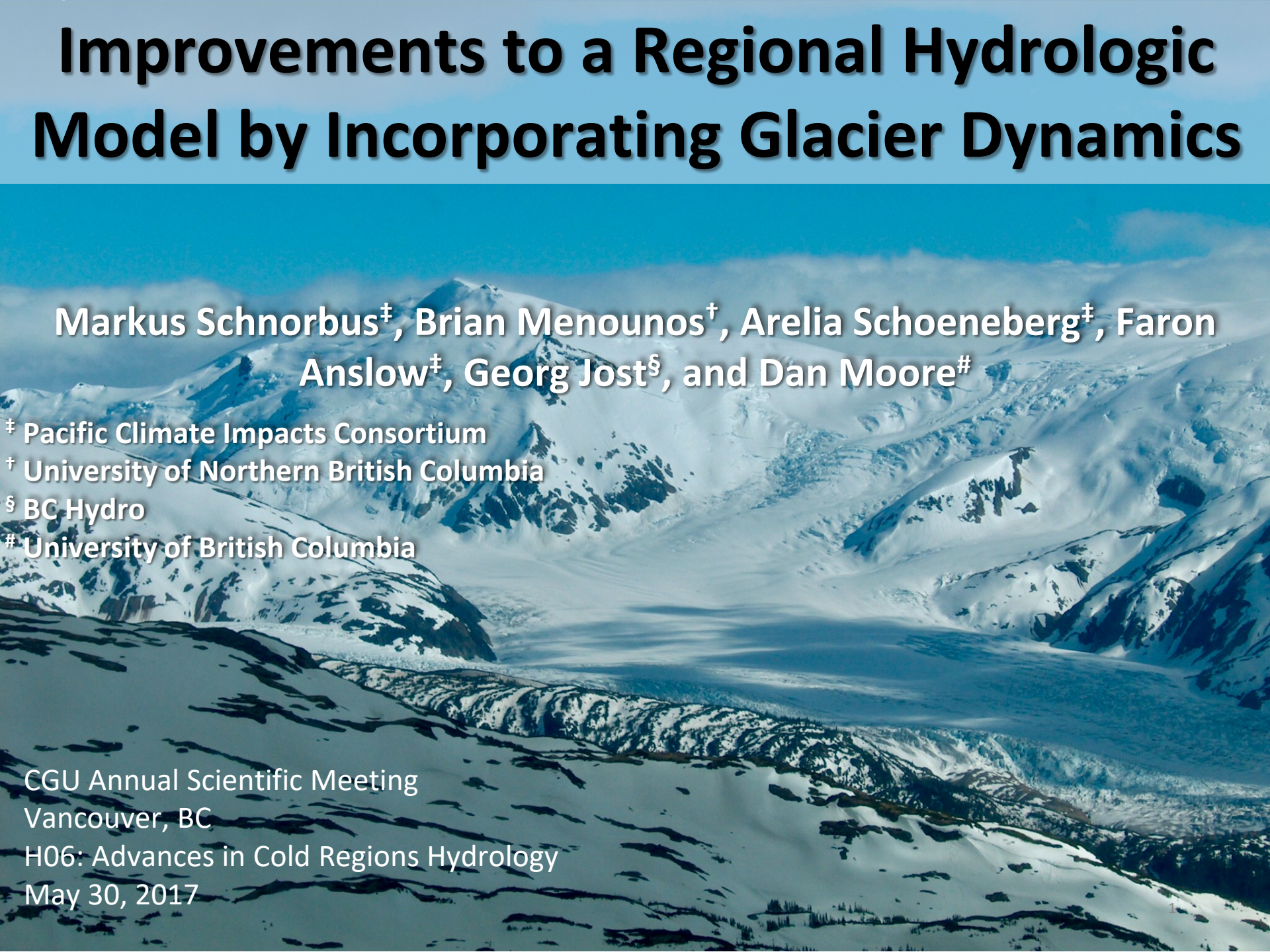
Improvements to a Regional Hydrologic Model by Incorporating Glacier Dynamics



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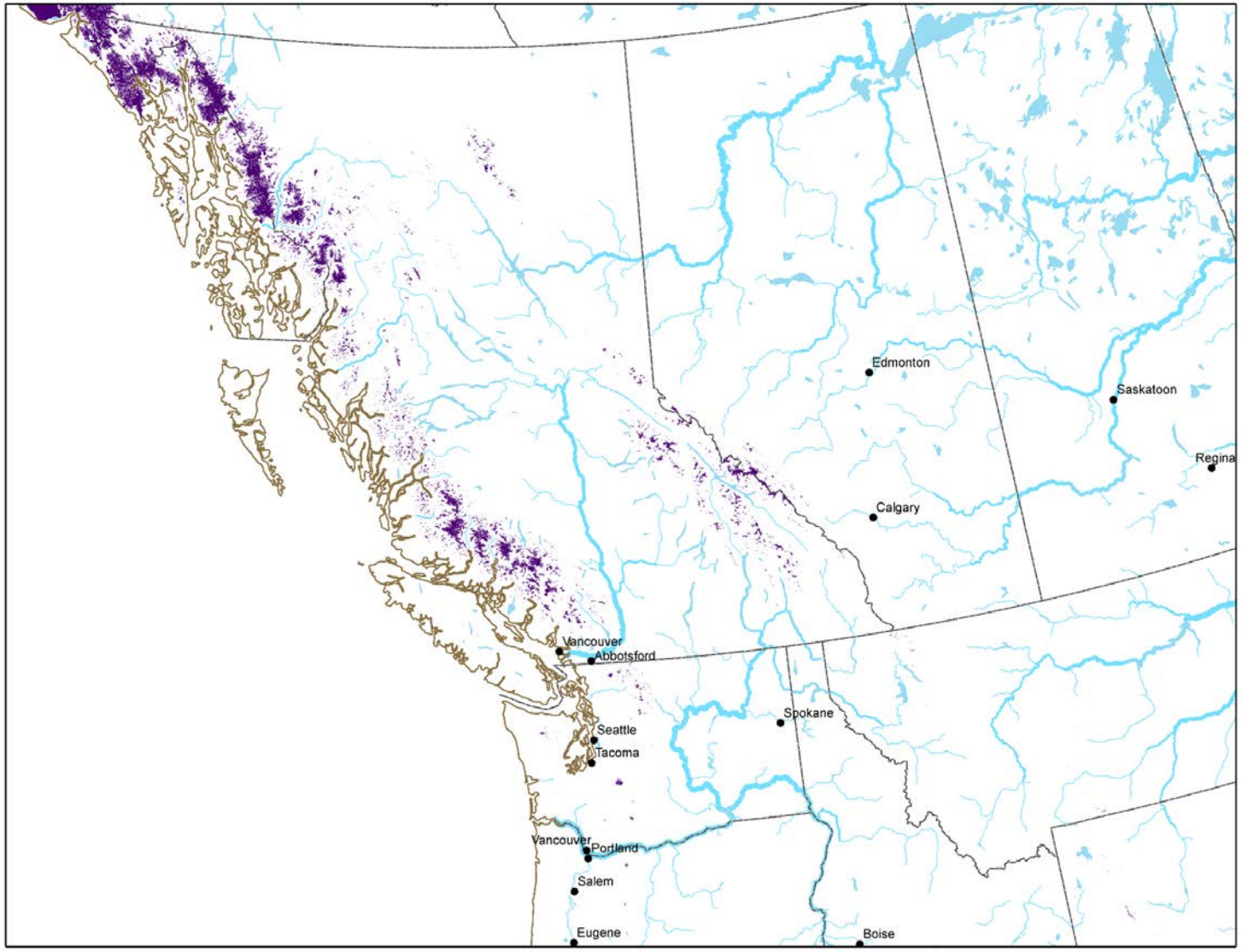
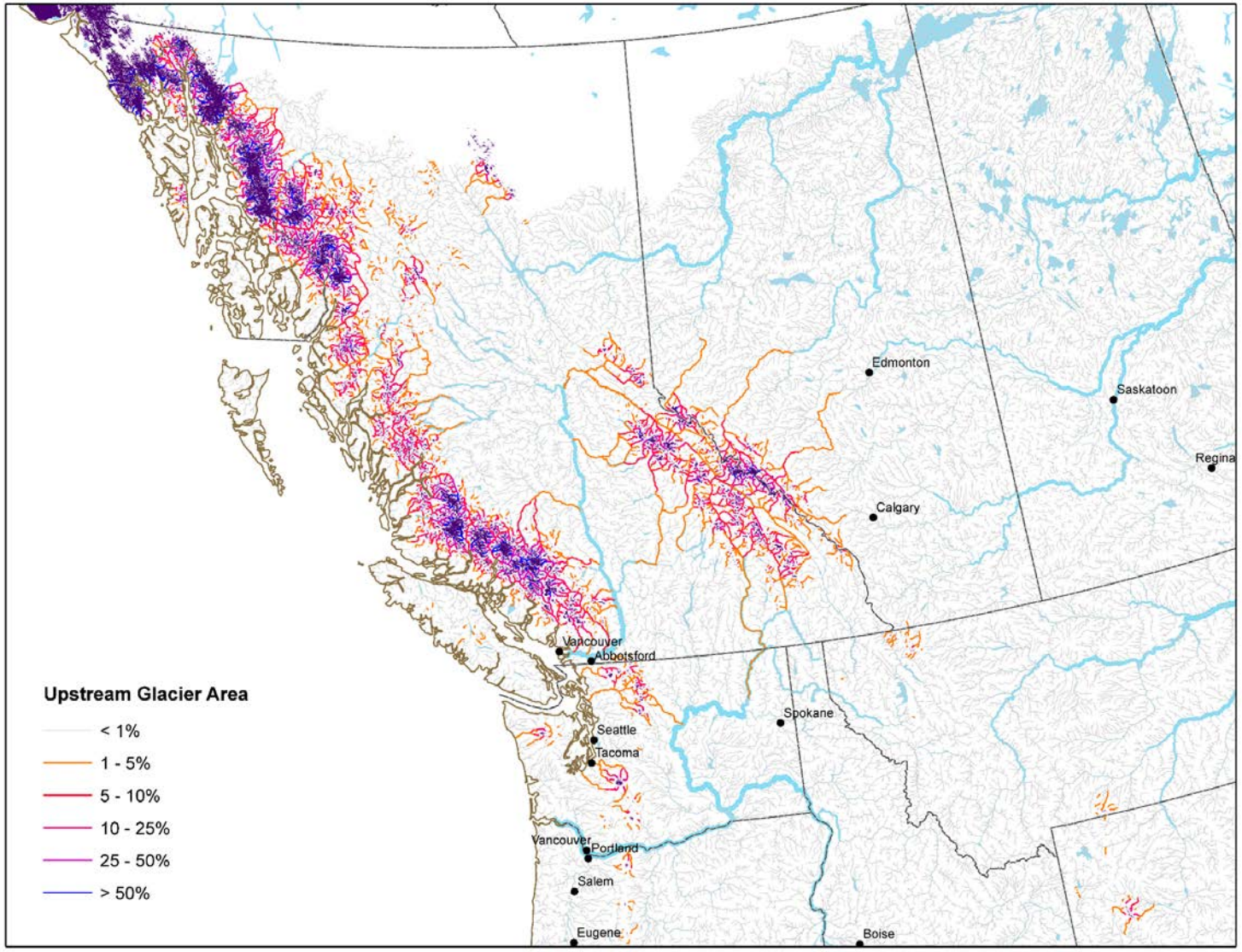
CGU Annual Scientific Meeting
Vancouver, BC
H06: Advances in Cold Regions Hydrology
May 30, 2017

Western North America Glaciers



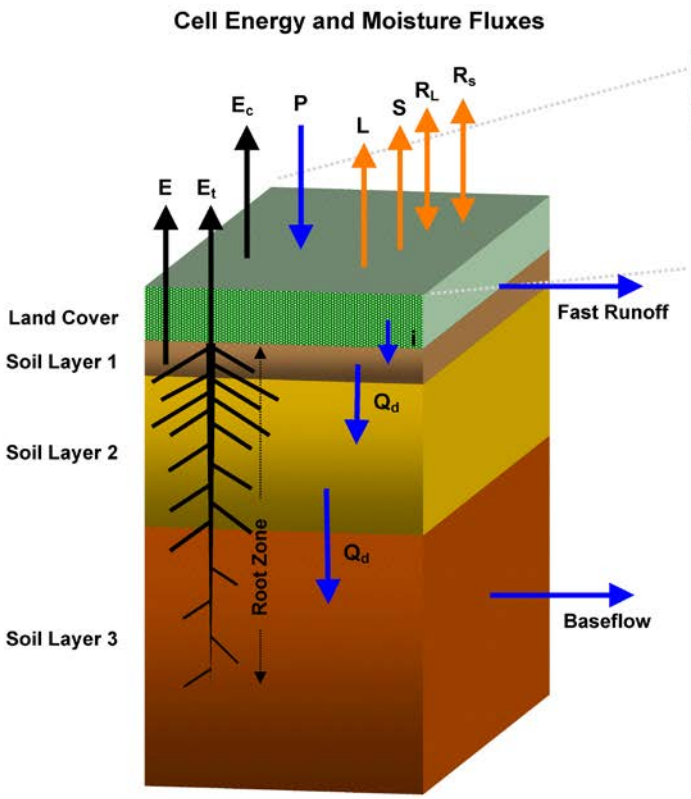
Western North America Glaciers

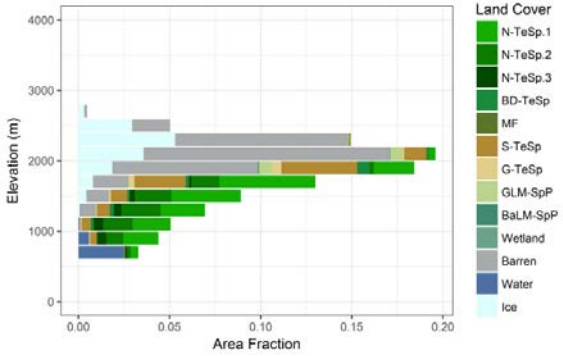
Downstream Influence – August Streamflow



Hydrology Model

Variable Infiltration Capacity (VIC) Model





Symbol Key:

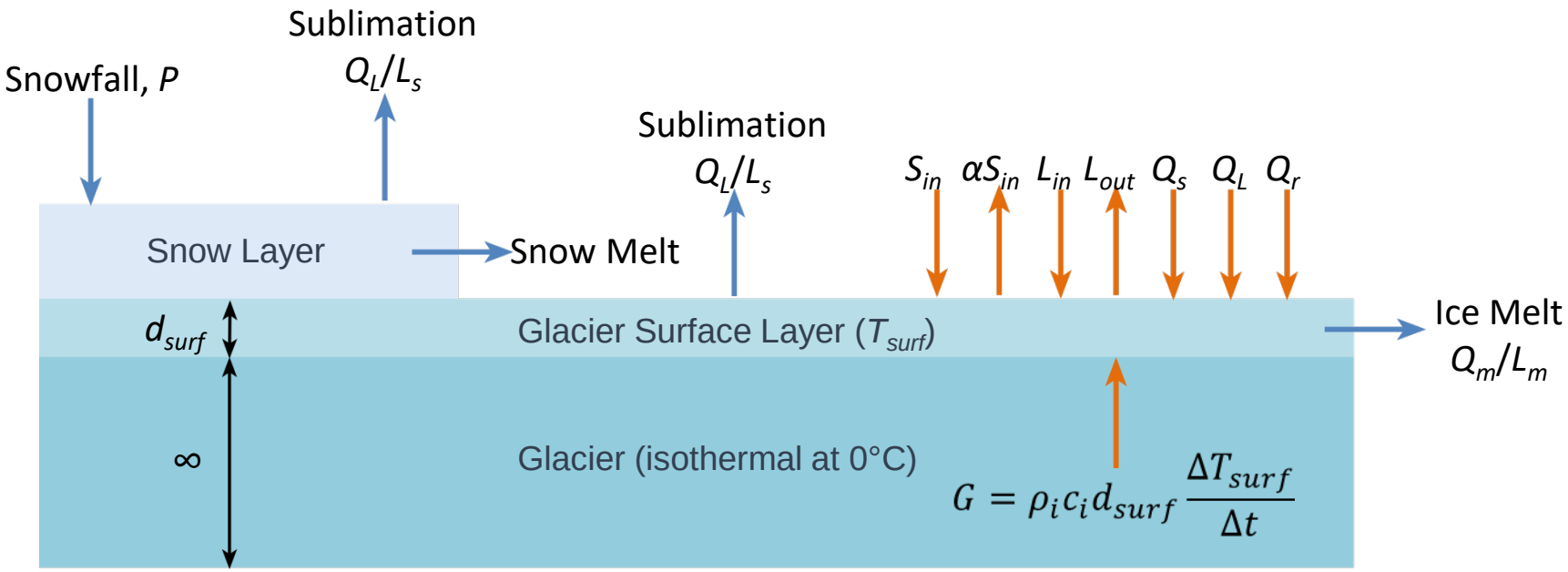
P – Precipitation
E – Evaporation
E_t – Transpiration
E_C – Evaporation from canopy storage
R_S – Shortwave (solar) radiation
R_L – Longwave radiation
S – Sensible heat
L – Latent heat
I – Infiltration
Q_d – Vertical drainage (percolation)

- Spatially distributed hydrologic model
- Model resolves water and energy balance at a daily or sub-daily time step for each grid cell
- Accounts explicitly for topography, soil and vegetation
- Energy-balance snow model
- Applied at a resolution of 1/16-degree (~5-6 km)
- Coupled to a routing a model to simulate streamflow

Liang et al. (1994, 1996)

VIC-GL Upgrades

Mass Balance Modelling



Predominantly based on model of *Klok and Oerlemans* (2002):

$$F = S_{in}(1-\alpha) + L_{in} + L_{out} + Q_s + Q_L + Q_r = Q_m + G$$

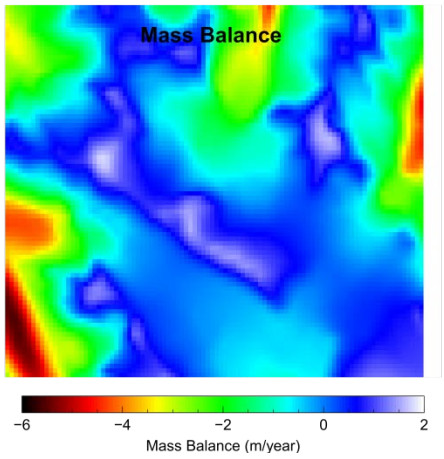
where:

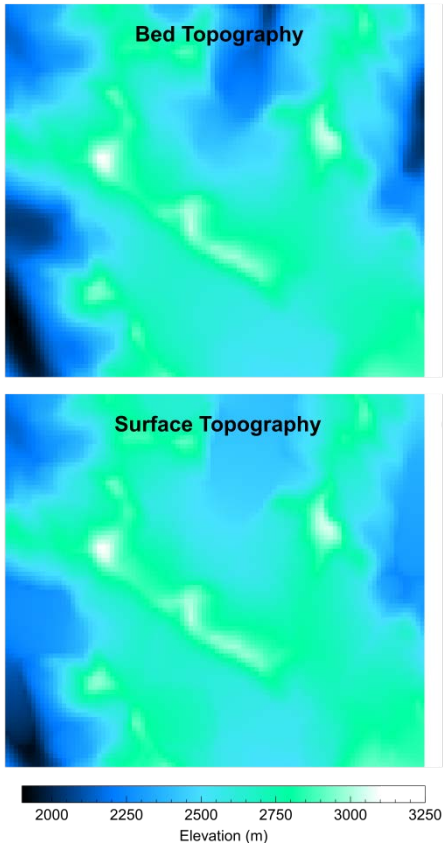
S_{in} = incoming solar radiation
L_{in} = incoming longwave radiation
L_{out} = outgoing longwave radiation
Q_s = sensible heat
Q_L = latent heat
Q_r = heat advected from rainfall
Q_m = energy for ice melt
G = glacier heat flux
L_s = latent heat of sublimation
L_m = latent heat of melt
d_{surf} = thickness of glacier surface layer
T_{surf} = glacier surface temperature
p_i = density of ice
c_i = heat capacity of ice
α = glacier albedo

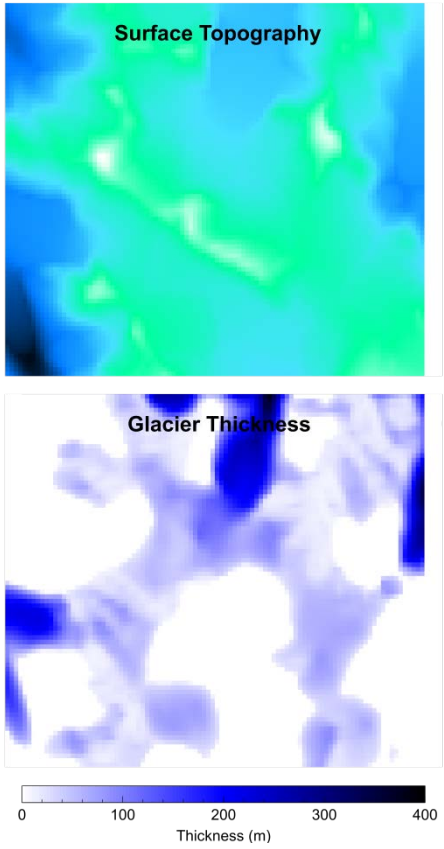
VIC-GL Upgrades

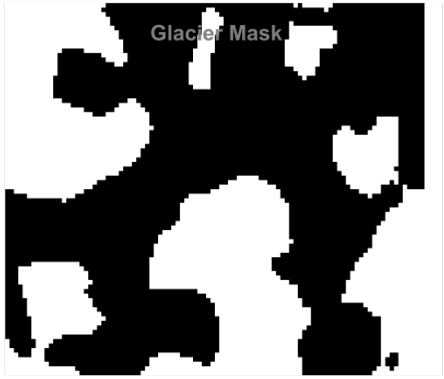
Dynamics Modelling - Regional Glaciation Model

- Simulates the physics of ice flow using a numerical ice dynamics model based on a three-dimensional representation of glacier geometry
- Shallow-ice approximation and isothermal ice
- Forced by an annual mass balance rate (updated annually), where $\Delta t = 0.1$ years





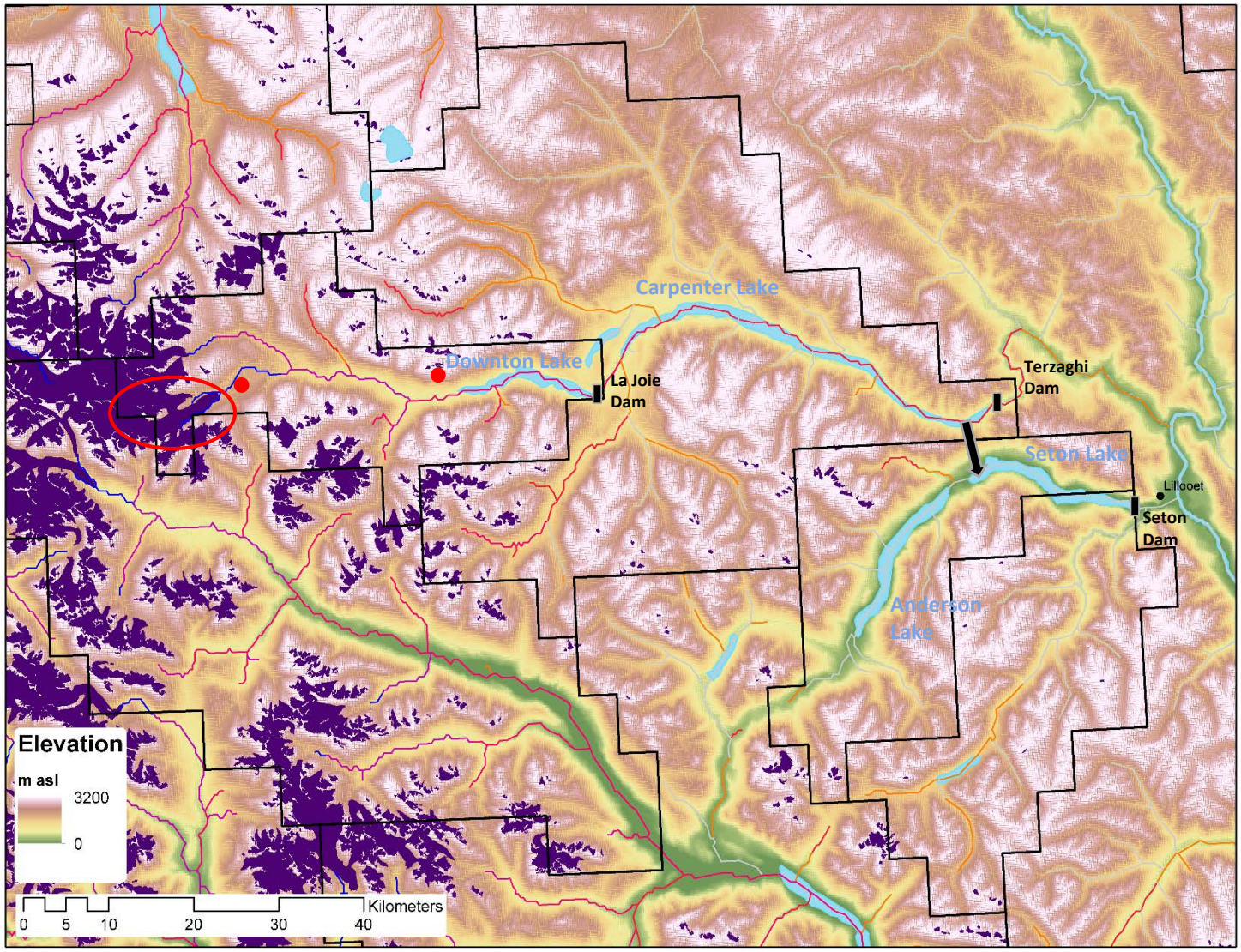




Jarosch et al. (2013); *Clark et al*. (2015)

Study Area

Bridge River above La Joie Dam



Model Calibration and Verification

Data Details

Data Type	Data Source	Calibration	Verification
Naturalized Inflow	BC Hydro	1991 - 2000	1961 - 1990
Snow Cover§	MODIS/Terra	2000 – 2005	
Evapotranspiration‡	LandFlux-EVAL	1991 – 2000	
Mass Balance – geodetic†	UNBC	1985 – 1999	
Mass Balance – glaciological	UNBC/UBC		1977 – 1985
Snow Water Equivalent+	BC Ministry of Environment		1995 – 2005
Glacier Area#	UNBC		1985, 2000, 2005

§ Hall, D. K. and G. A. Riggs, 2015: *MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG, Version 6,* Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: http://dx.doi.org/10.5067/MODIS/MOD10CM.006.

‡ Mueller, B. et al., 2013: Benchmark products for land evapotranspiration: LandFlux-EVAL multi-dataset synthesis, *Hydrol. Earth Syst. Sci.*, 17, 3707-3720, doi:10.5194/hess-17-3707-2013

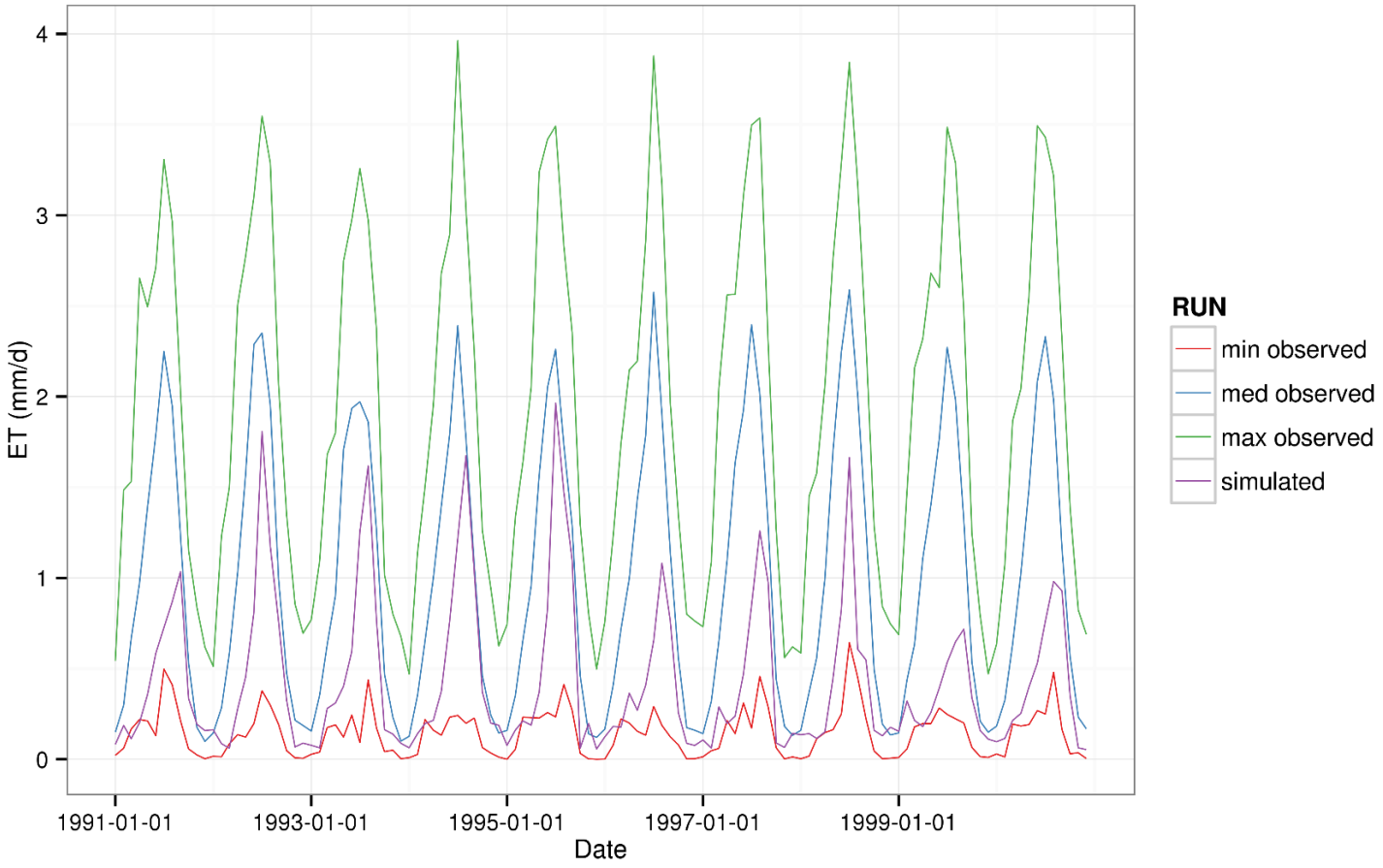
† Schiefer, E., B. Menounos, and R. Wheate, 2007: Recent volume loss of British Columbian glaciers, Canada. *Geophys. Res. Lett.*, 34, L16503, doi:10.1029/2007GL030780.

+ BC River Forecast Centre; http://bcrfc.env.gov.bc.ca/data/survey/

Bolch, T., B. Menounos, and R. Wheate, 2010: Landsat-based inventory of glaciers in western Canada, 1985–2005. *Remote Sensing of Environment*, 114, 127–137, doi:10.1016/j.rse.2009.08.015.

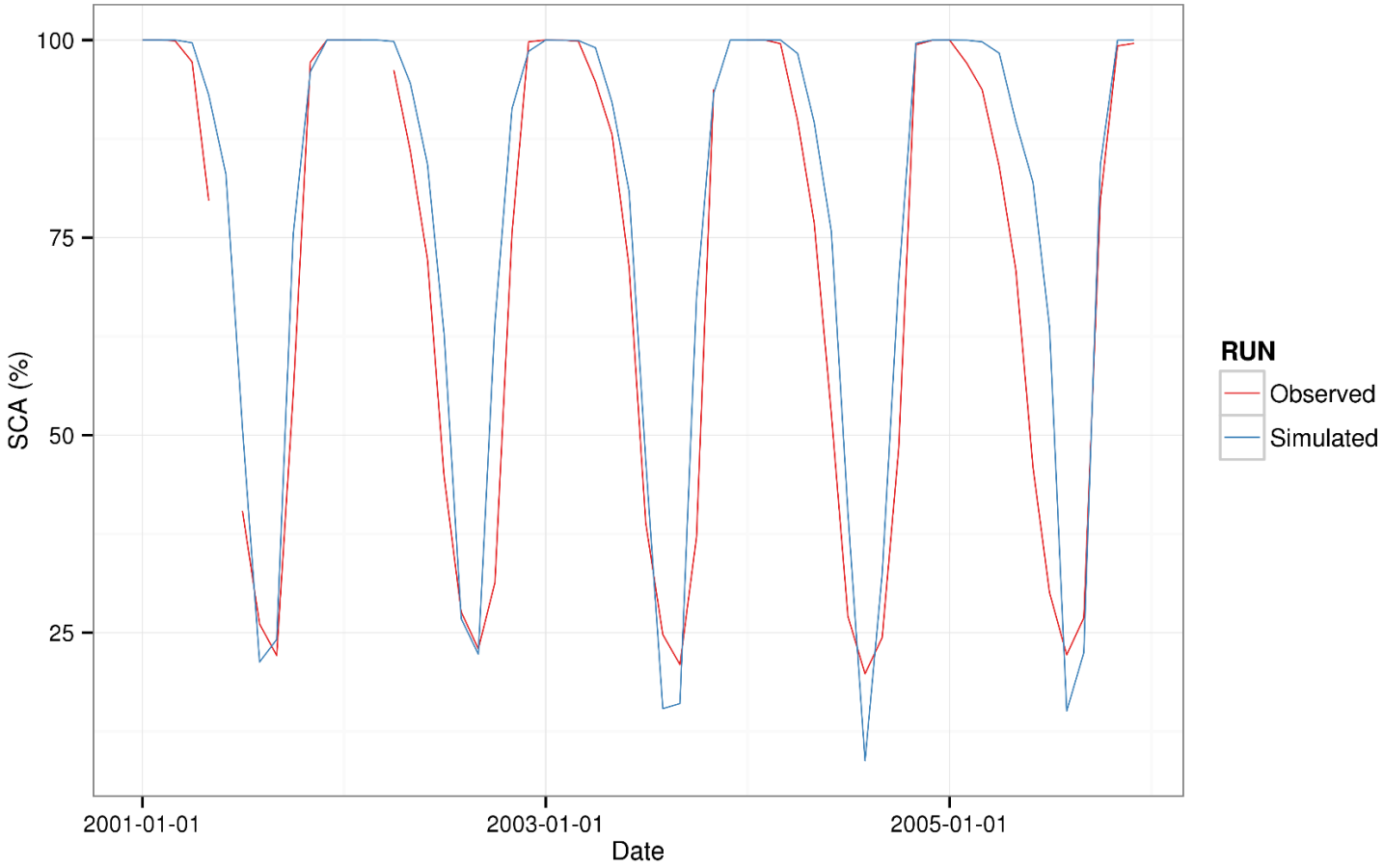
Model Performance

Evapotranspiration



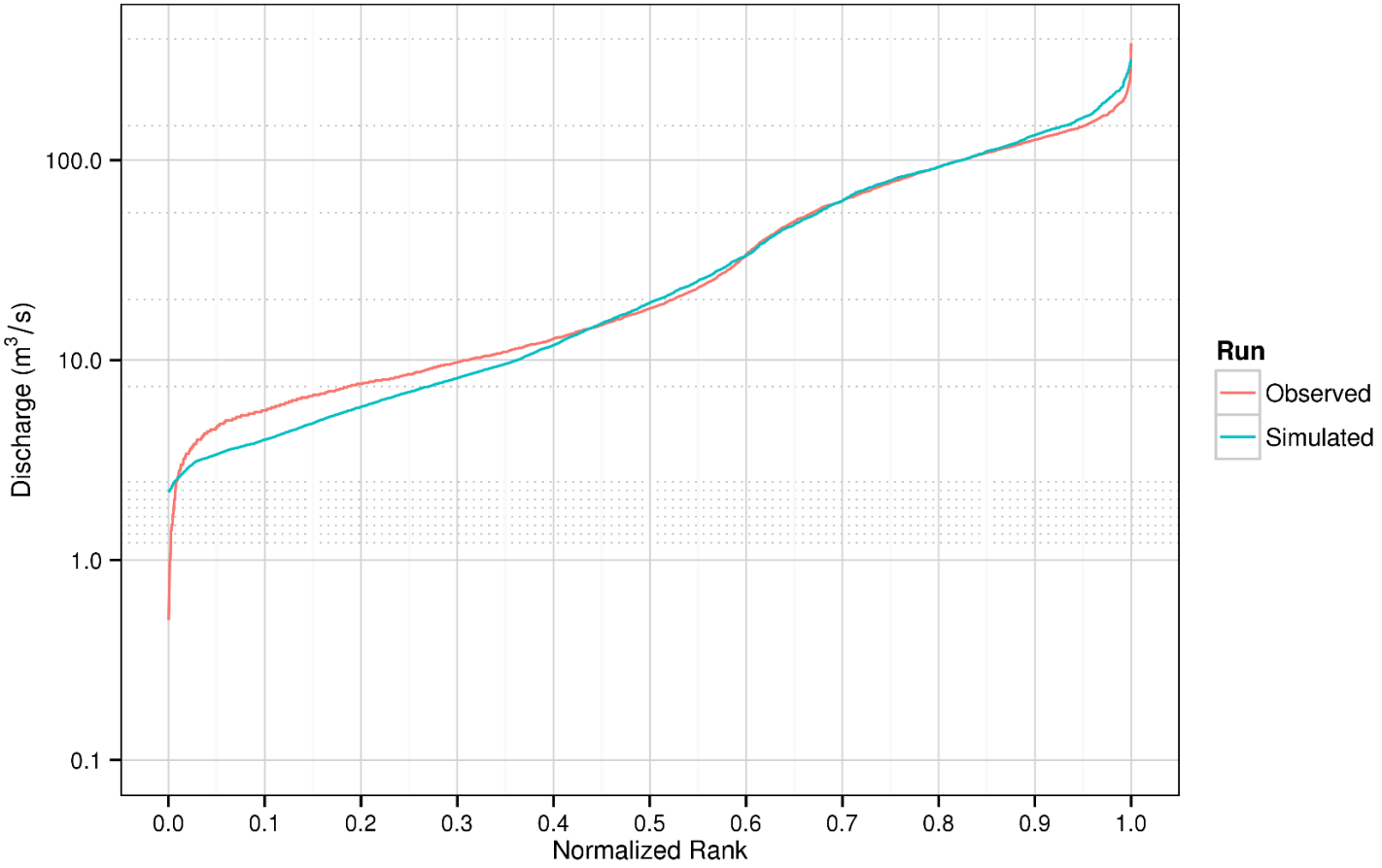
Model Performance

Snow Cover Area



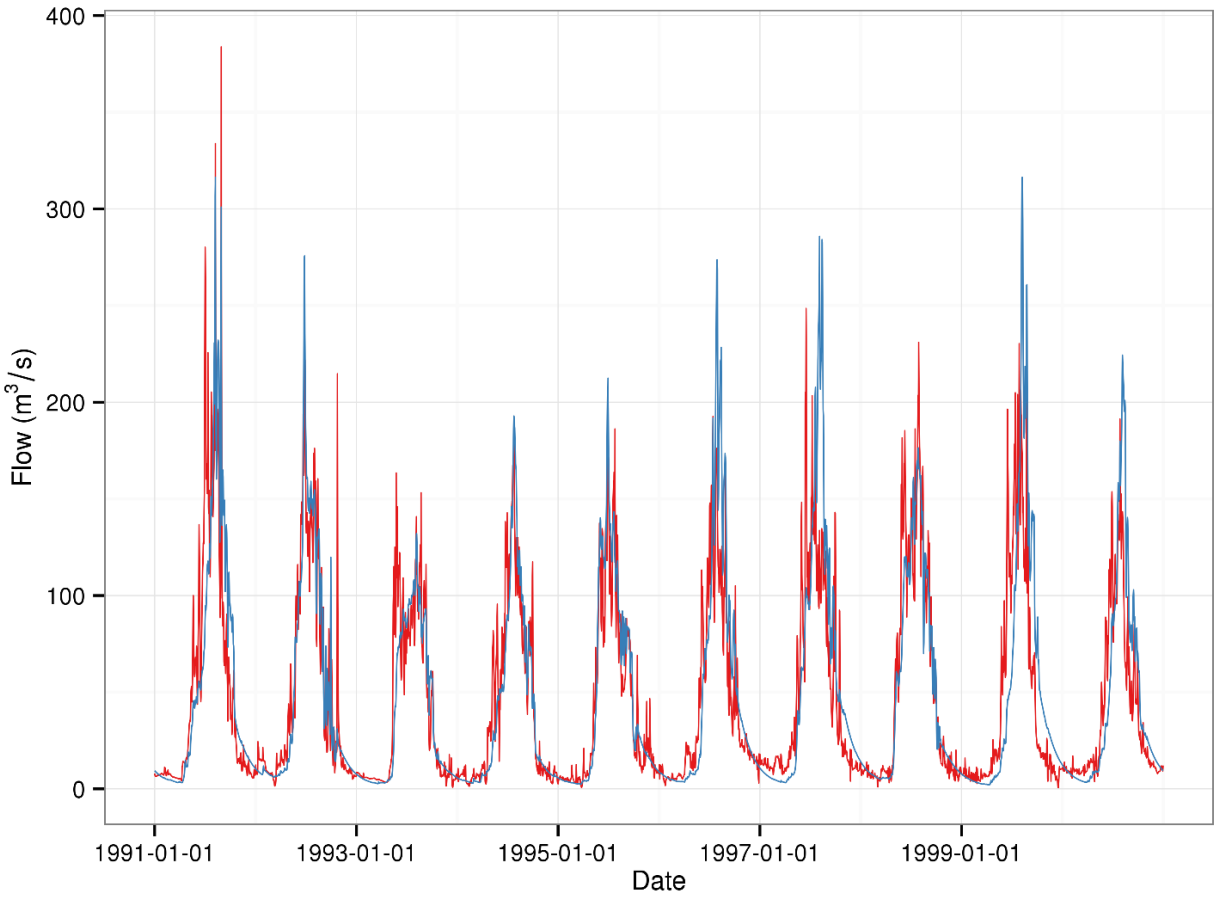
Model Performance

Discharge – Flow Duration



Model Performance

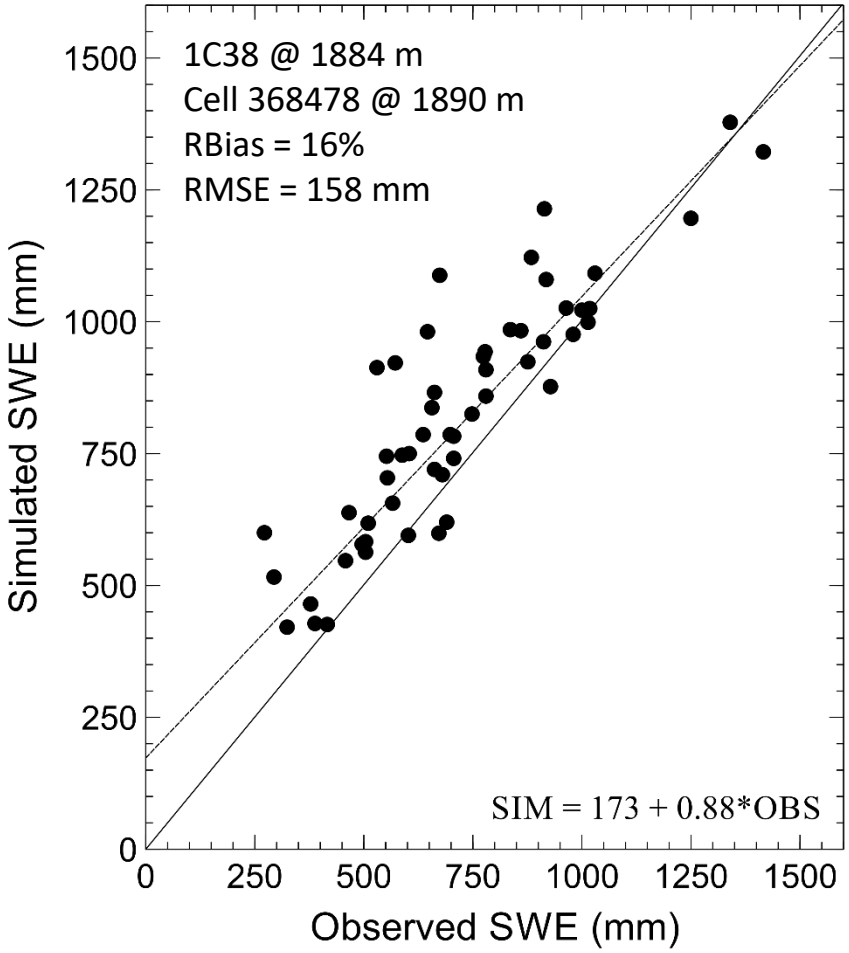
Discharge - Hydrograph

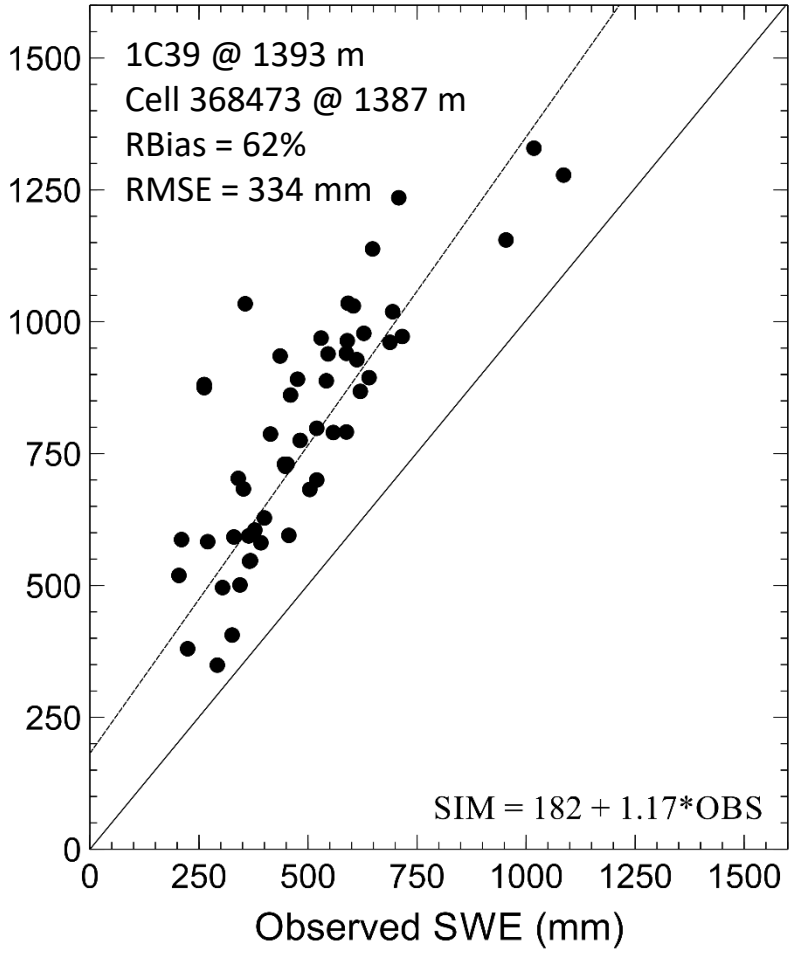


RBias = 0.04
R^2 = 0.75
NSE = 0.69
LNSE = 0.78
KGE = 0.82

Model Verification

Snow Water Equivalent – Manual Snow Surveys

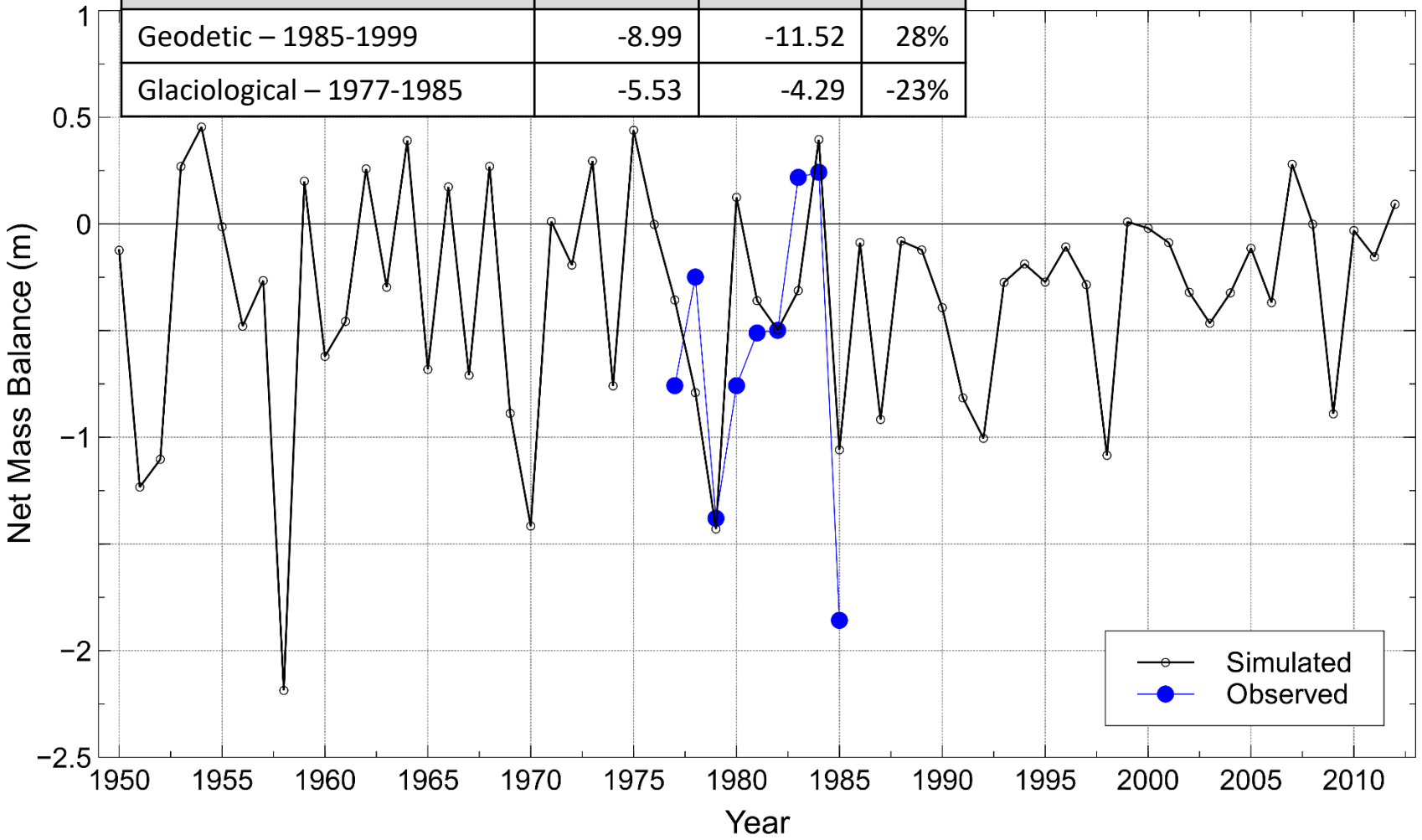




Model Verification

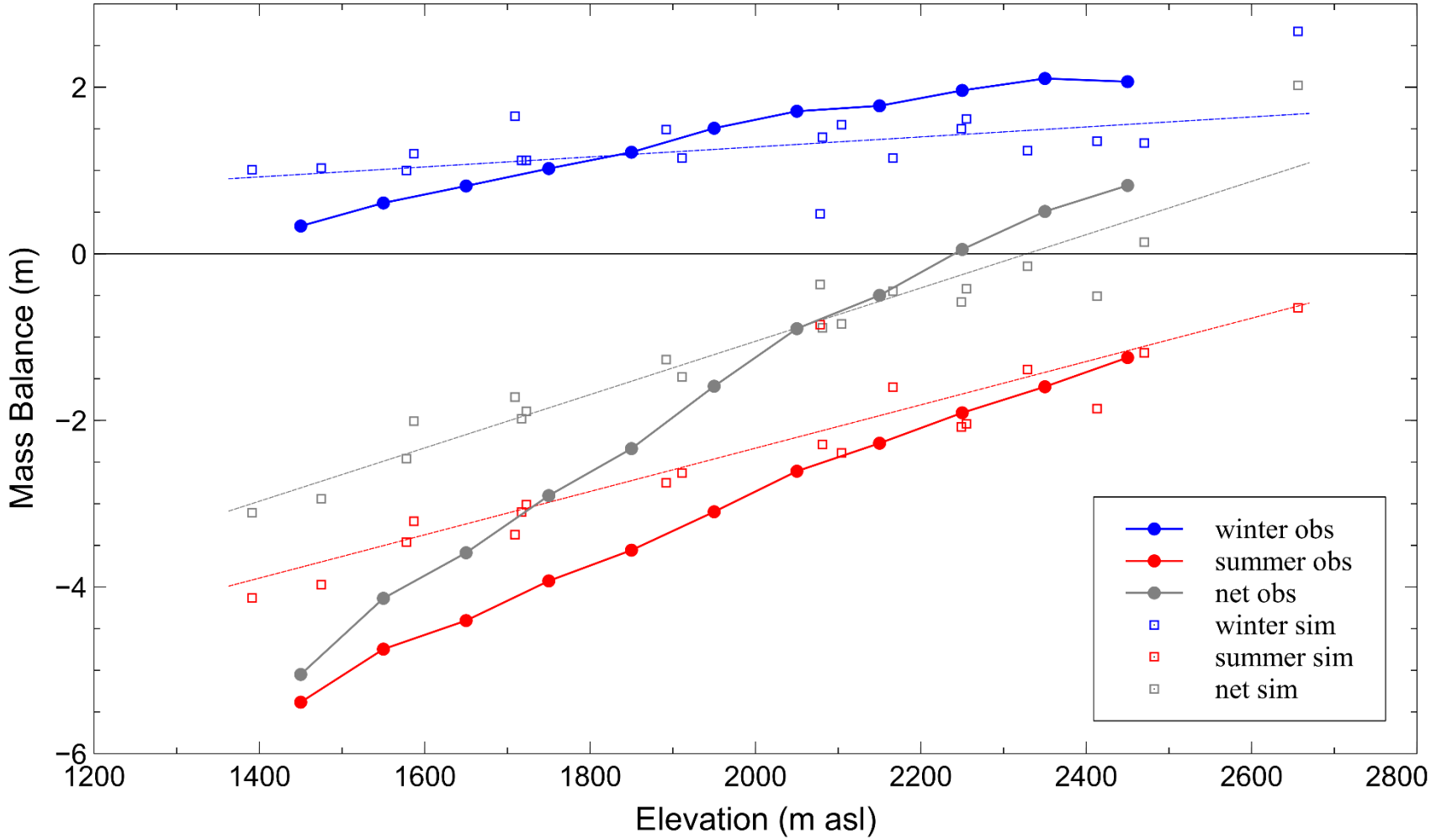
Annual Surface Mass Balance – Bridge Glacier

Statistic	Observed	Simulated	Error
Geodetic – 1985-1999	-8.99	-11.52	28%
Glaciological – 1977-1985	-5.53	-4.29	-23%



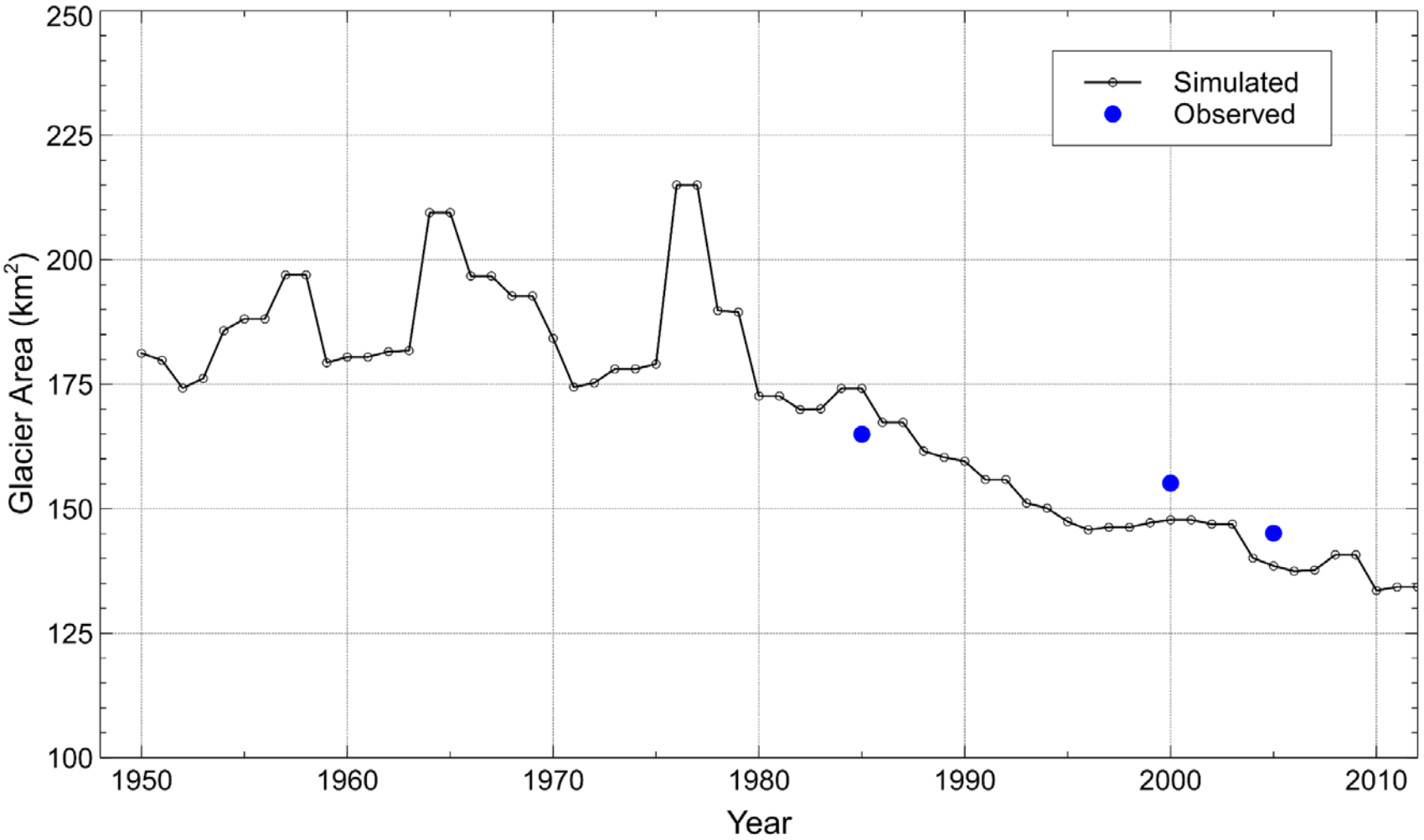
Model Verification

Surface Mass Balance Gradient – Bridge Glacier, 1977-1985



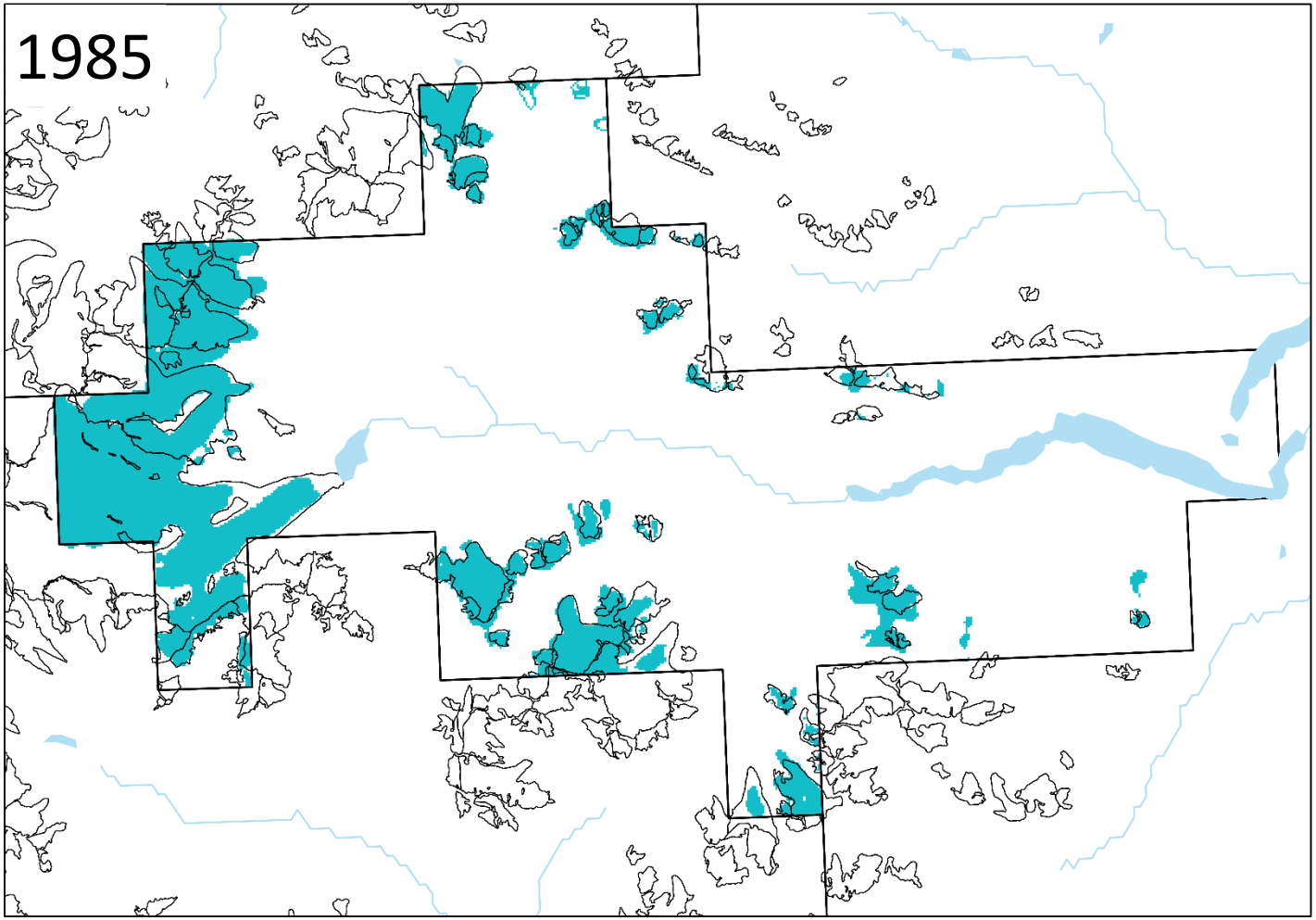
Model Verification

Basin-wide Glacier Area Change



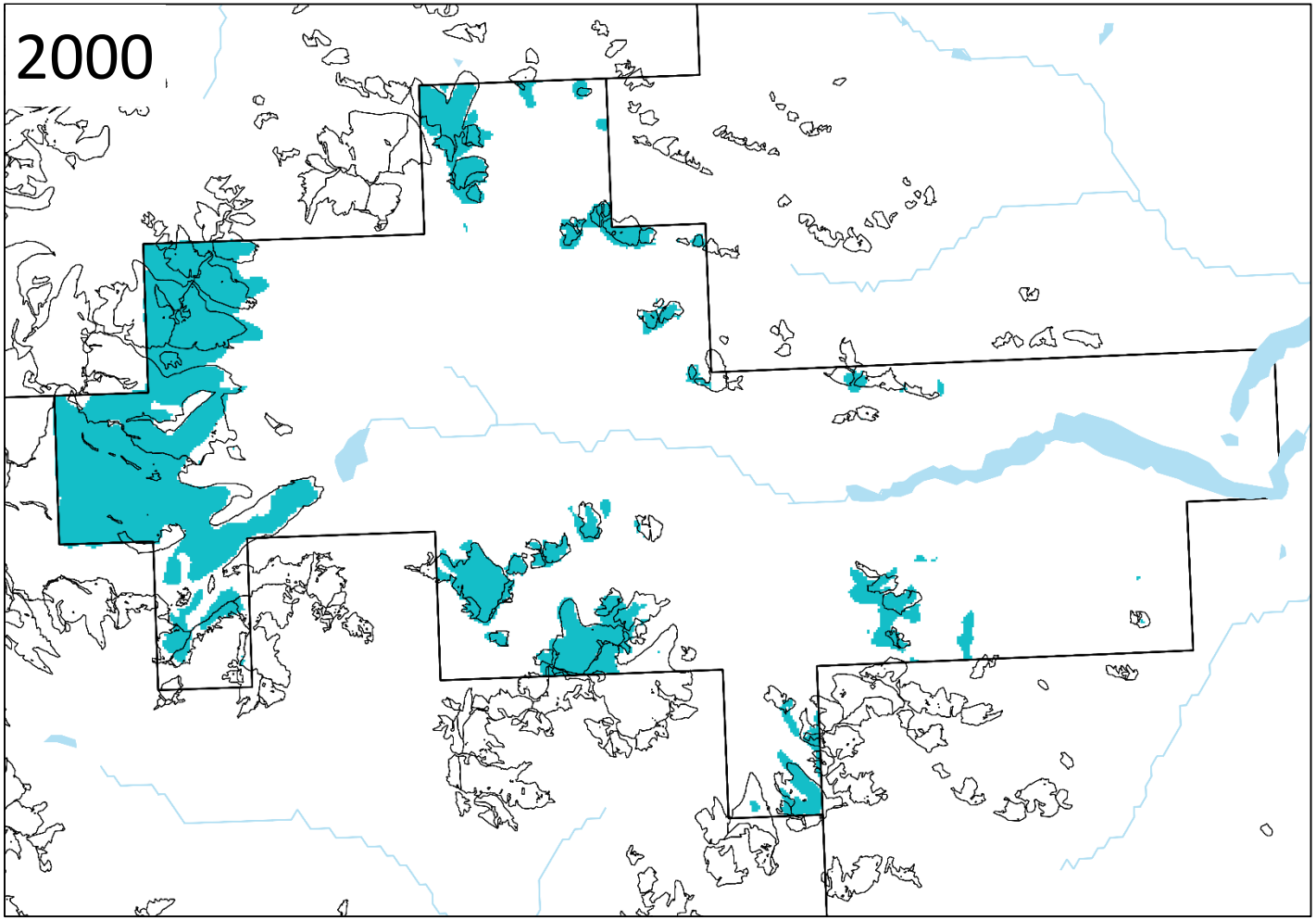
Model Verification

Glacier Mask



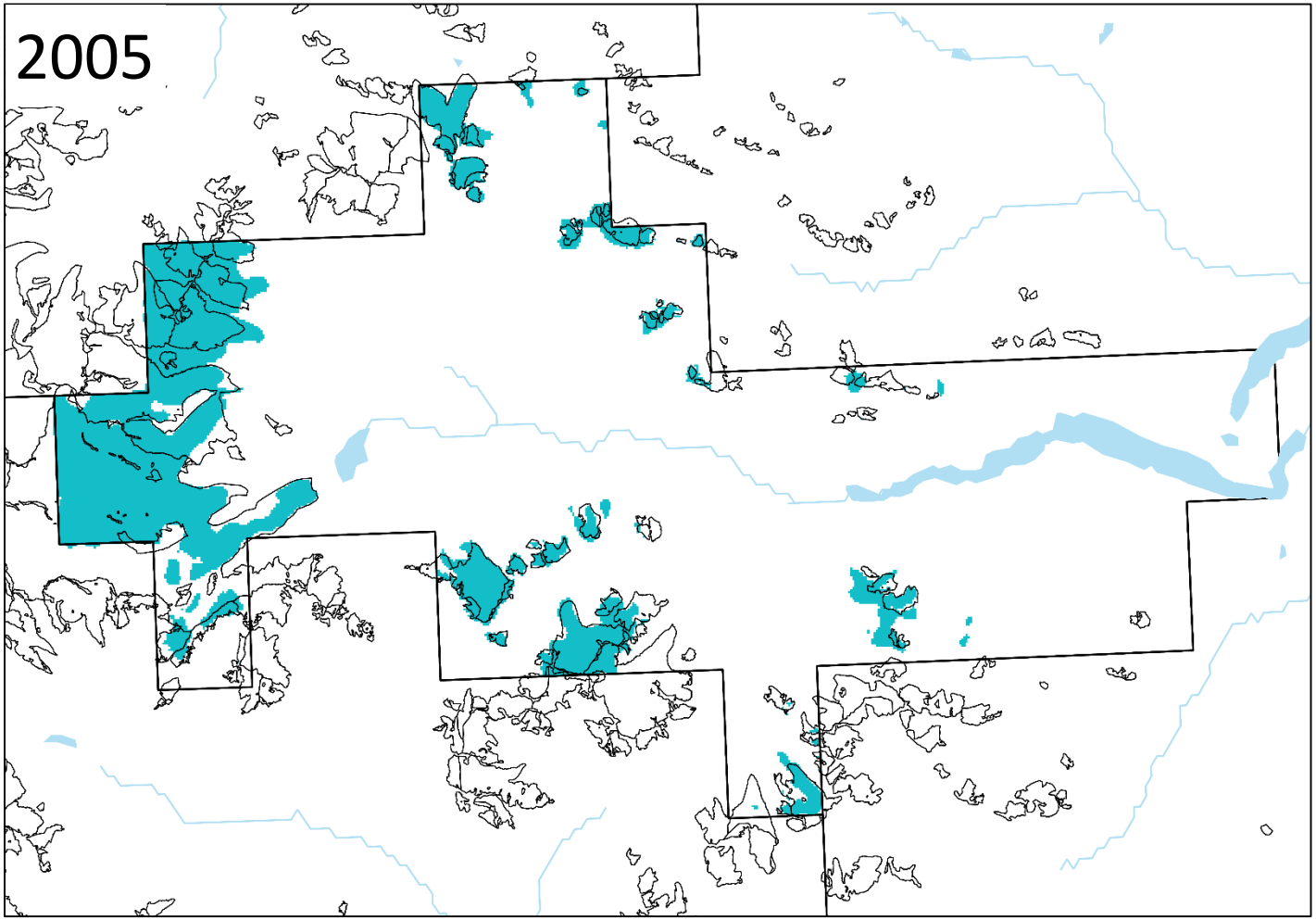
Model Verification

Glacier Mask



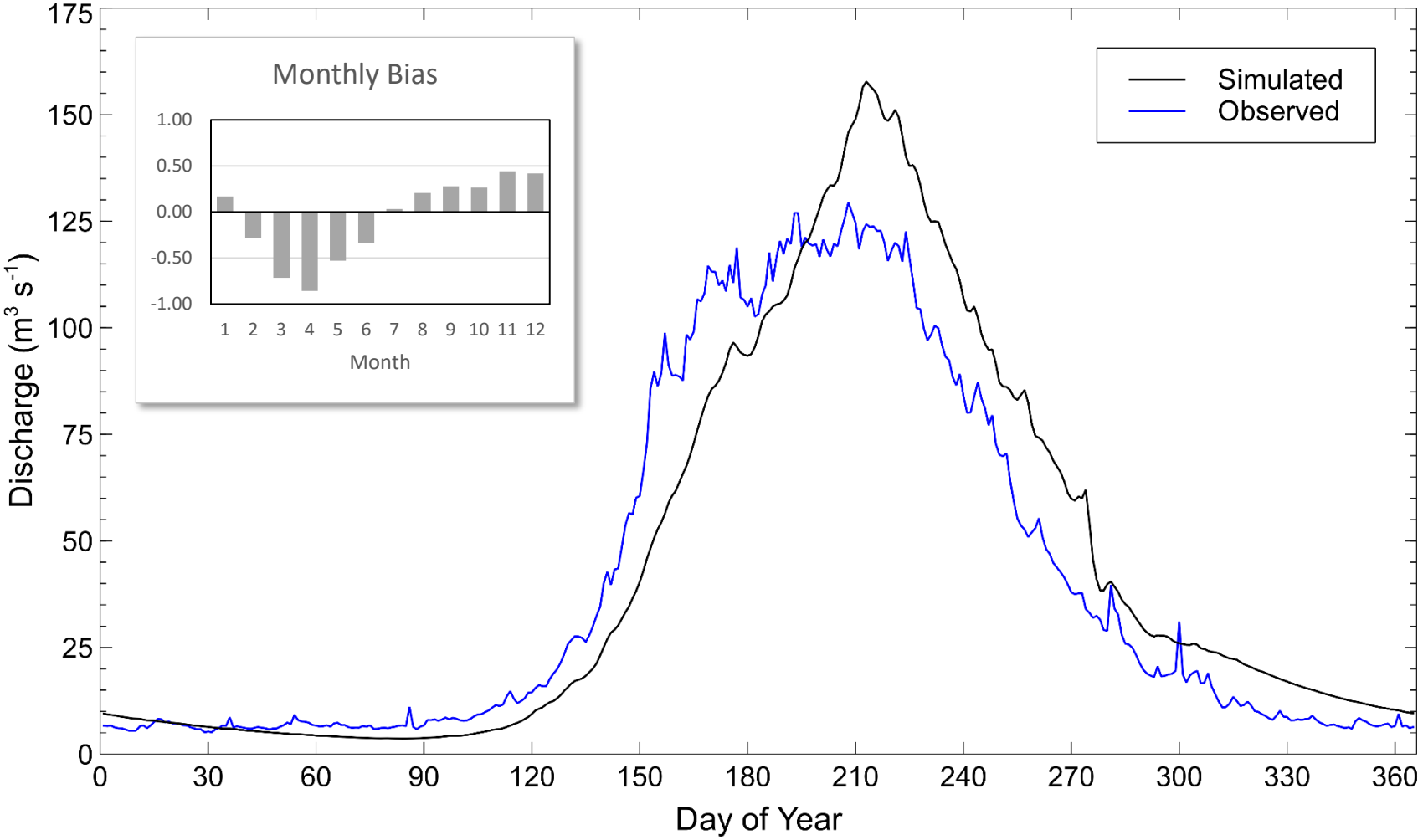
Model Verification

Glacier Mask



Verification - Discharge

Daily Average Discharge, 1961 - 1990



Next Steps

Examiniation of the Pareto set indicates a clear trade-off with respect to parameter selection: Discharge ↔ Mass Balance

- Account for additional sources of sub-grid variability on mass balance:
  - Slope, aspect, shading and reflection effects on net radiation
  - Mechanical redistribution of snow (wind and gravity)
  - Account for glacier boundary layer processes (katabatic forcing)
- Calibrate explicitly to gradient data (where available, e.g. higher resolution SCA)
- Explicit calibration of glacier outflow parameters (storage-discharge relationship)
- More careful consideration of modelling domain when simulating dynamics

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Power smart

University of Victoria

PACIFIC CLIMATE IMPACTS CONSORTIUM