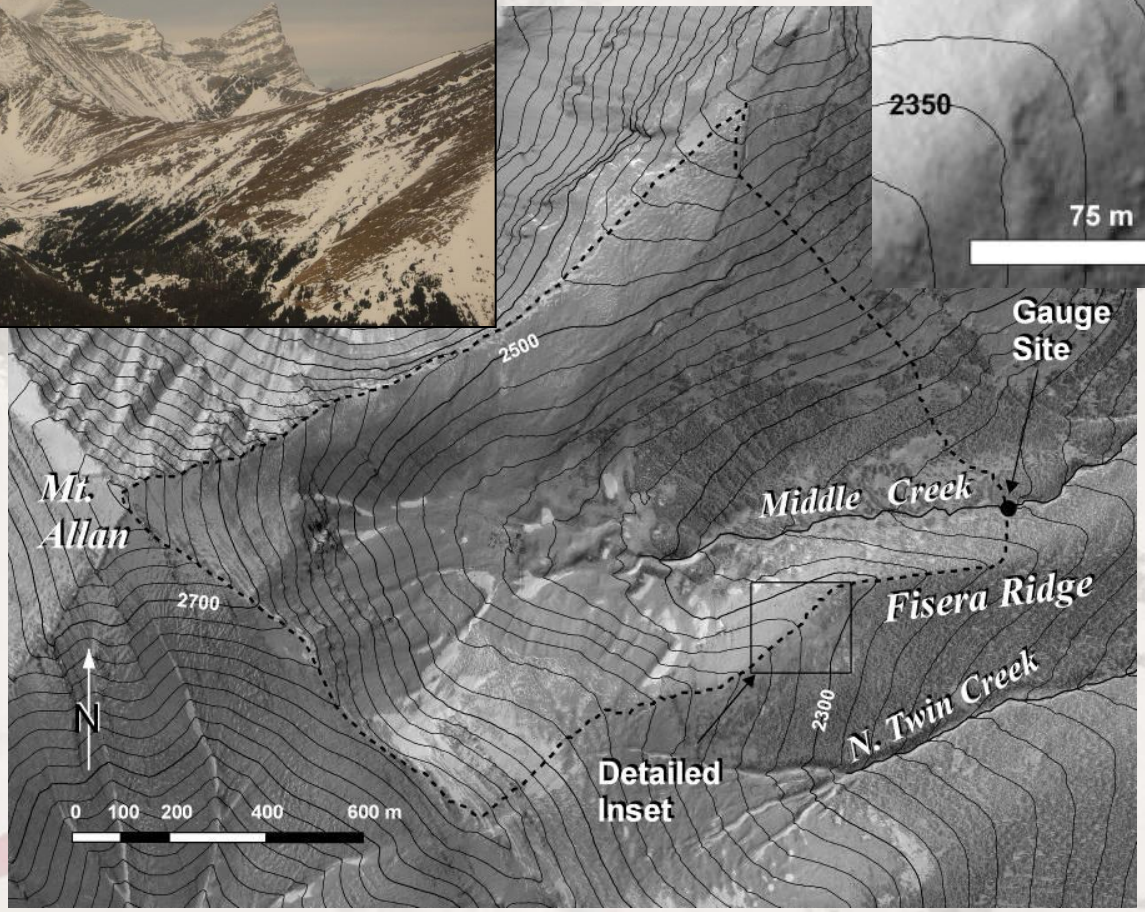


Field Study Site

- Focused data collection at Fisera Ridge and Upper Middle Creek

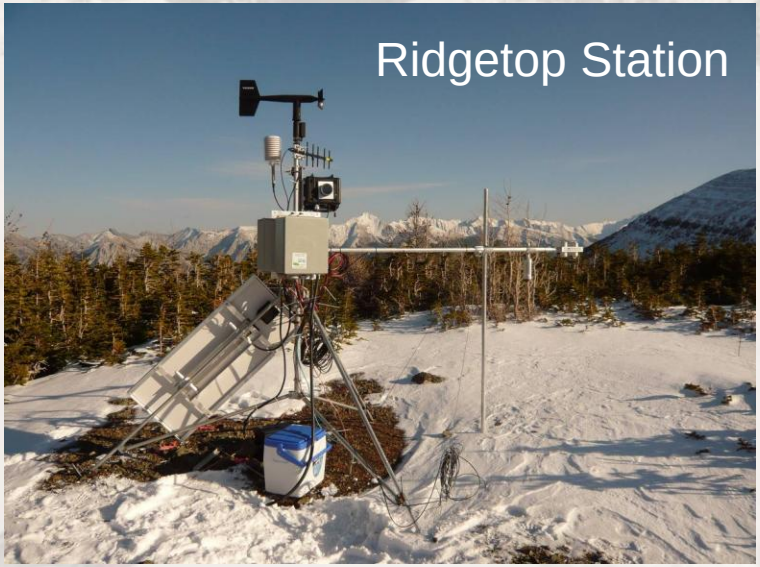


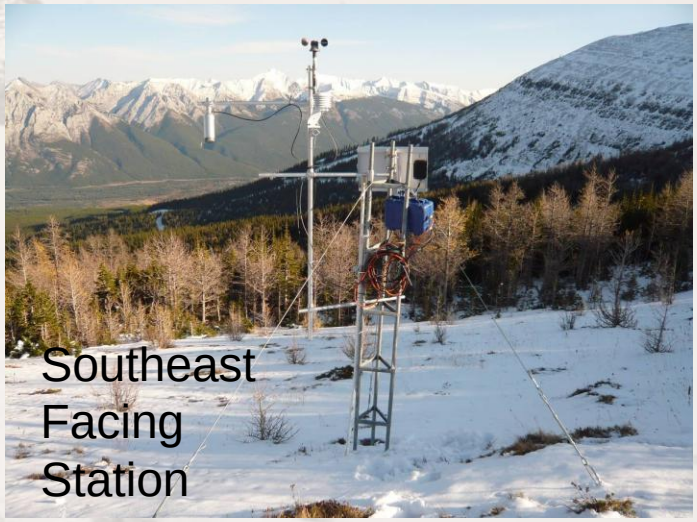




Field Methods and Observations

- Data collection over three years (2007-09) involved:
  - Meteorological observation
  - Snow surveys
  - Daily terrestrial photos
  - Lidar snowcover mapping
  - Streamflow measurement



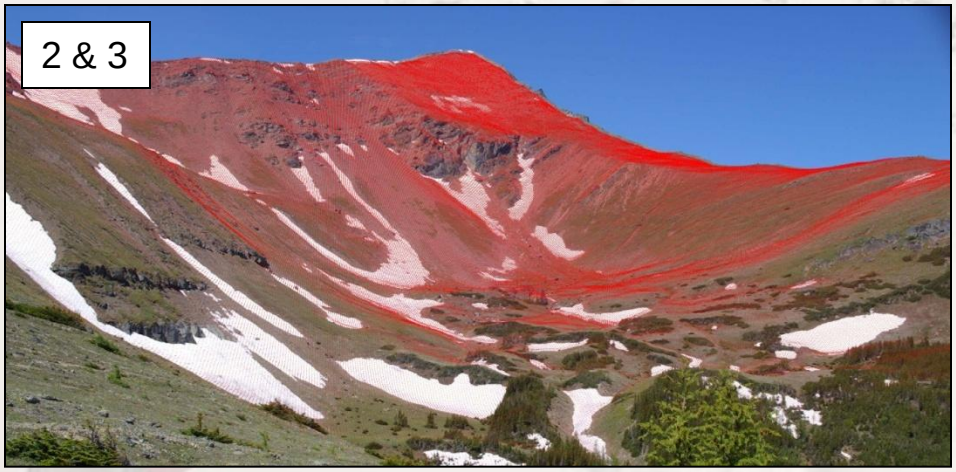


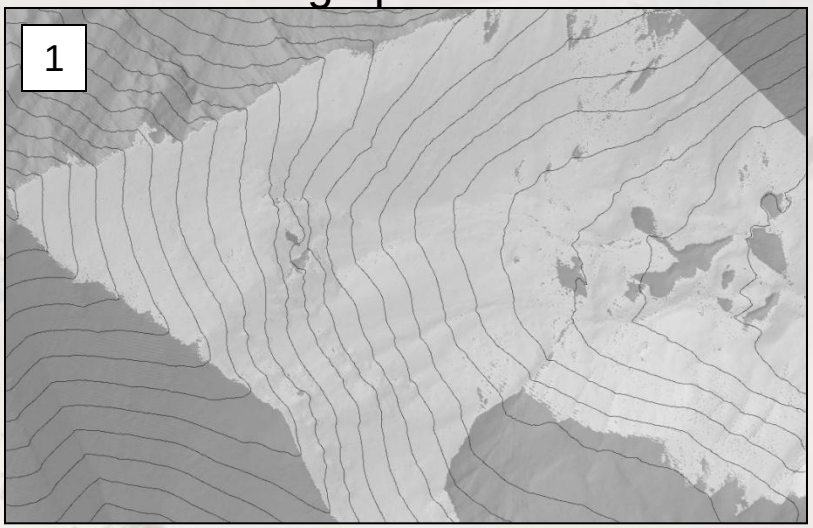
Field Methods and Observations

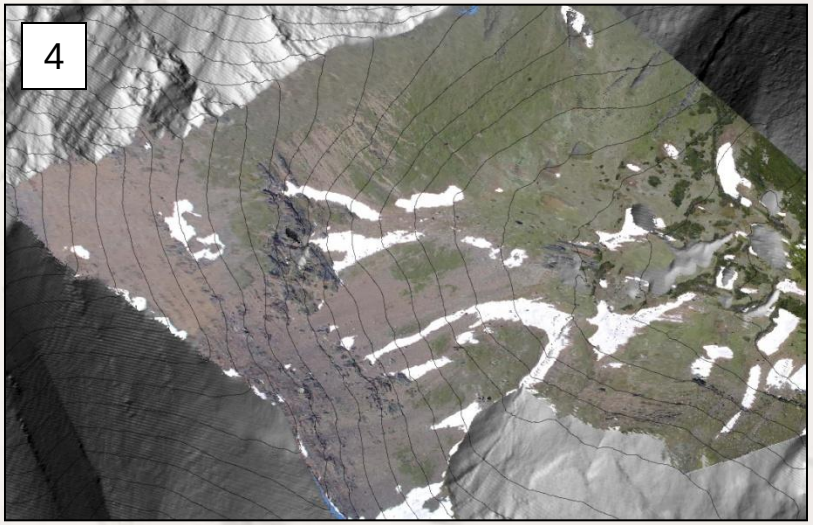
- 100’s of snow surveys over 3 years
- Setup and maintenance of many instruments and met stations
- Dozen’s of manual stream discharge measurements

Terrestrial Oblique Photo Correction

1) Viewshed mask created from camera perspective
2) DEM projection in camera coordinate system
3) Correspondence established between DEM cells and image pixels
4) Image reprojection in DEM coordinates







Areal Snowcover Observations

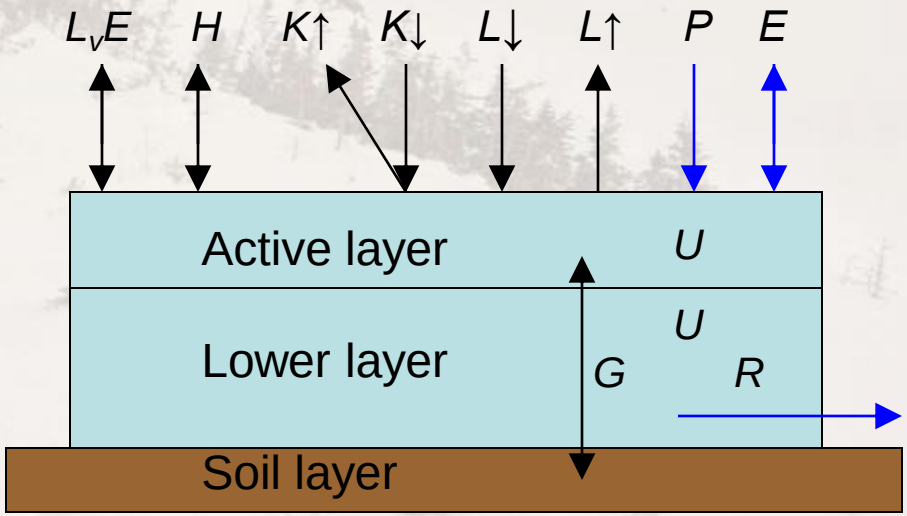
Time lapse digital photography used to monitor areal SCD

Snowmelt Modelling and Validation

- Snowpack evolution simulated using the *Snobal* energy balance model within Cold Regions Hydrological Model (CRHM) platform

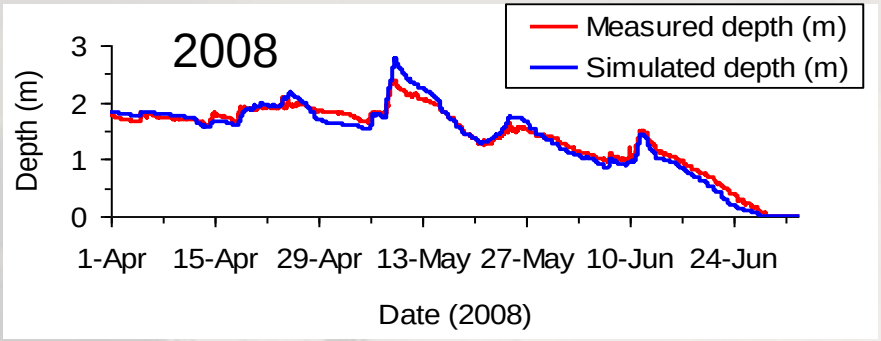
Shortwave and longwave radiation inputs corrected for slope, aspect, skyview fraction using algorithms in CRHM

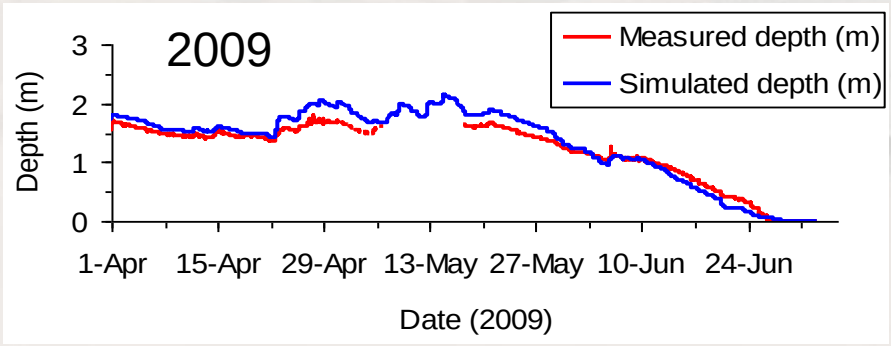
($Q_m = L_vE + H - K\uparrow + K\downarrow + L\downarrow - L\uparrow + G - \mathrm{d}U/\mathrm{d}t$)

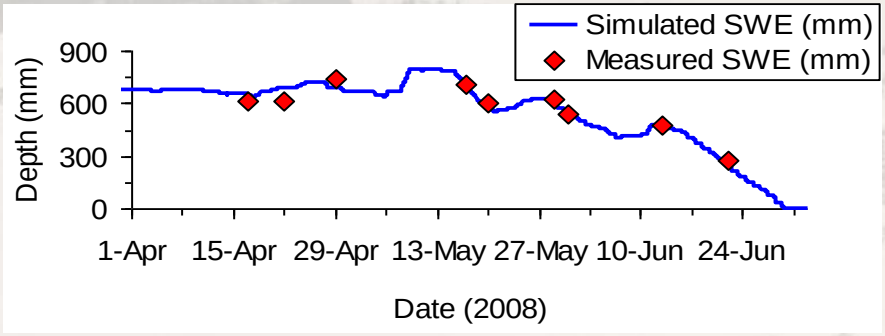


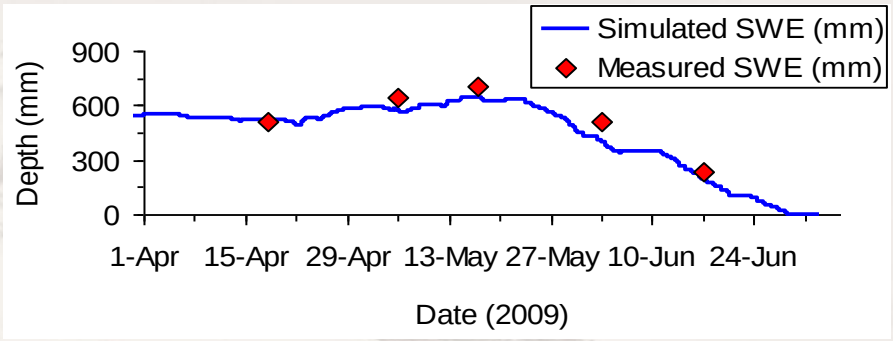
Snowmelt Modelling and Validation

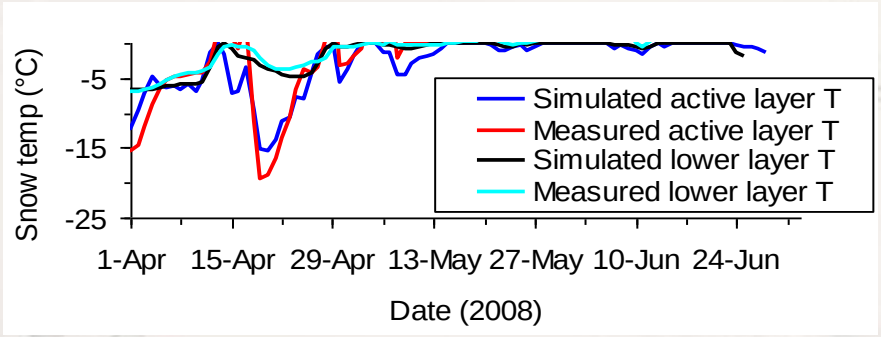
- Model performs well for depth, SWE, internal energy

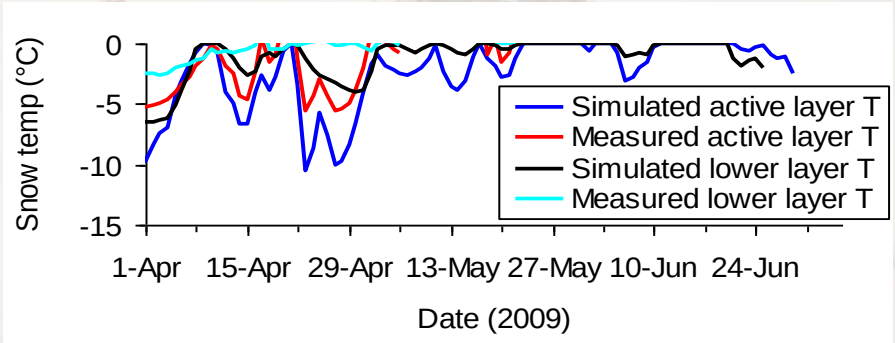








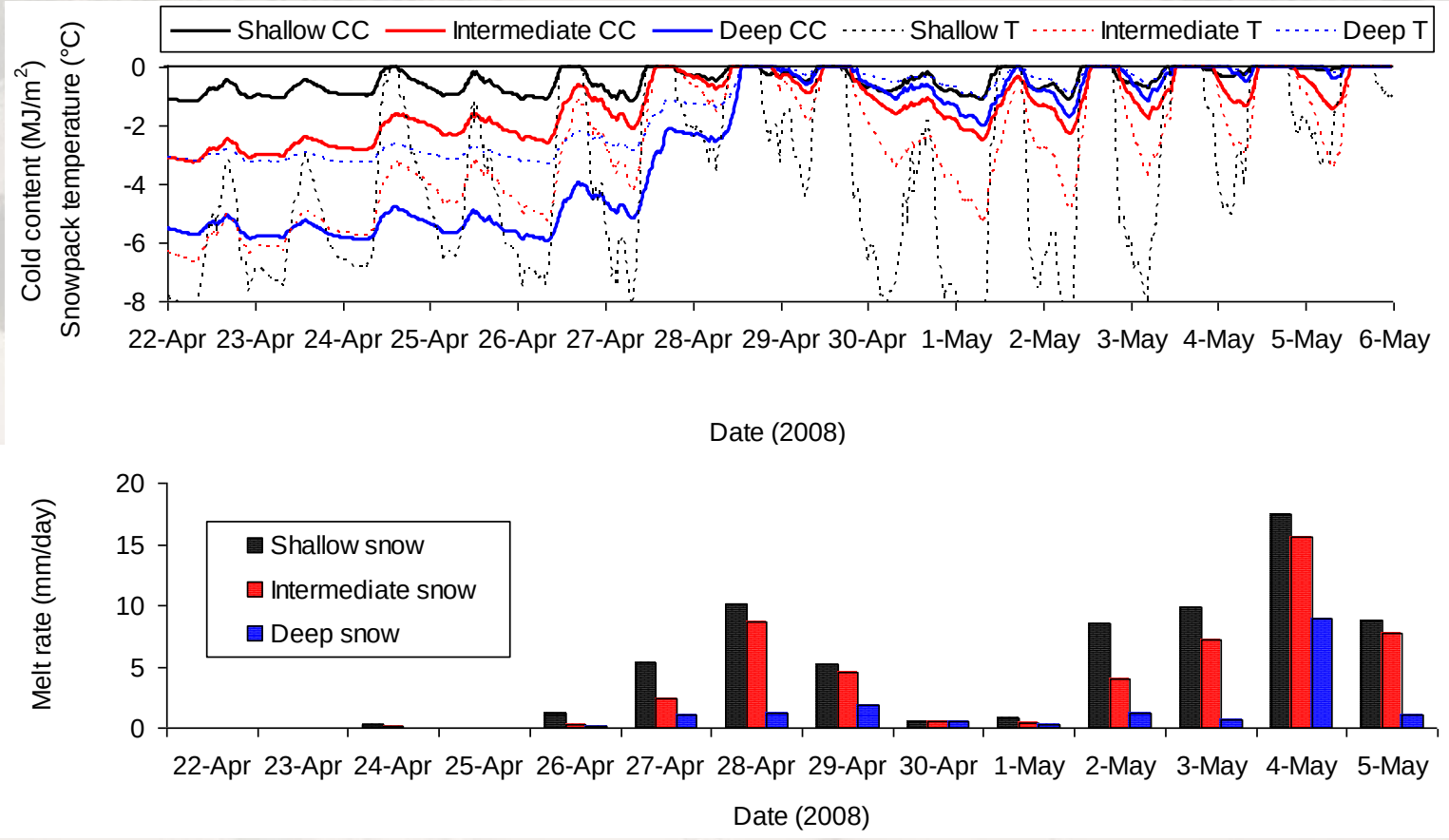




Effects of Snow Mass and Internal Energy

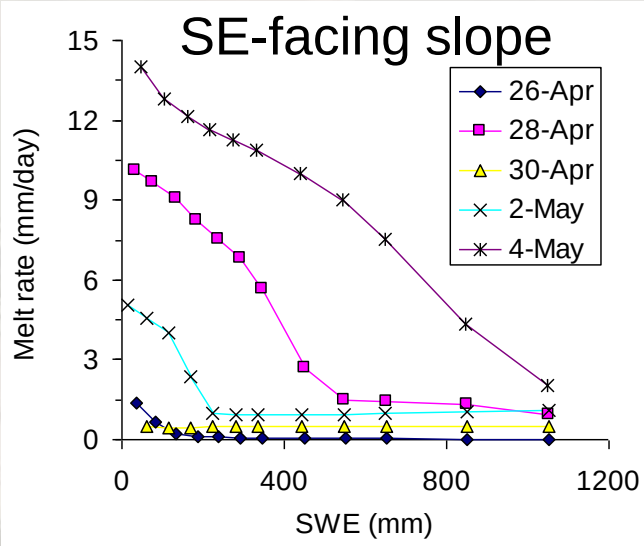
- Differences in initial state have large influence on computation of snowmelt timing and rate

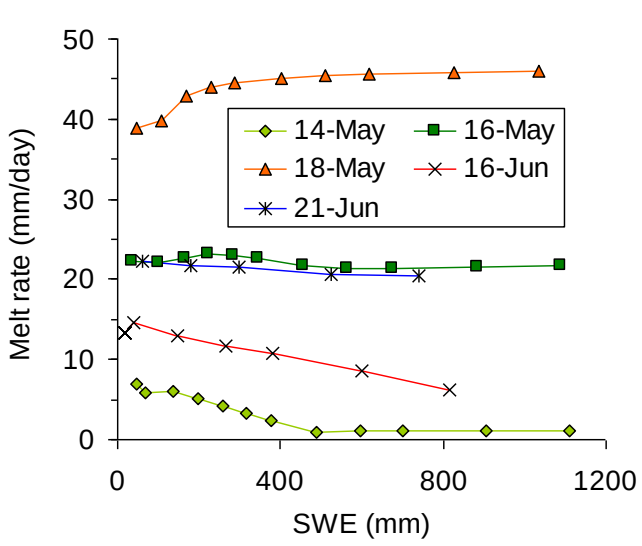
Cold Content: Energy required to bring snowpack to 0 °C and satisfy liquid water holding capacity

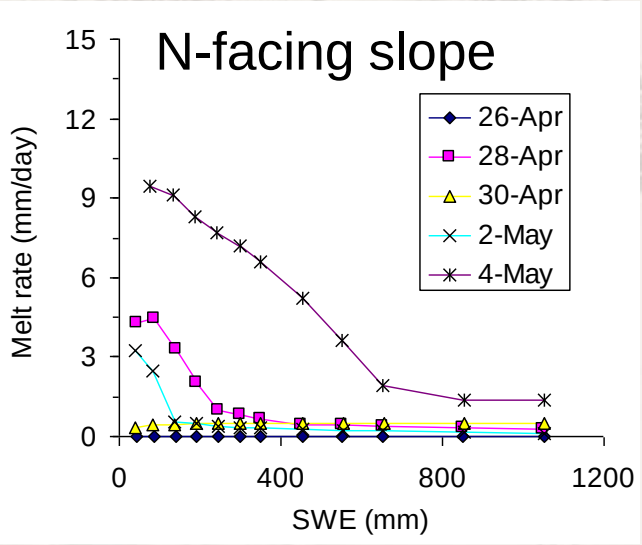


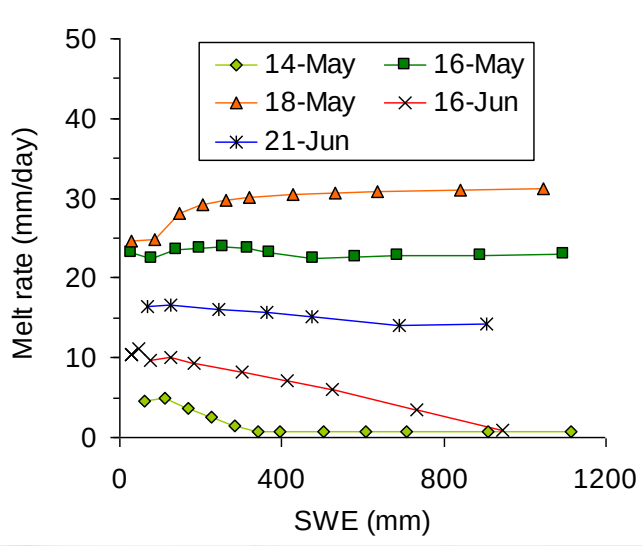
Spatial – Temporal Snowmelt Variability

- Differences in melt energy and SWE lead to large differences in snowmelt that change over time





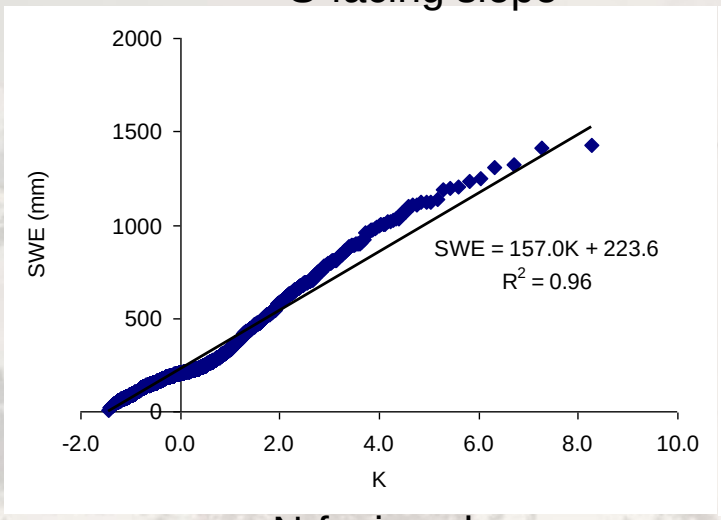


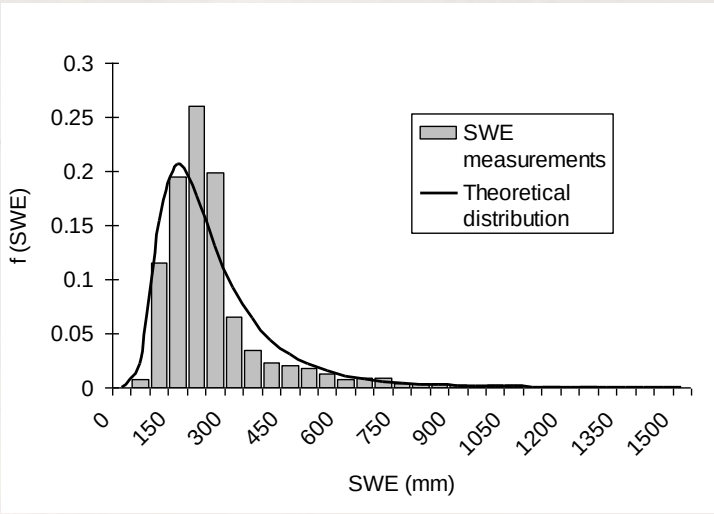


Landscape Disaggregation for SCD Simulation

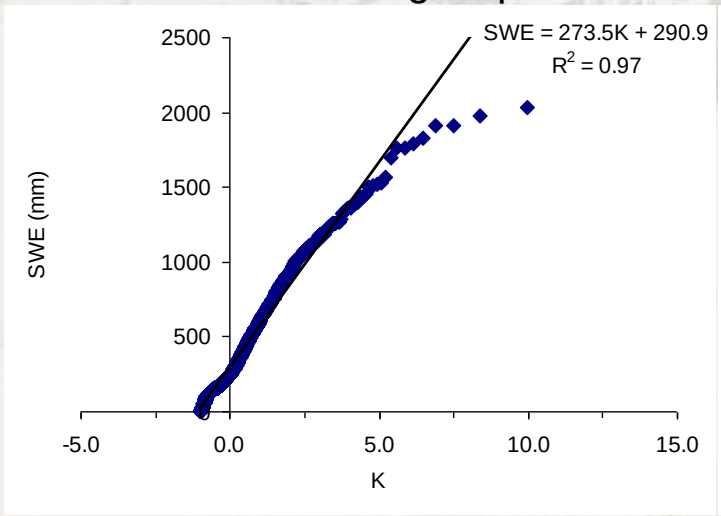
- SWE values on different slopes fit theoretical lognormal distribution

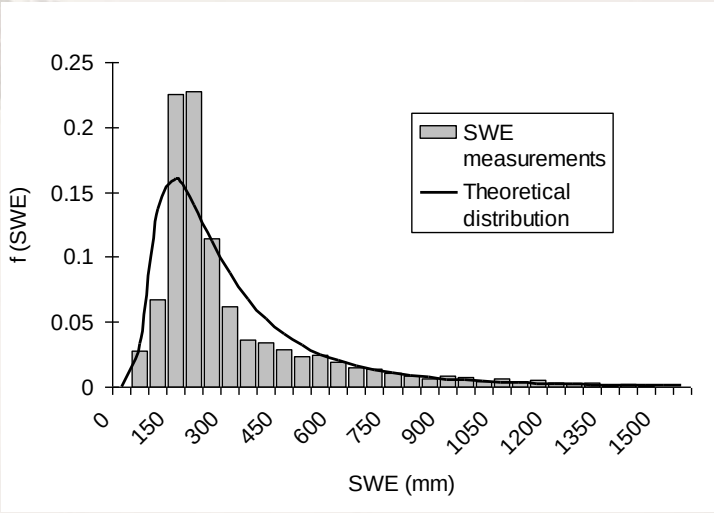
S-facing slope





N-facing slope

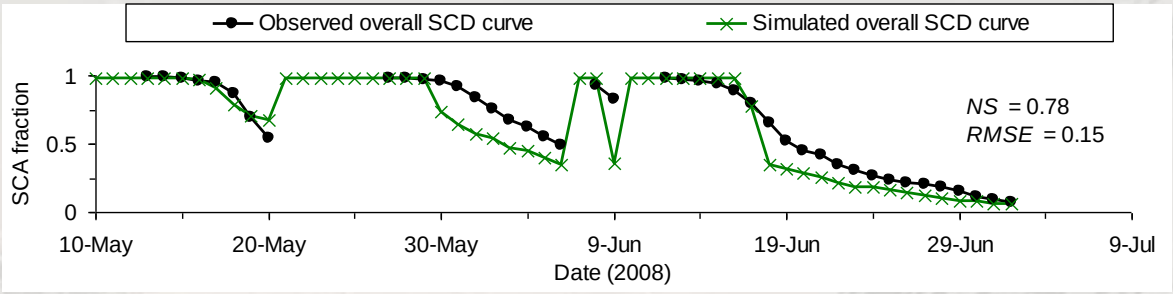


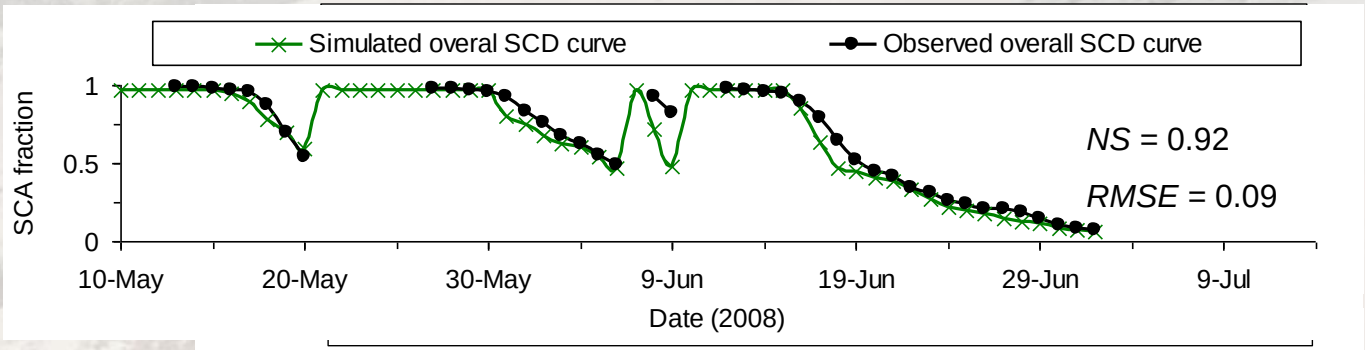


Simulation of Areal SCD over Landscape

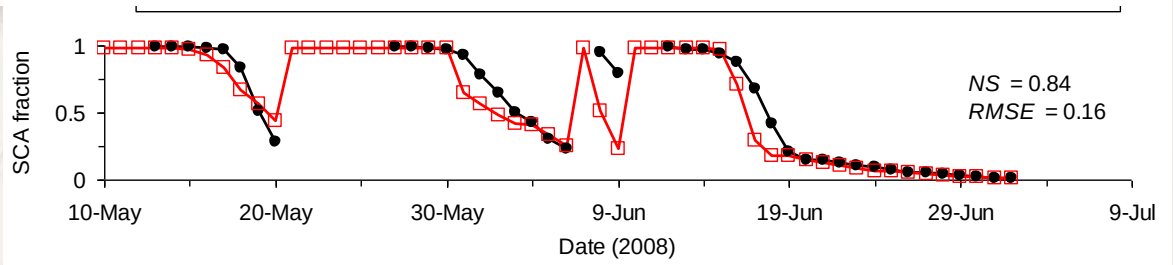
- Framework applied to predict areal SCD
- Results were improved by considering separate distributions and melt rates on each slope

Overall basin

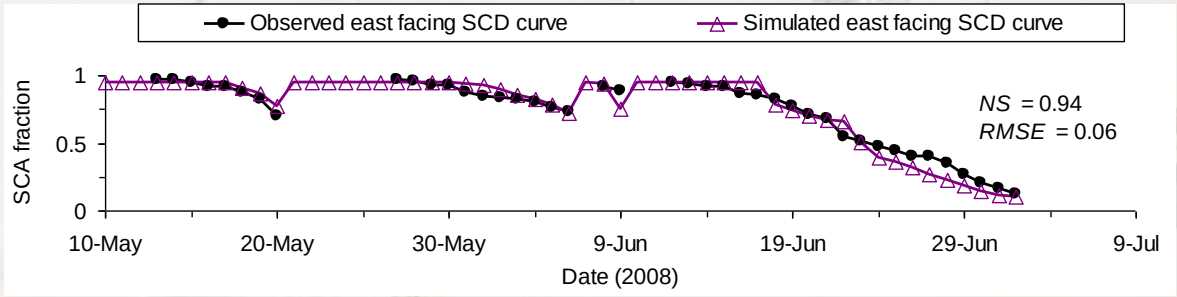




South facing

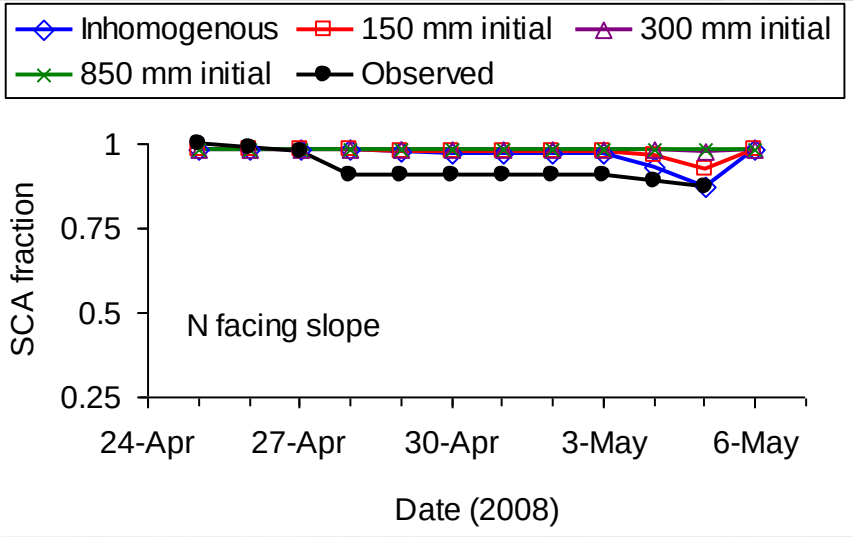


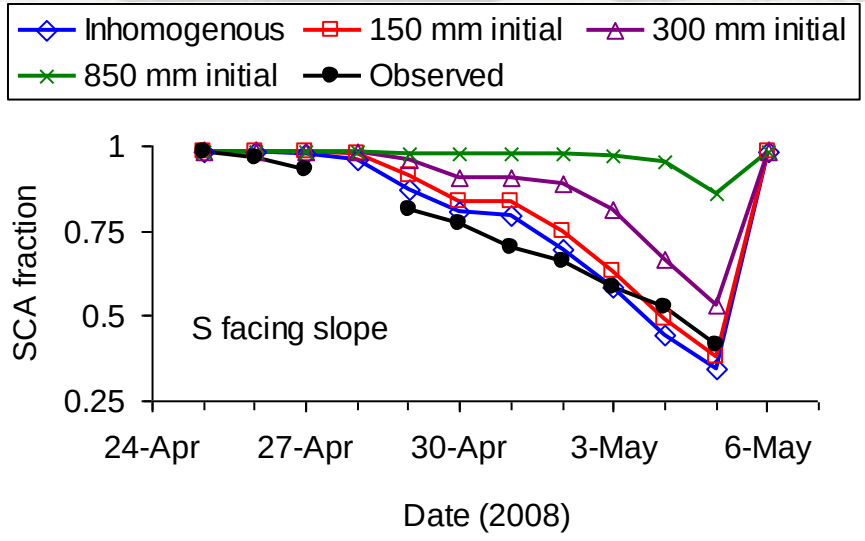
East facing

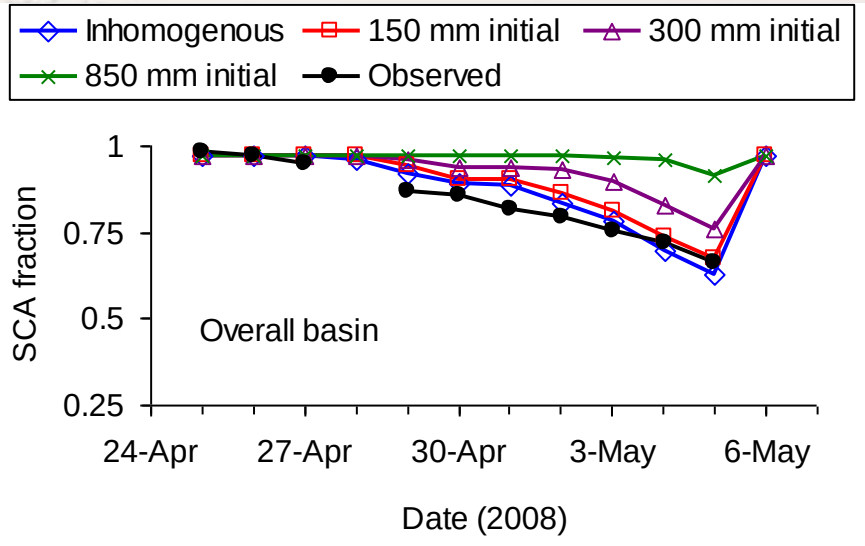


Influence of “Inhomogeneous” Snowmelt

- Earlier and more rapid melt of shallow snow on some slopes led to an initial acceleration of SCD

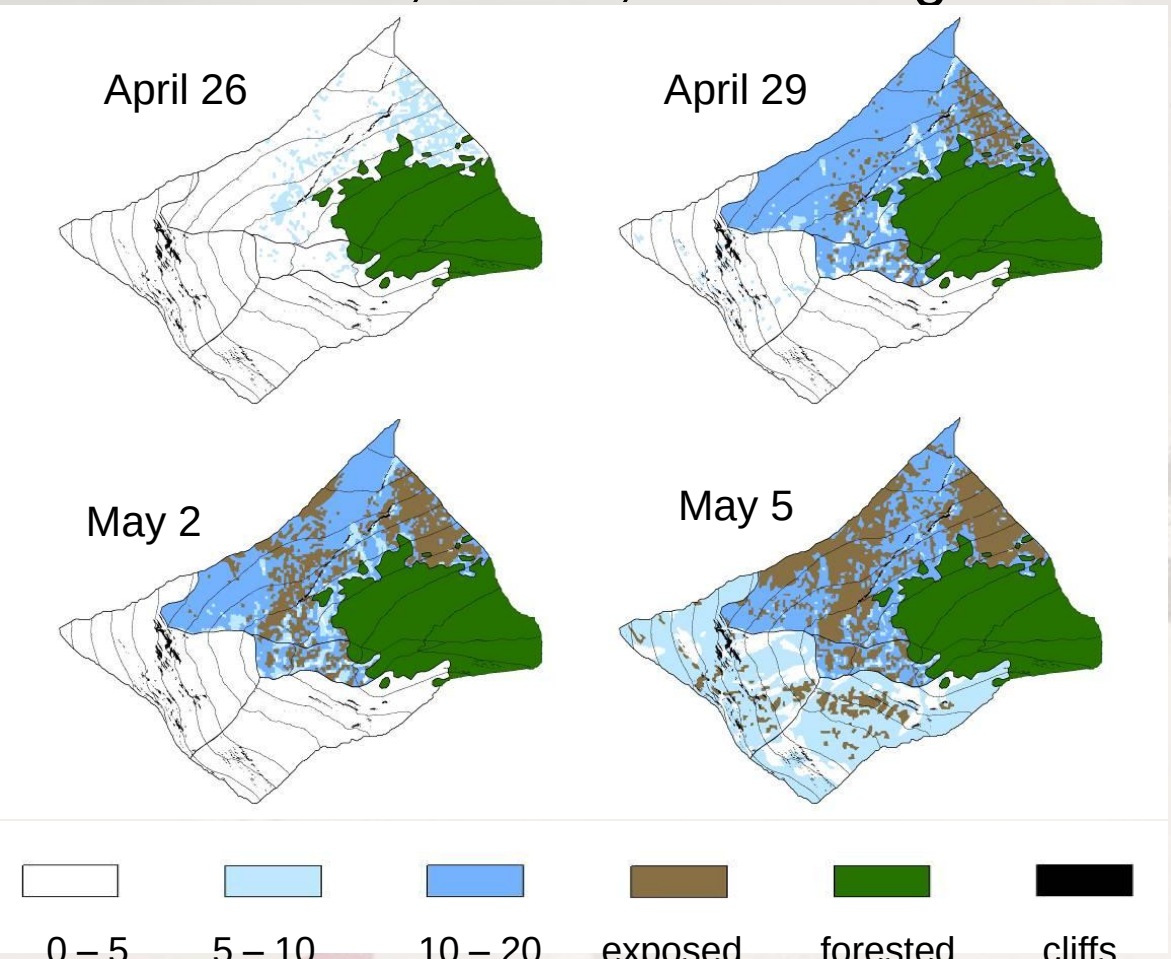


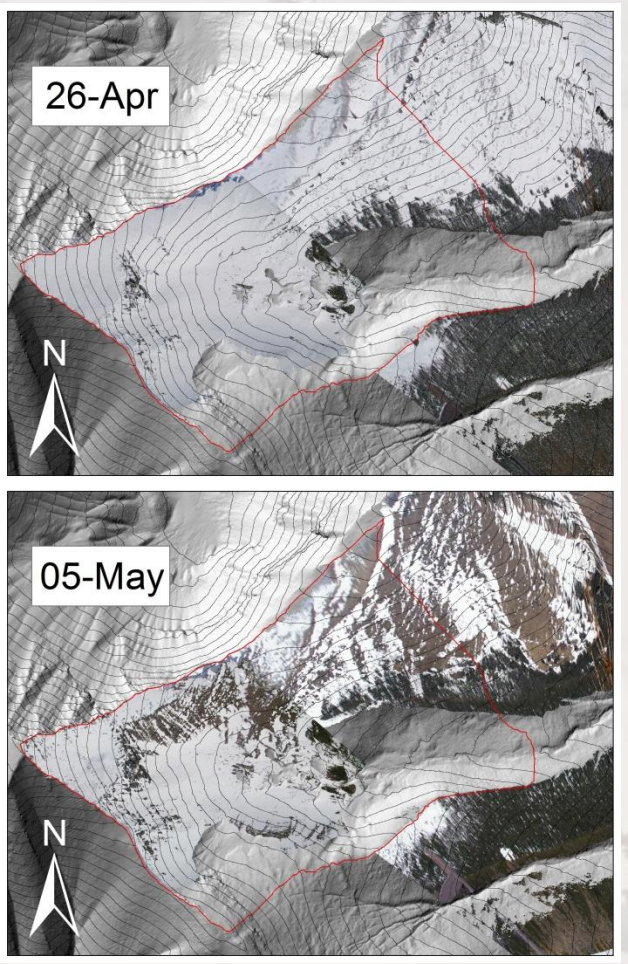




Spatial Variability of Meltwater Generation

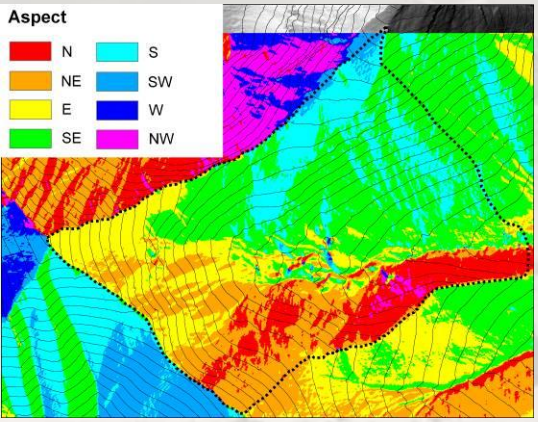
- Variability in melt over landscape and SWE dist's. affects location, extent, and timing of meltwater generating area

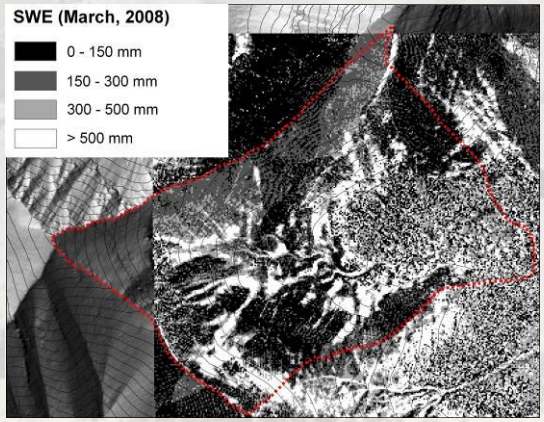


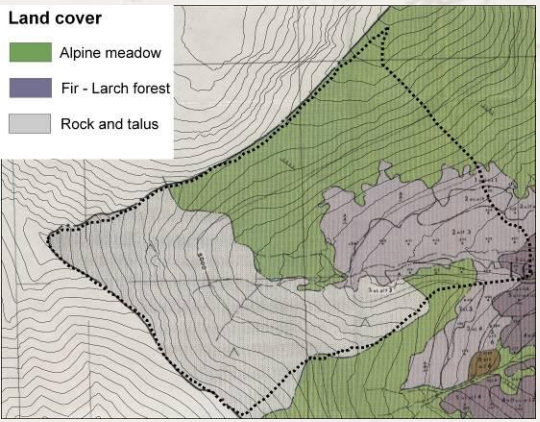


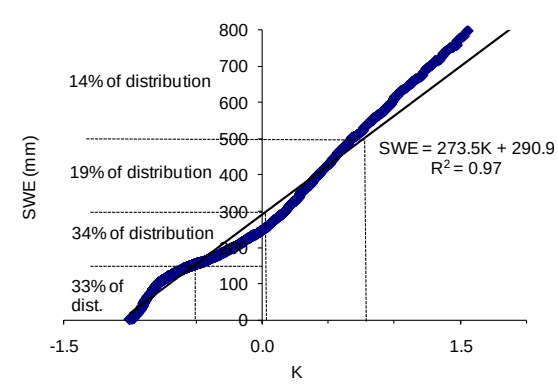
Hydrological Model Development

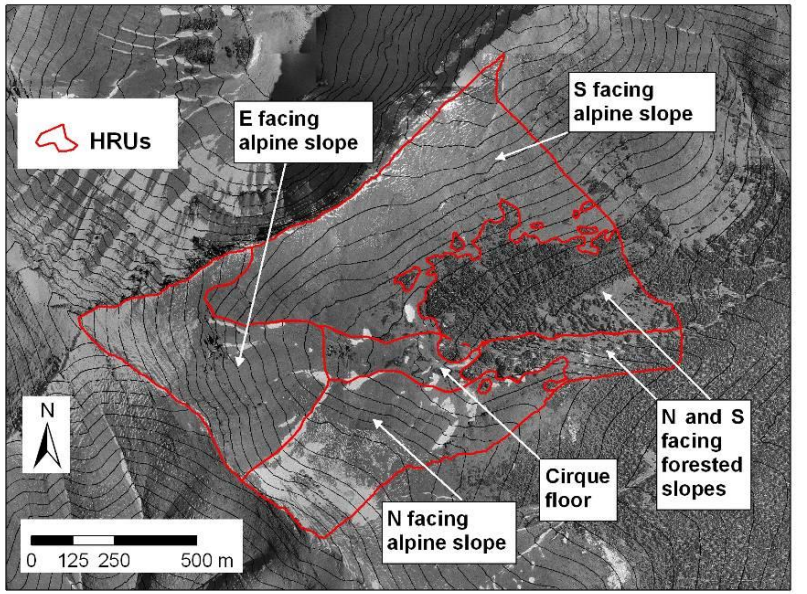
- Process-based and conceptual model with spatial structure based on topography, land cover, and SWE distributions







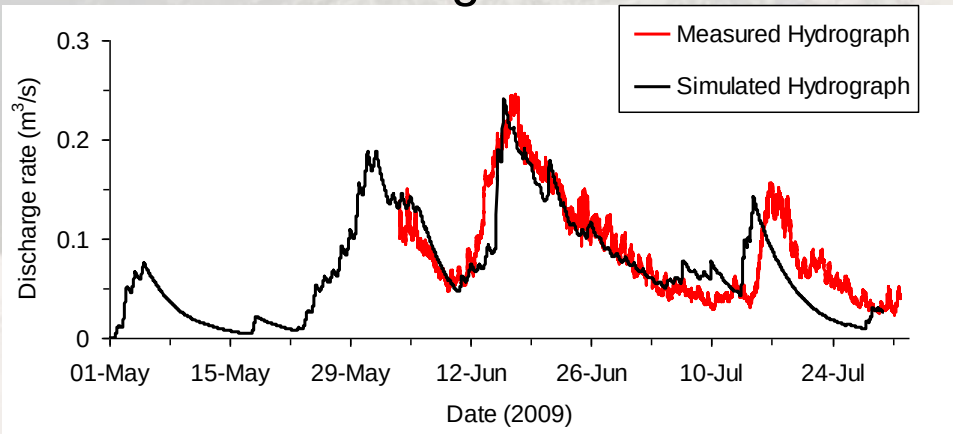


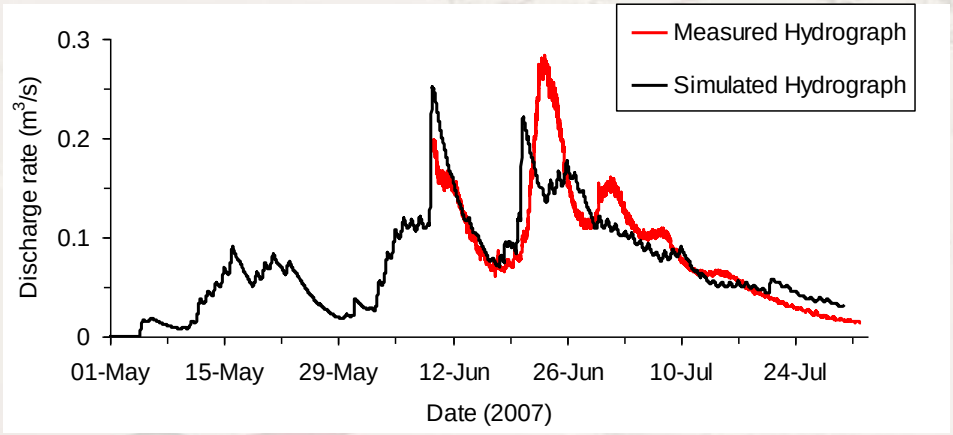


Model Evaluation for Snowmelt Hydrograph

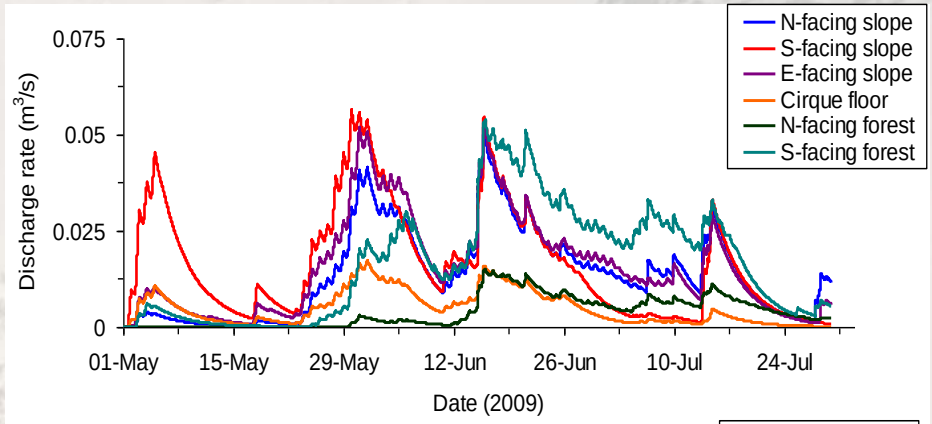
- Model is capable of producing reasonable hydrographs with correct volume of runoff

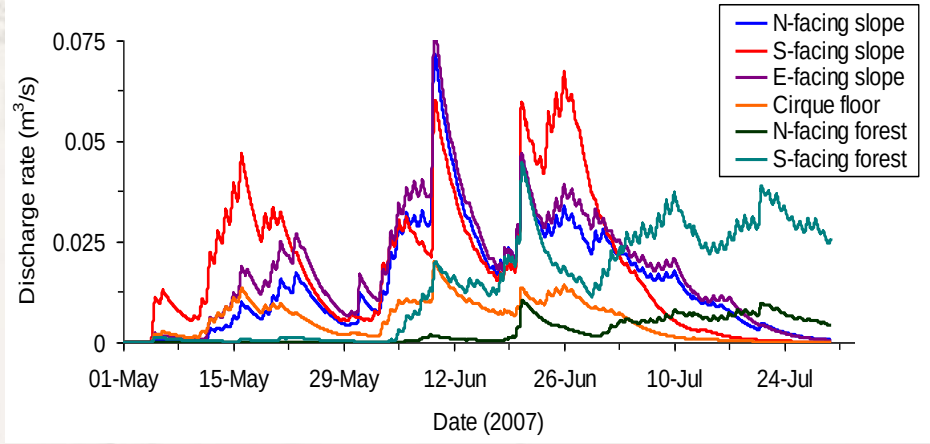
Total Discharge





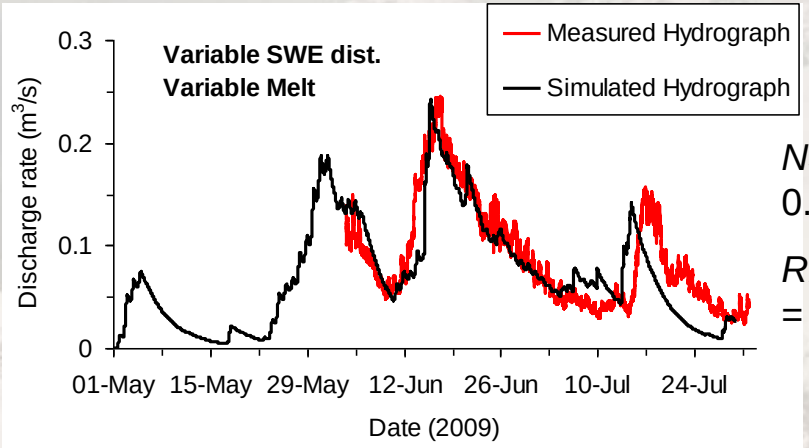
Component Hydrographs





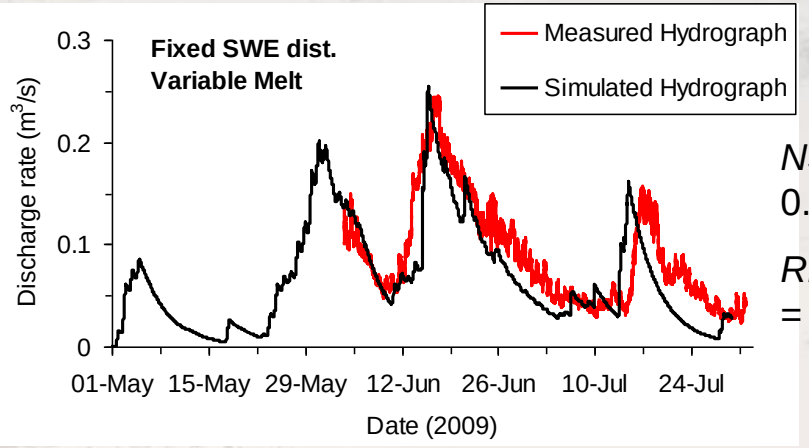
Hydrograph Sensitivity Analysis

- Various simulation approaches were used to examine influence on the basin hydrograph



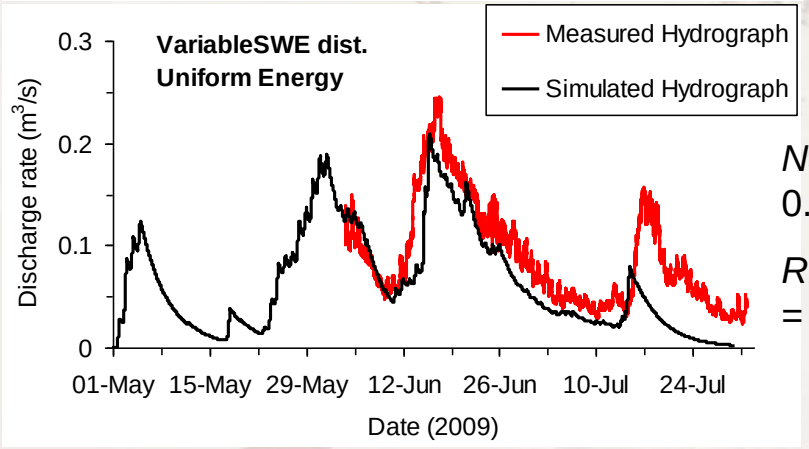
NS = 0.62

RMSE = 0.03



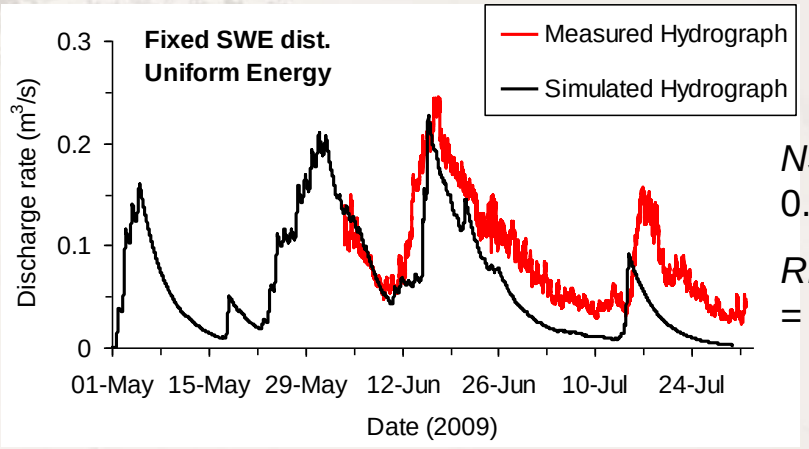
NS = 0.53

RMSE = 0.03



NS = 0.39

RMSE = 0.04

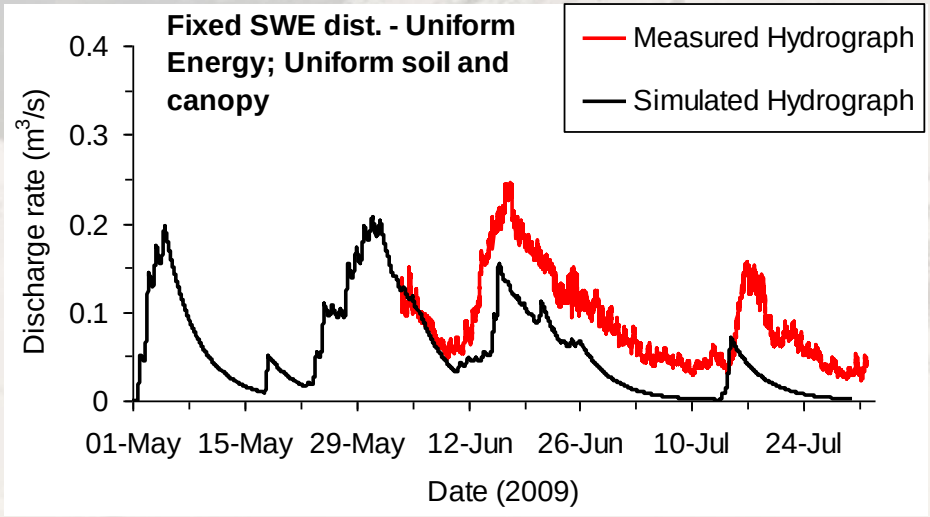


NS = 0.23

RMSE = 0.04

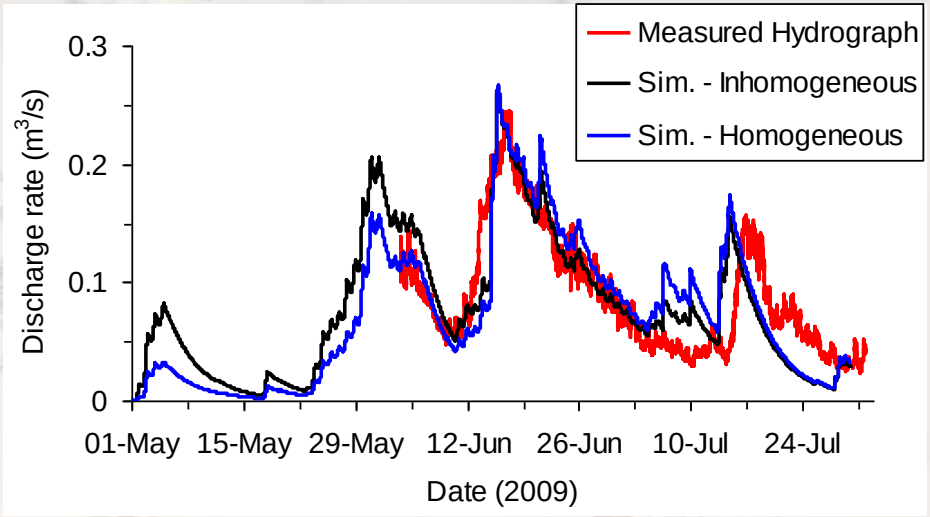
Hydrograph Sensitivity Analysis

- Other approaches were used to examine effects of forest canopy and soil depth, and inhomogeneous melt



NS = -0.28

RMSE = 0.06



Homogeneous

NS = 0.47

RMSE = 0.04

Inhomogeneous

NS = 0.62

RMSE = 0.03

Key Conclusions, Significance

- Novel framework that allows for physical, yet spatially simple snowmelt and SCD simulation
  - Incorporation of sub-grid distributions of internal energy for melt computation
- Application of the framework, together with a hydrological model showed the influence of the spatial variability of both SWE and snowmelt energy on areal SCD and snowmelt runoff in an alpine environment

Key Conclusions, Significance

- Important to take inhomogeneous melt into account for areal SCD simulations
  - Implications for remote sensing, climate models and modelling applications using depletion curves
- Effects are not as important for snowmelt runoff and hydrograph simulation, as other processes tend to overwhelm the response
  - Still important to account for spatial variability of snowmelt energy on the slope, and land cover scale

Thank You

- NSERC
- CFCAS
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