Reconstruction of Glacier Mass Balance with Surface Energy Balance Modeling across Southwestern Canada

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THE UNIVERSITY OF BRITISH COLUMBIA

Photo: Kaskawulsh Glacier (Draeger)

Overview

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Photo: Kaskawulsh Glacier (Saibene)

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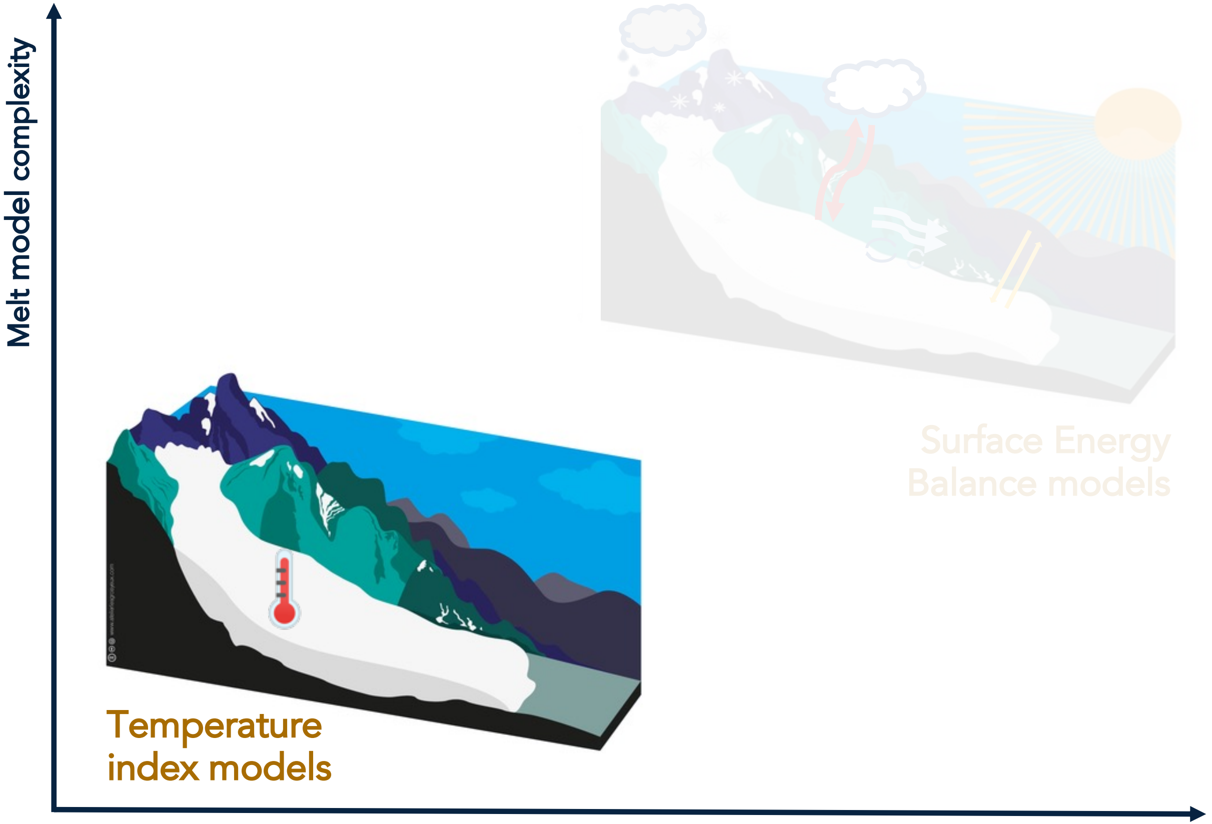
Problem:

Current models are (semi-) empirical with poorly constrained parameters



Melt model

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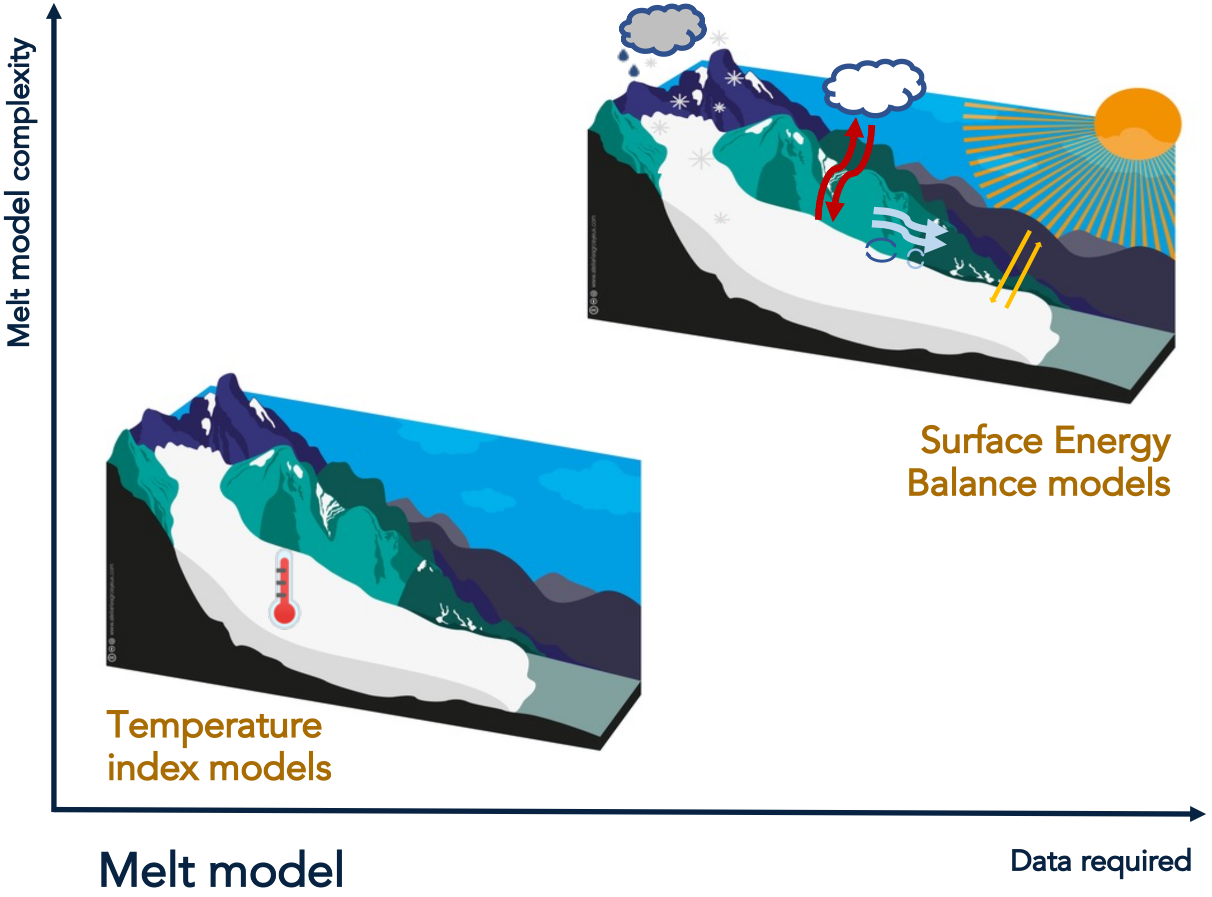
Problem:

Current models are (semi-) empirical with poorly constrained parameters

Project goal:

Incorporate a Surface Energy Balance model and a model for ice dynamics into an existing glacier evolution model by Radić et al. (2014)



Glacier Evolution Model

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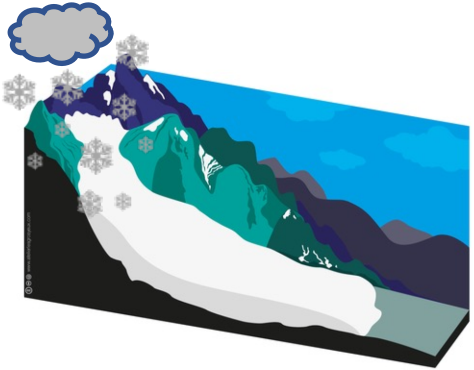

Accumulation

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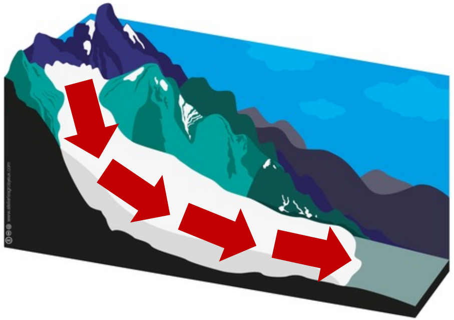
Ablation: Surface Energy Balance Model



Model for ice dynamics

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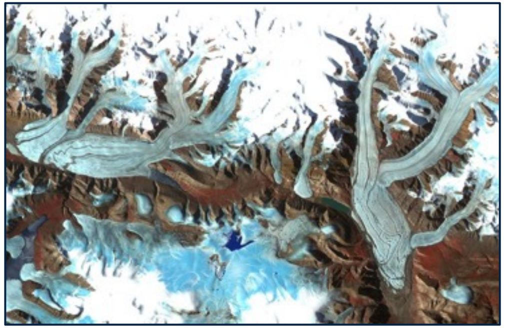

Surface mass balance

Glacier Evolution Model

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Accumulation

Ablation: Surface Energy Balance Model

$$Q_{MELT} = \underbrace{K_{in}(1-\alpha)}_{\text{Shortwave radiation}} + \underbrace{L_{in} - \sigma T_0^4}_{\text{Longwave radiation}} + \underbrace{Q_H}_{\text{Sensible heat}} + \underbrace{Q_L}_{\text{Latent heat}}$$

$Q_H \propto T_z, U$

$Q_L \propto q_z, U$

Glacier Evolution Model

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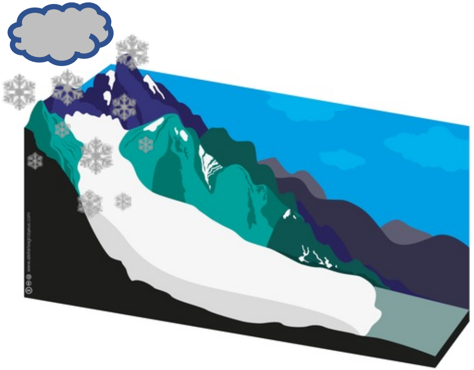

Accumulation

Ablation: Surface Energy Balance Model

Calibration:

Observations: 17 glaciers in the region from the World Glacier Monitoring Service (WGMS)

- Precipitation factor
- Precipitation gradient
- Temperature bias additional to lapse-rate correction
- Albedo factor
- Wind factor

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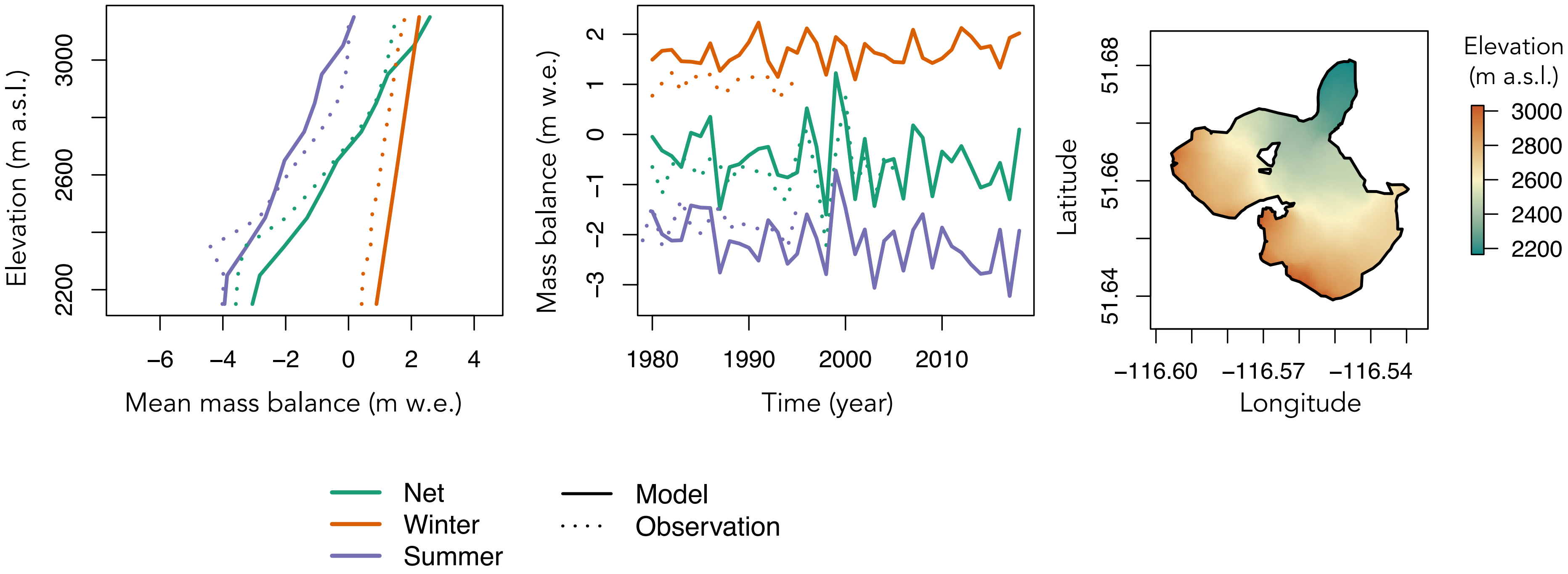
First results for Peyto Glacier



Details

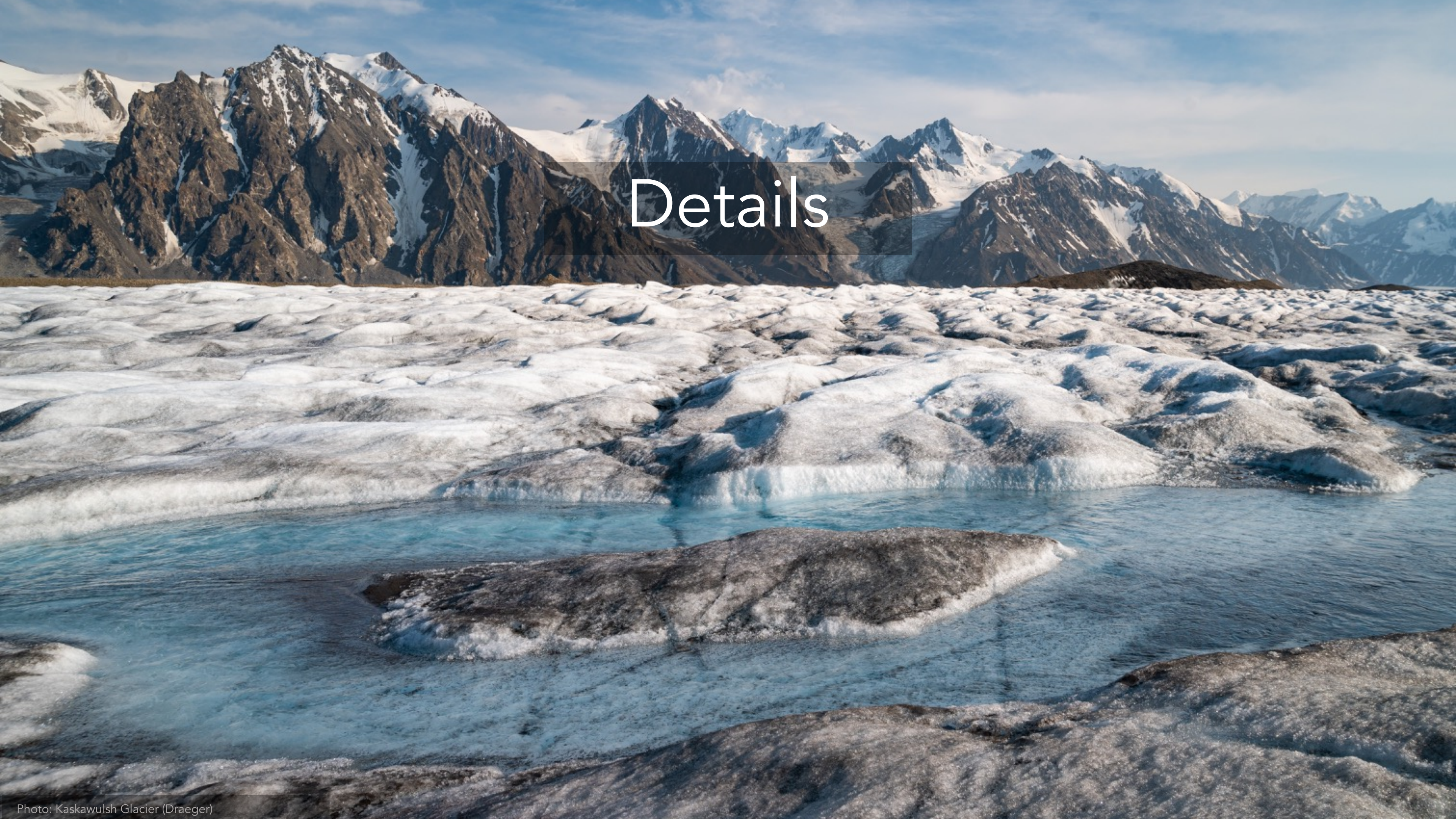


Photo: Kaskawulsh Glacier (Draeger)

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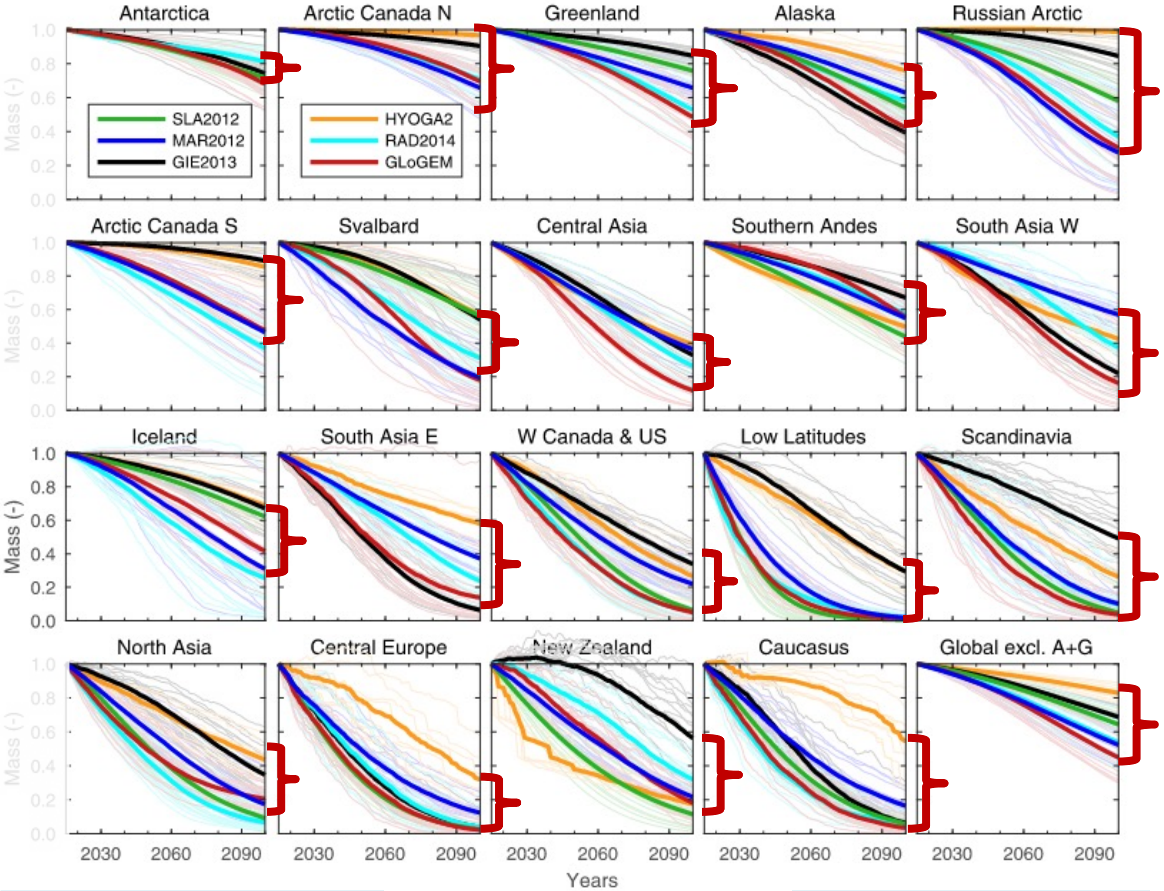
Projected relative glacier mass changes by 2100



Large uncertainties in projections on global and regional scales

Hock et al., 2019

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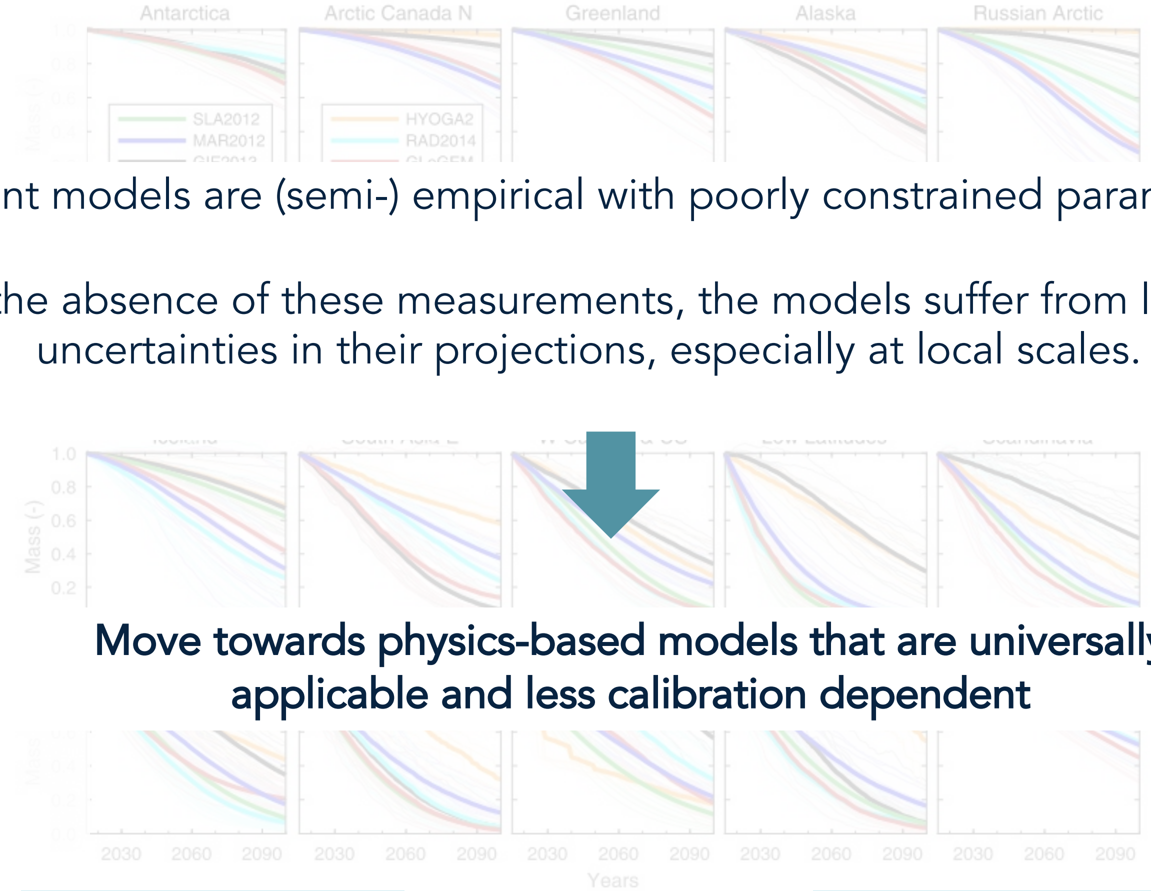
Projected relative glacier mass changes by 2100



Current models are (semi-) empirical with poorly constrained parameters.

In the absence of these measurements, the models suffer from large uncertainties in their projections, especially at local scales.

Move towards physics-based models that are universally applicable and less calibration dependent

Hock et al., 2019

Summary and objectives

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This study aims to narrow the uncertainties in regional glaciation modeling by incorporating a **Surface Energy Balance (SEB) model** for melt modeling into an existing glacier evolution model.

The **objective** is to simulate the mass balance of all glaciers across Southwestern Canada (~18’000 glaciers) using the improved version of the glacier evolution model developed in Radić et al. (2014).

The **key improvement** is the replacement of the temperature index model with a simple SEB model with minimal calibration to simulate glacier ablation. The SEB model is forced by ERA5 data with **minimal bias corrections** or statistical downscaling for the period of 1979–2022. We also add a simple model for ice dynamics.

The simulated mass balance and area change is then **evaluated against the observed glacier volume changes** (Schiefer et al., 2007) and **area changes** (Bevington and Menounos, 2022) across the region as previously derived from remote sensing.

Glacier evolution model based on Radić et al. (2014)

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Surface mass balance

$$\underbrace{b}_{\text{Mass balance}} = \underbrace{a}_{\text{ablation}} + \underbrace{c}_{\text{accumulation}} + \underbrace{R}_{\text{refreezing}}$$

Accumulation

$$c(h) = \delta(h)\underbrace{P(h)}_{\text{precipitation}}, \qquad \delta(h) = \begin{cases} 1, & \text{if } T(h) < T_{snow} \\ 0, & \text{else} \end{cases}$$

h: mean height per elevation band

Ablation

$$\underbrace{Q_{MELT}}_{\text{Melt energy}} = \underbrace{K_{in}(1-\alpha)}_{\text{Shortwave radiation}} + \underbrace{L_{in} - \sigma T_0^4}_{\text{Longwave radiation}} + \underbrace{Q_H}_{\text{Sensible heat}} + \underbrace{Q_L}_{\text{Latent heat}}$$

Conceptual model

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Variables:

From ERA5

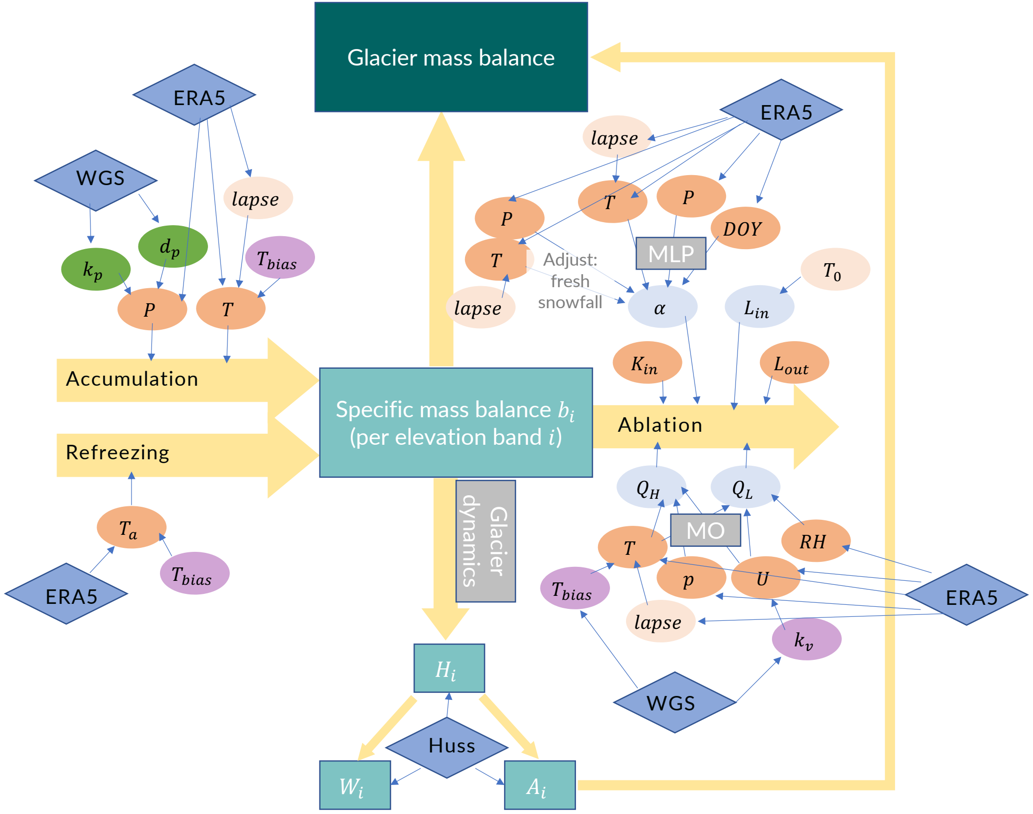
Calculated

Calibrated (winter)

Calibrated (summer)

Input:

Data sets



T: temperature
lapse: lapse rate
P: precipitation
DOY: day of year
L_{out}: outgoing longwave radiation
L_{in}: incoming longwave radiation
RH: relative humidity
MO: Monin-Obukhov
Q_H: Sensible heat flux
Q_L: Latent heat flux
p: surface pressure
U: wind speed
d: precipitation gradient
k_P: precipitation factor
α: albedo
T_{bias}: temperature bias
WGS: World Glacier Monitoring Service
Huss: Huss and Farinotti (2012)

Ice dynamics

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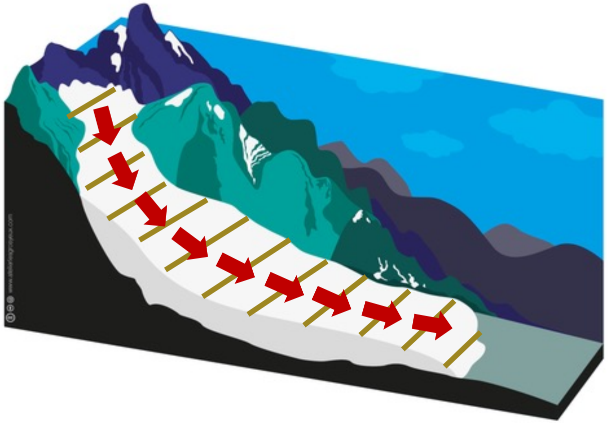
Ice dynamics:

Redistribute the annual glacier-wide mass change over each elevation bin using empirical mass redistribution curves derived from 34 glaciers in the Swiss Alps (Huss and Hock, 2015) at the end of each mass-balance year

→ No surface lowering at the glacier's highest elevation and maximum surface lowering at the terminus



Ice thickness:

$$H_{bin,t+1} = \left(H_{bin,t}^{1.5} + \frac{b_{bin,t}\, A_{bin,t}\, H_{bin,t}^{0.5}}{A_{bin,t}} \right)^{\frac{2}{3}}$$

Area:

$$A_{bin,t+1} = A_{bin,t} \left(\frac{H_{bin,t+1}}{H_{bin,t}} \right)^{0.5}$$

Width:

$$W_{bin,t+1} = W_{bin,t} \left(\frac{H_{bin,t+1}}{H_{bin,t}} \right)$$

Calibration and validation

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Calibration

- Minimize the discrepancies between observed and simulated seasonal mass balance for 17 glaciers in the study region from WGMS
- First calibrate k_p and d_p with winter mass balance
- Then calibrate T_{bias}, k_α and k_v with summer mass balance
- **Objective functions:** specific mass balances, the mass balance gradients and the area-averaged mass balances
- Optimization Method: Quasi-Newton (BFGS)

Model evaluation (1979-2021)

- Run the model for each glacier in British Columbia and Alberta with the calibrated parameters per subregion
- Compare model results with

  (1) the net volume changes (1985-1999) (Schiefer et al., 2007)

  (2) the net area changes (1984-2020) (Bevington and Menounos, 2022)

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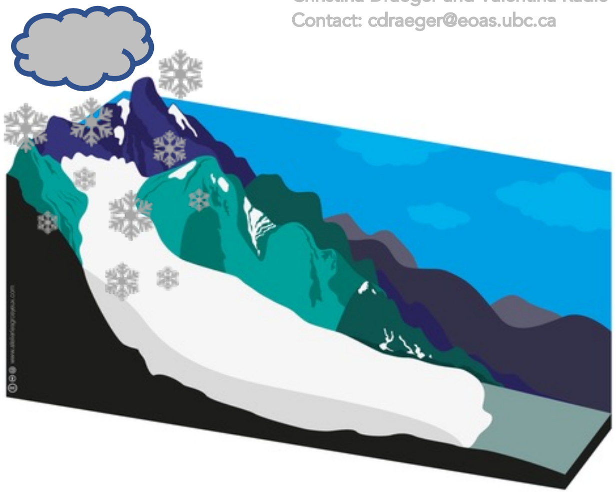
Model parameters for calibration



Winter mass balance

$$P(h) = \begin{cases} \boxed{k_p} \cdot P_{ERA} \cdot (1 + \boxed{d_p} \cdot (h - h_{ERA})) & \text{if } h < h_{firn} \\ \boxed{k_p} \cdot P_{ERA} \cdot (1 + \boxed{d_p} \cdot (h_{firn} - h_{ERA})) & \text{if } h \geq h_{firn}, \end{cases}$$

precipitation

k_p precipitation factor

d_p precipitation gradient

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Model parameters for calibration

Summer mass balance

$$T(h) = T_{ERA} + l_{ERA} \cdot (h - h_{ERA}) + \boxed{T_{bias}}$$

temperature — lapse rate (from ERA5 pressure levels)

$$U(h) = \begin{cases} \boxed{k_v} \cdot U_{ERA} & \text{if } P_{ERA} < P_{thres} \\ U_{ERA} & \text{if } P_{ERA} \geq P_{thres}. \end{cases}$$

wind speed

$$\alpha(h) = \begin{cases} \alpha_{snow} - \boxed{k_\alpha} \ln\left(\sum PDD\right) & \text{if } d_{snow}(h) > 0 \\ \alpha_{firn} & \text{if } d_{snow}(h) = 0 \text{ and } h \geq h_{firn} \\ \alpha_{ice} & \text{if } d_{snow}(h) = 0 \text{ and } h < h_{firn} \end{cases}$$

albedo

Hirose and Marshall (2013)

T_{bias} temperature bias

k_α albedo factor

k_v wind factor

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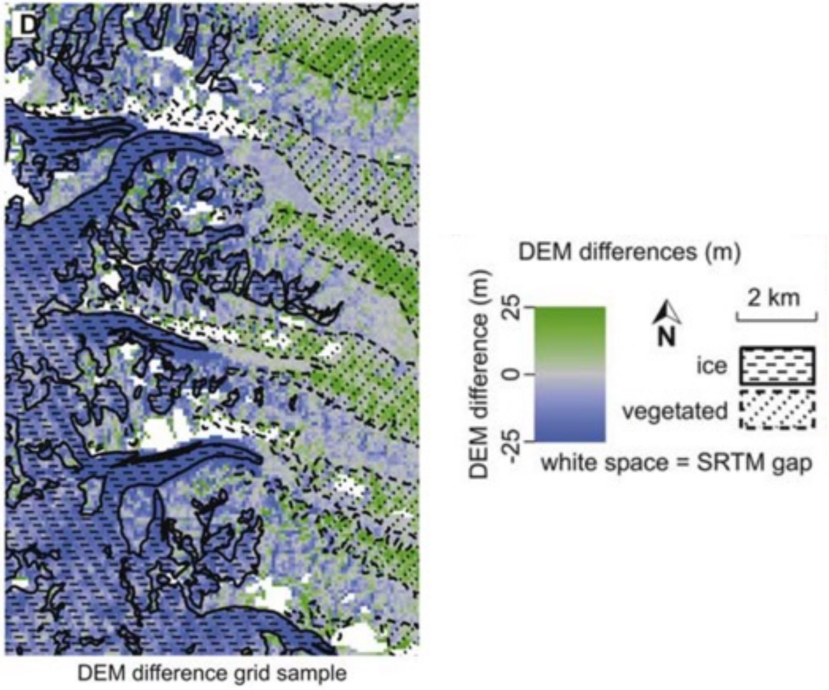
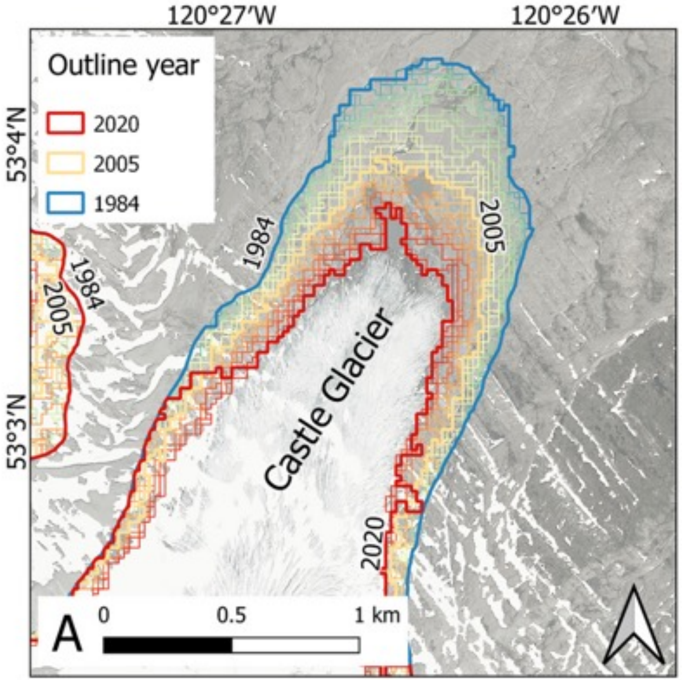
Model evaluation

Volume changes + Area changes



Schiefer et al., 2007



Bevington and Menounos, 2022

Subregions

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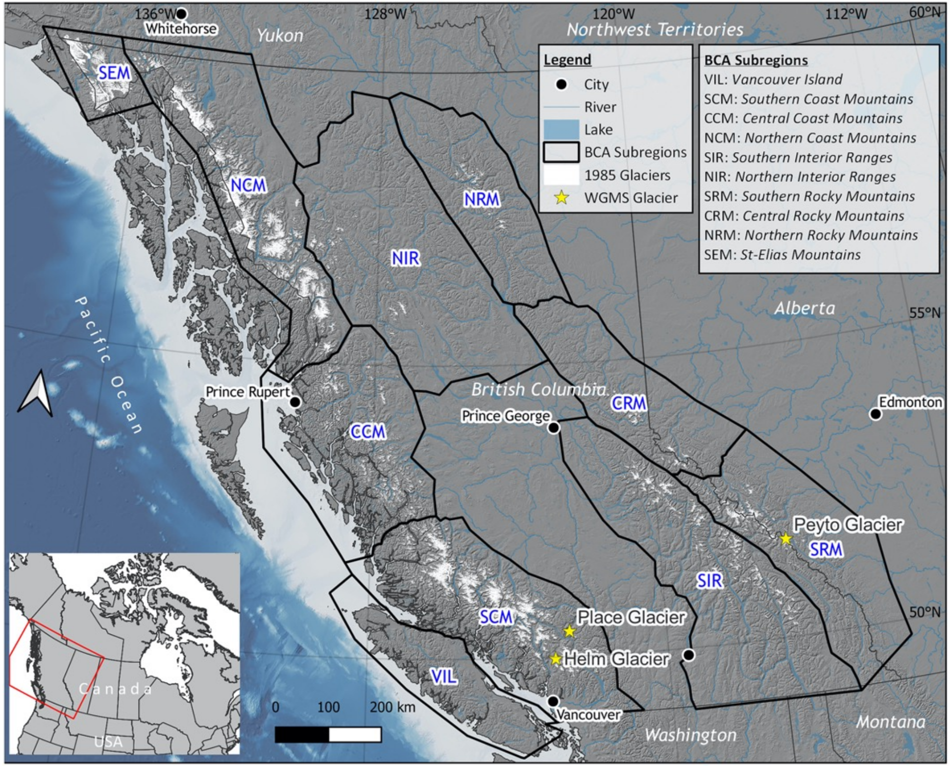
- Model calibration and evaluation will be carried out by subregion according to Bevington and Menounos (2022)

- For each glacier in a subregion, the parameter choice is the mean of the parameters for all glaciers in WGMS in the subregion. In case there are no glaciers in the subregion, the mean of neighboring subregions is taken



Bevington and Menounos (2022)

Model variations and tests (selection)

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Parameter calibration:

1) Only use precipitation gradient and factor
2) Only use precipitation gradient and factor, and distinguish between summer and winter precipitation factor
3) Add temperature bias, albedo factor and wind factor

Albedo:

1) Albedo model from Hirose and Marshall (2013)
2) Neural network: Multi Layer Perceptron (MLP) model based on Phelps and Radić (2022)

Precipitation:

1) Constant precipitation adjustment above the firn line
2) Varying precipitation adjustment above the firn line

Area-averaged mass balance for WGMS glaciers

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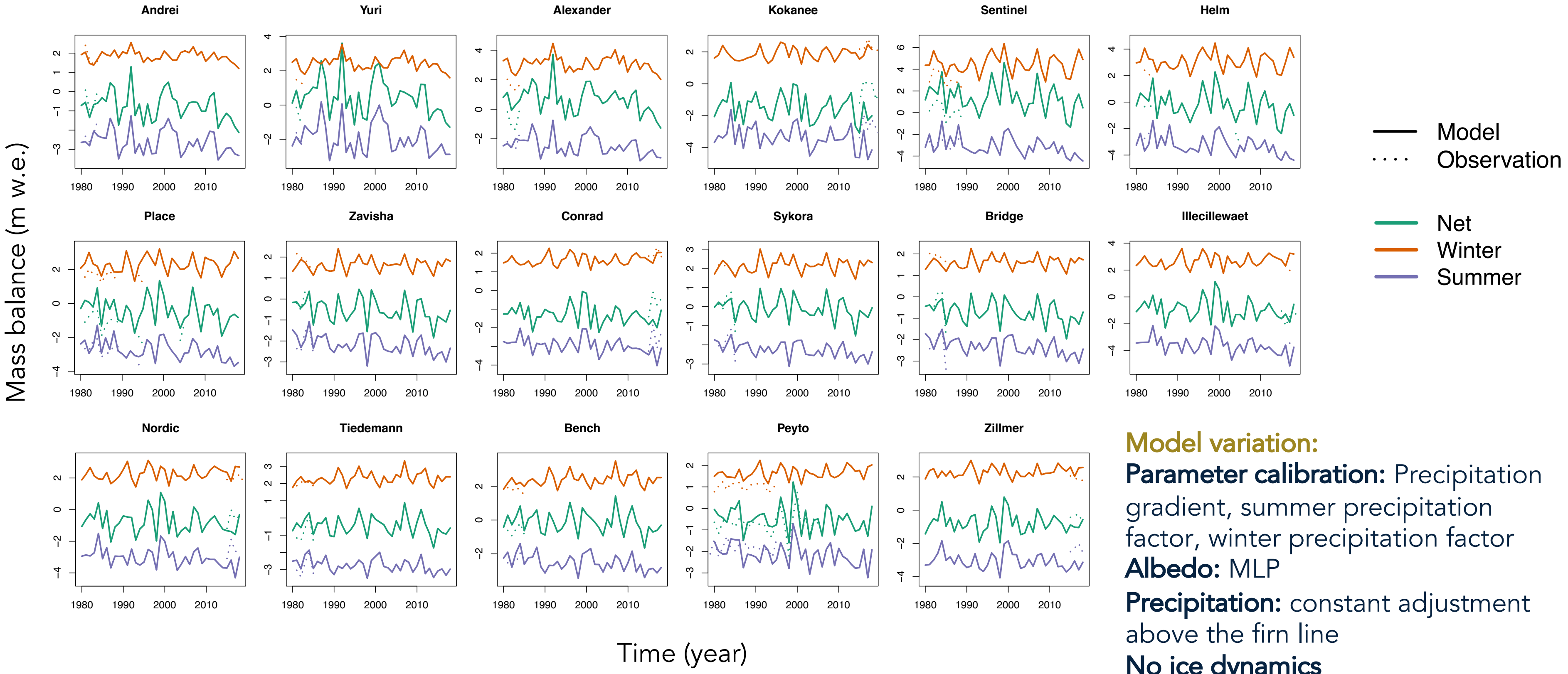

Model variation:

Parameter calibration: Precipitation gradient, summer precipitation factor, winter precipitation factor

Albedo: MLP

Precipitation: constant adjustment above the firn line

No ice dynamics

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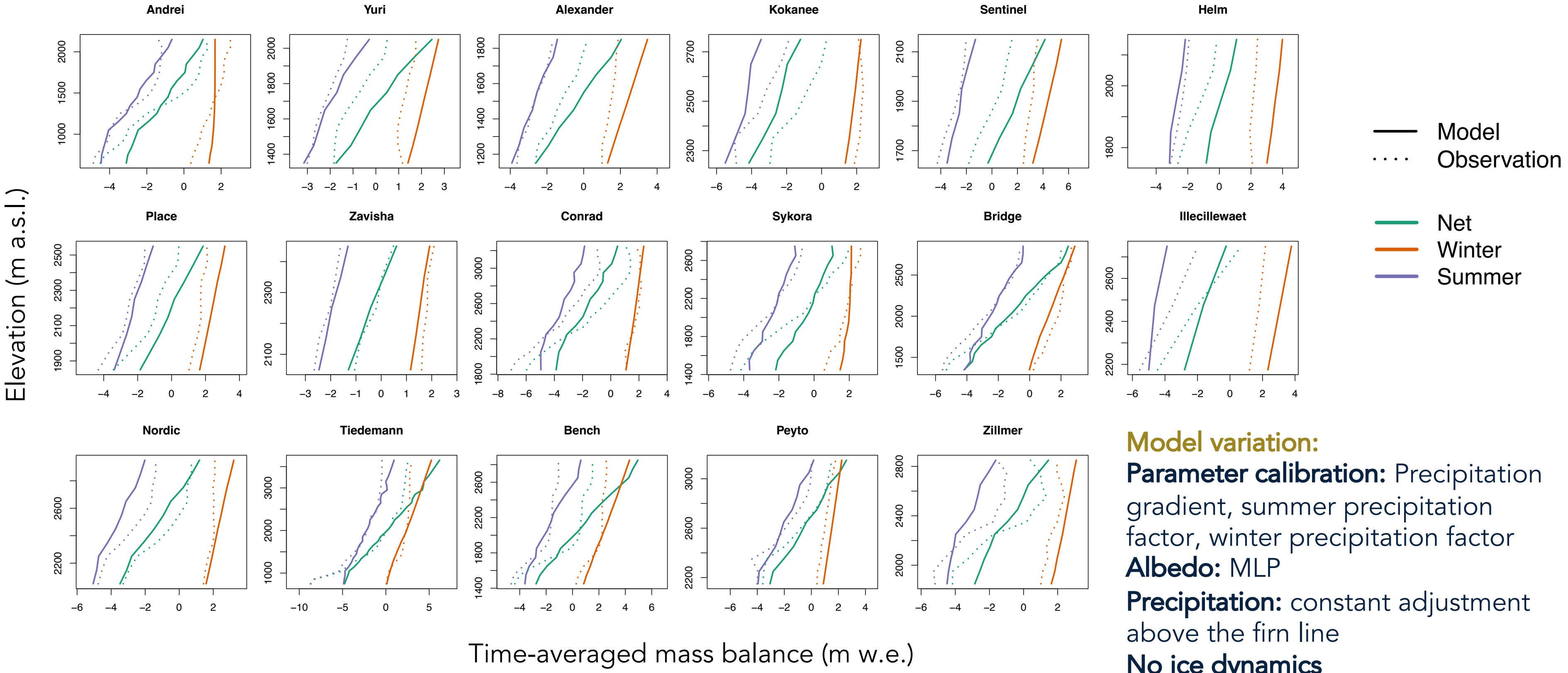
Mass balance profiles for WGMS glaciers



Model variation:

Parameter calibration: Precipitation gradient, summer precipitation factor, winter precipitation factor

Albedo: MLP

Precipitation: constant adjustment above the firn line

No ice dynamics

Mass balance profiles vs. slope

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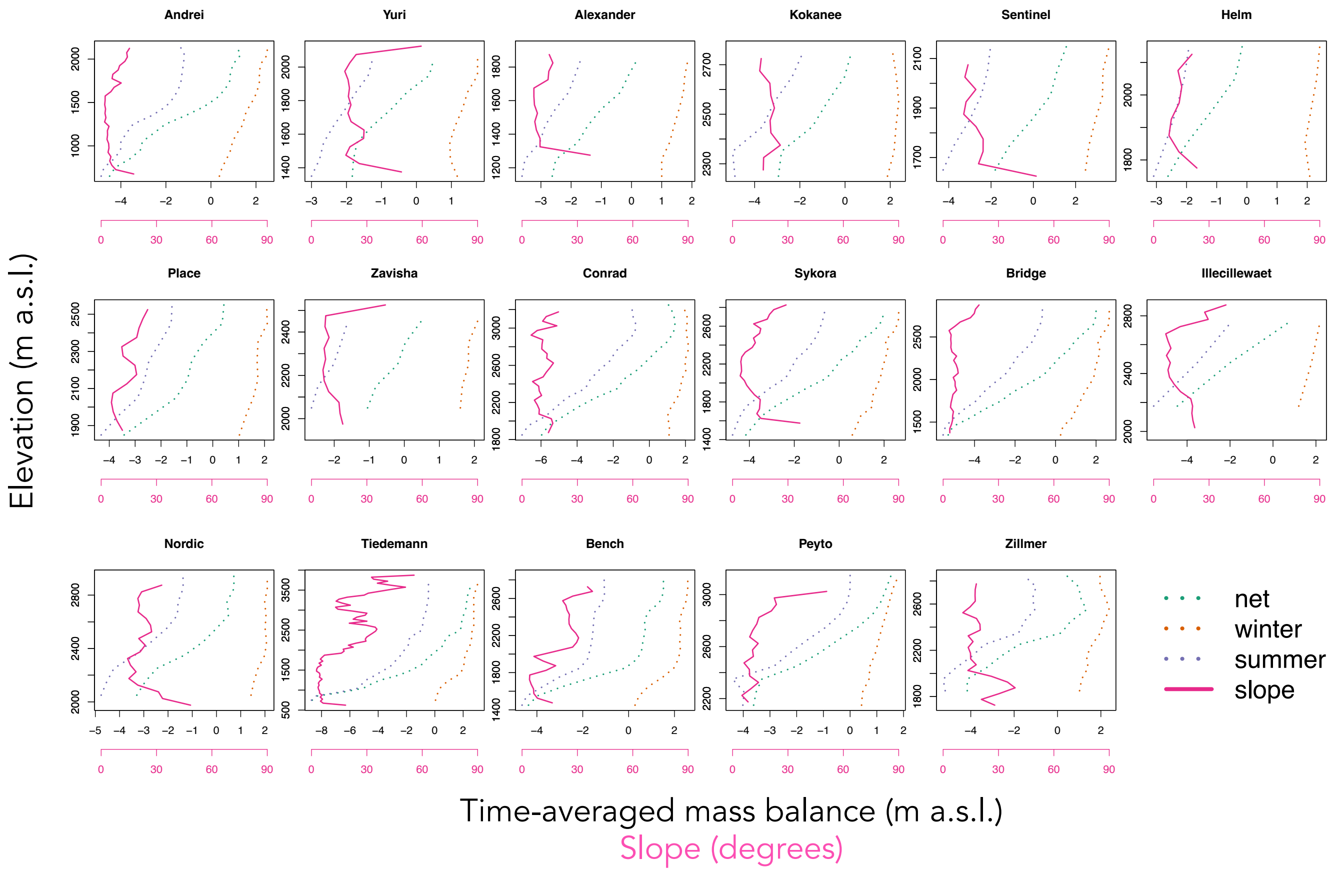

WGMS glacier outlines

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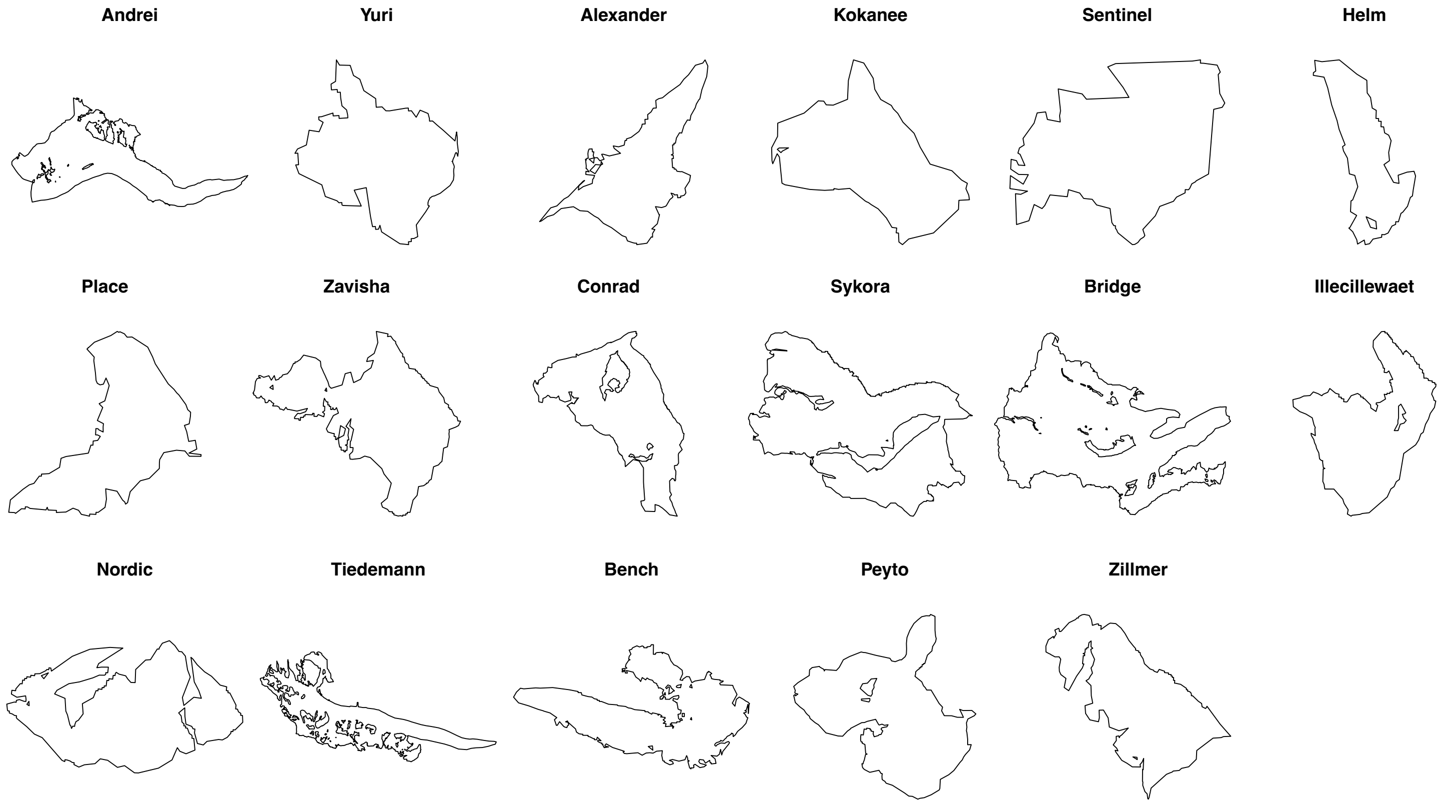

WGMS glacier area vs. elevation

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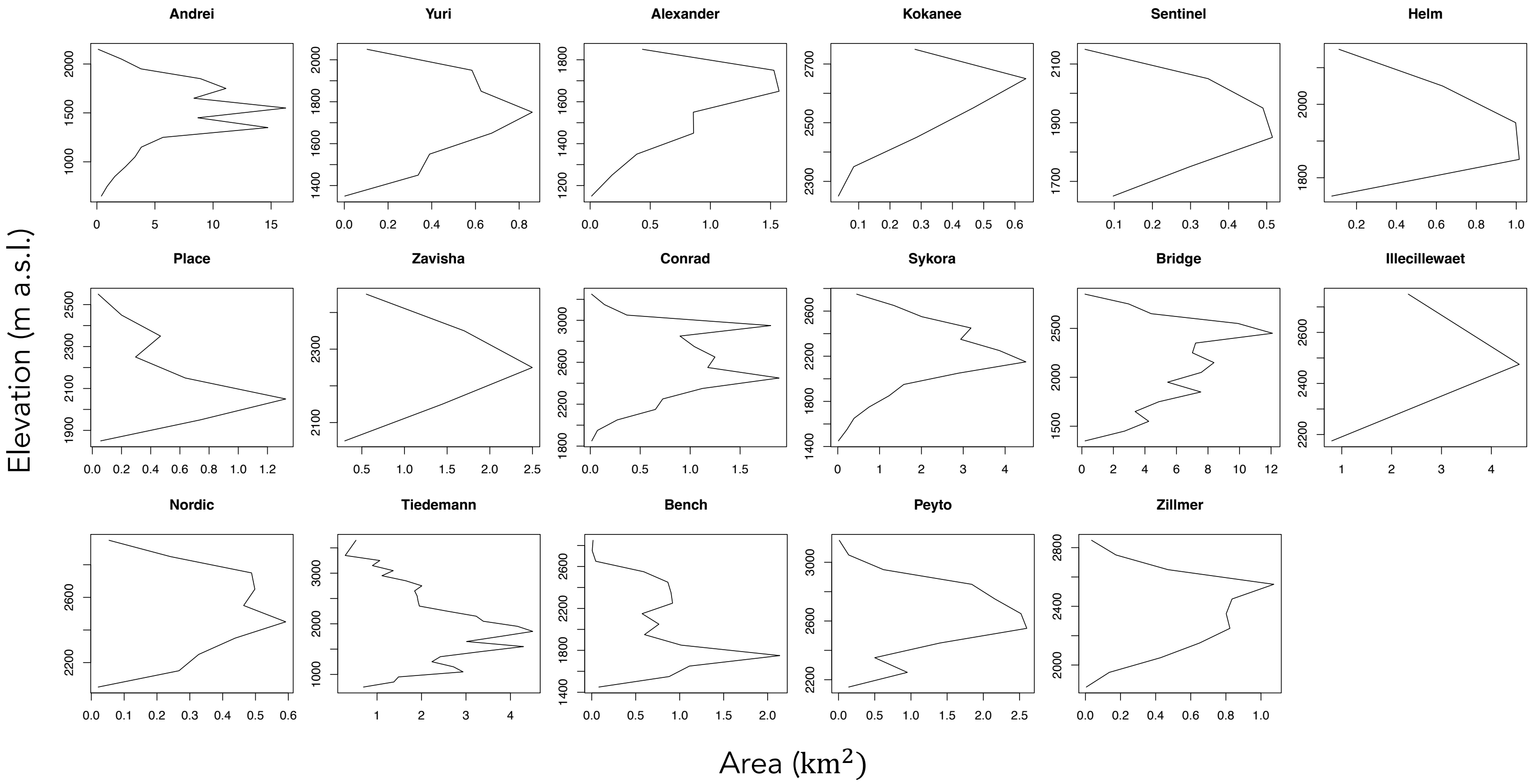

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First results:

- Summer mass balance is relatively well simulated without using any calibrated parameters for ablation
- Winter mass balance (adjusted with precipitation gradient and factor) is overestimated

Next steps:

- Find better representation for winter mass balance (function of slope, other climatic variables, etc.)
- Compare model results for all model variations (albedo model, representation of precipitation, number of calibrated parameters, etc.) with observed volume changes from remote sensing
- Add ice dynamics model and compare with observed area changes from remote sensing. Develop methodology to treat glacier fragmentation

References

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