SWAT-GL:
Benefits, Challenges & the Way Forward

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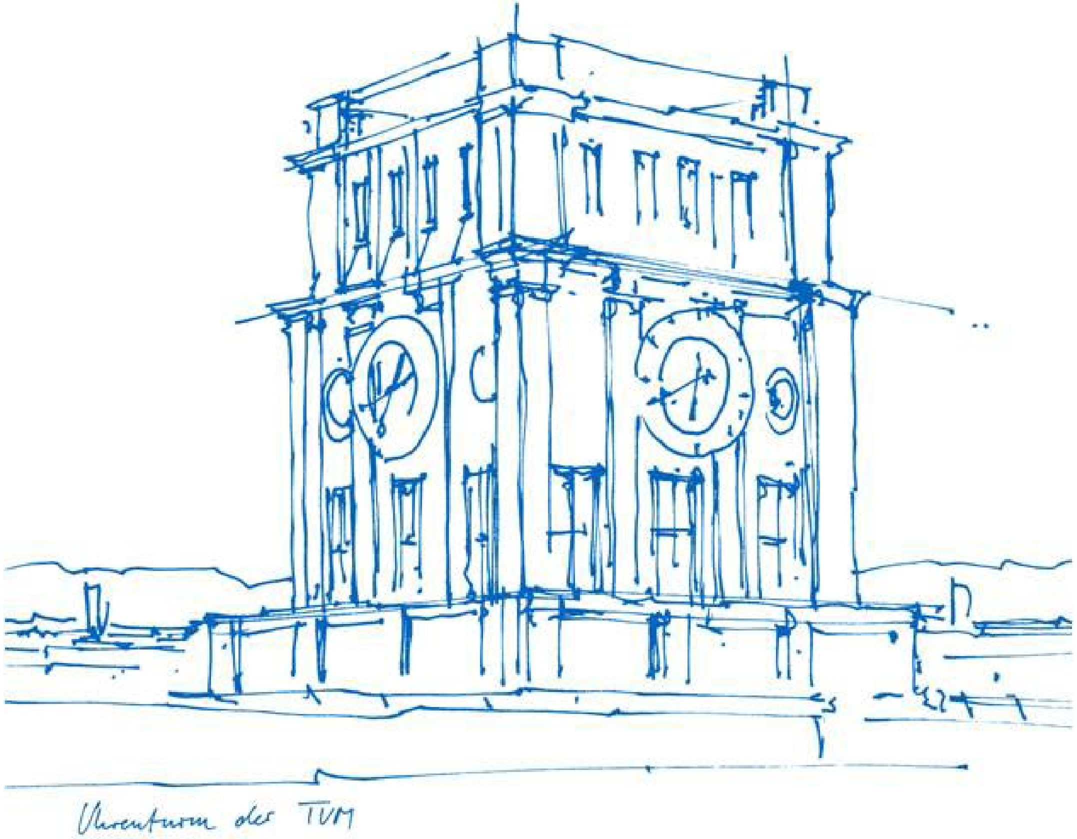


SWAT User Conference

Strasbourg, July 2024

Contact: t.schaffhauser@tum.de

Outline

I. **SWAT-GL: Technical Background**
   a. Glacier Module
   b. Snow Module
II. **SWAT-GL: Benchmarking**
   a. USGS Benchmark Glacier Project
   b. Methodology
   c. Results

I. SWAT-GL: Technical Background

Motivation

SWAT widely used in alpine & glaciated catchments

but has deficiencies in relation to glaciers

-> Are glaciers neglected?

Past efforts often focus on simplistic approaches

-> Shouldn‘t we provide an advanced „built-in“ glacier routine?

Past efforts not freely or easily accessible

- FAIR principles

-> Shouldn‘t we promote accessibility & transparency?

S-GL

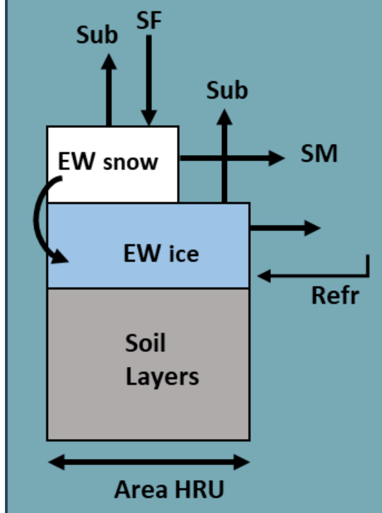
SWAT-GL

SWAT-GL – What is it?

SWAT-GL: A revised version of **SWAT** considering **Glacier Processes**

1 Mass Balance Routine

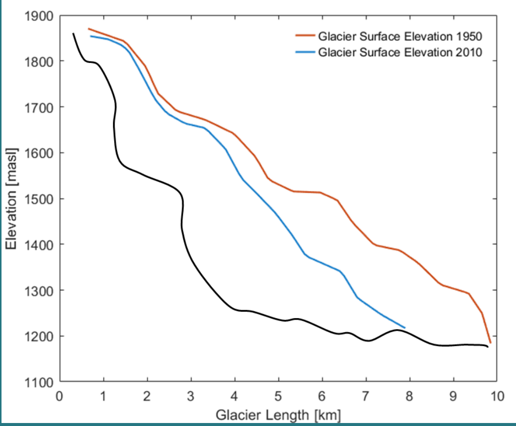
- Melt
- Accumulation
- Sublimation



2 Glacier Evolution Routine

Dynamic Glacier Change

- Retreat & Advance
- ΔV & ΔA



But…

Glaciers not the only objective!

Objectives

1. Glacier Module

*To offer a **built-in glacier representation** to improve SWAT's credibility in gacier basins*

….to reduce misapplication

Multiple approaches for **glacier** processes

2. Snow Module

*To improve & extend **existing snow** module*

…to collect past efforts in SWAT-GL
Coordinate Fragmented work

Multiple approaches for **snow** processes

S-GL
SWAT-GL

…to encourage community making model code **available** and **easily accessible**
FAIR Principles

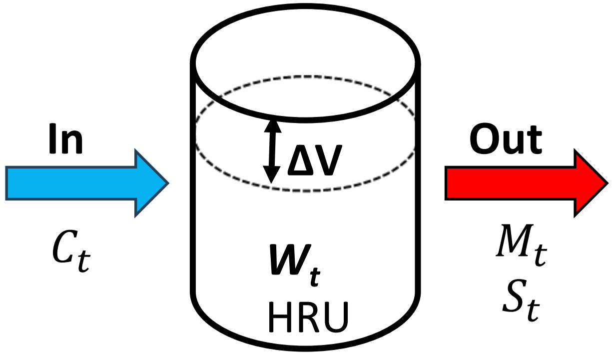
Glacier Module

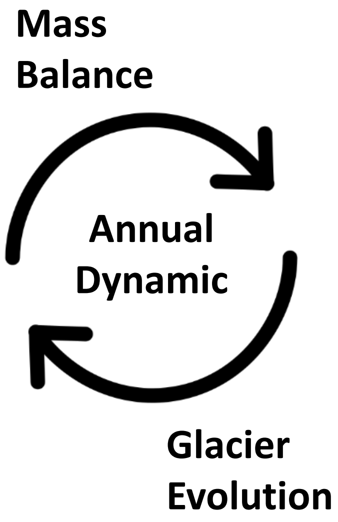
SWAT-GL: Glacier Module

1. Mass Balance

$$W_t = W_{t-1} - M_t \cdot (1 - \beta_f) - S_t + C_t$$

W:	*Water Equivalent of Ice [mm]*
M:	*Glacier Melt [mm/d]*
β_f:	*Refreezing Rate [-]*
S:	*Sublimation [mm/d]*
C:	*Glacier Accumulation [mm/d]*





2. Glacier Evolution

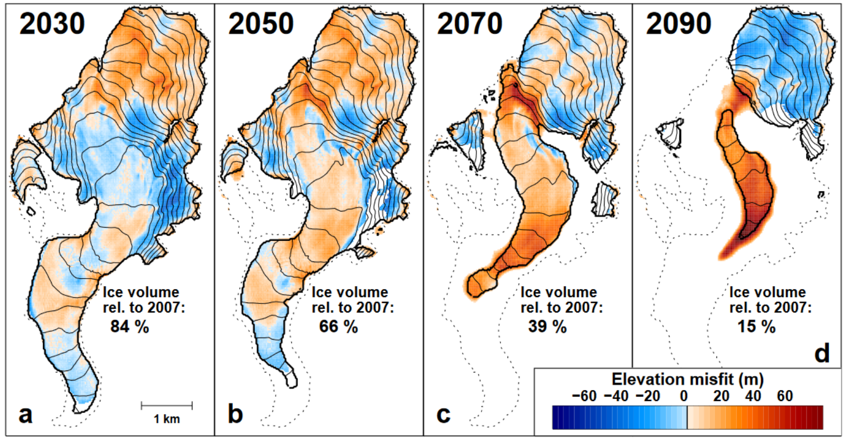
Representation of **spatio-temporal** glacier **dynamics**

- Retreat
- Advance

How?

Δh-Parameterization from *Huss et al. 2010*

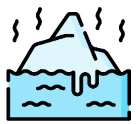
- Ice thickness change (Δh) = function of elevation (E)



Reference: Huss et al. 2010

Glacier Evolution: Δh-Parameterization

Δh = Normalized Ice Thickness Change



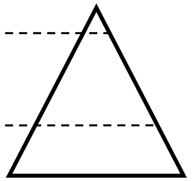
Annual Mass Balance Change

Δh_1 ⟷ Elevation 1

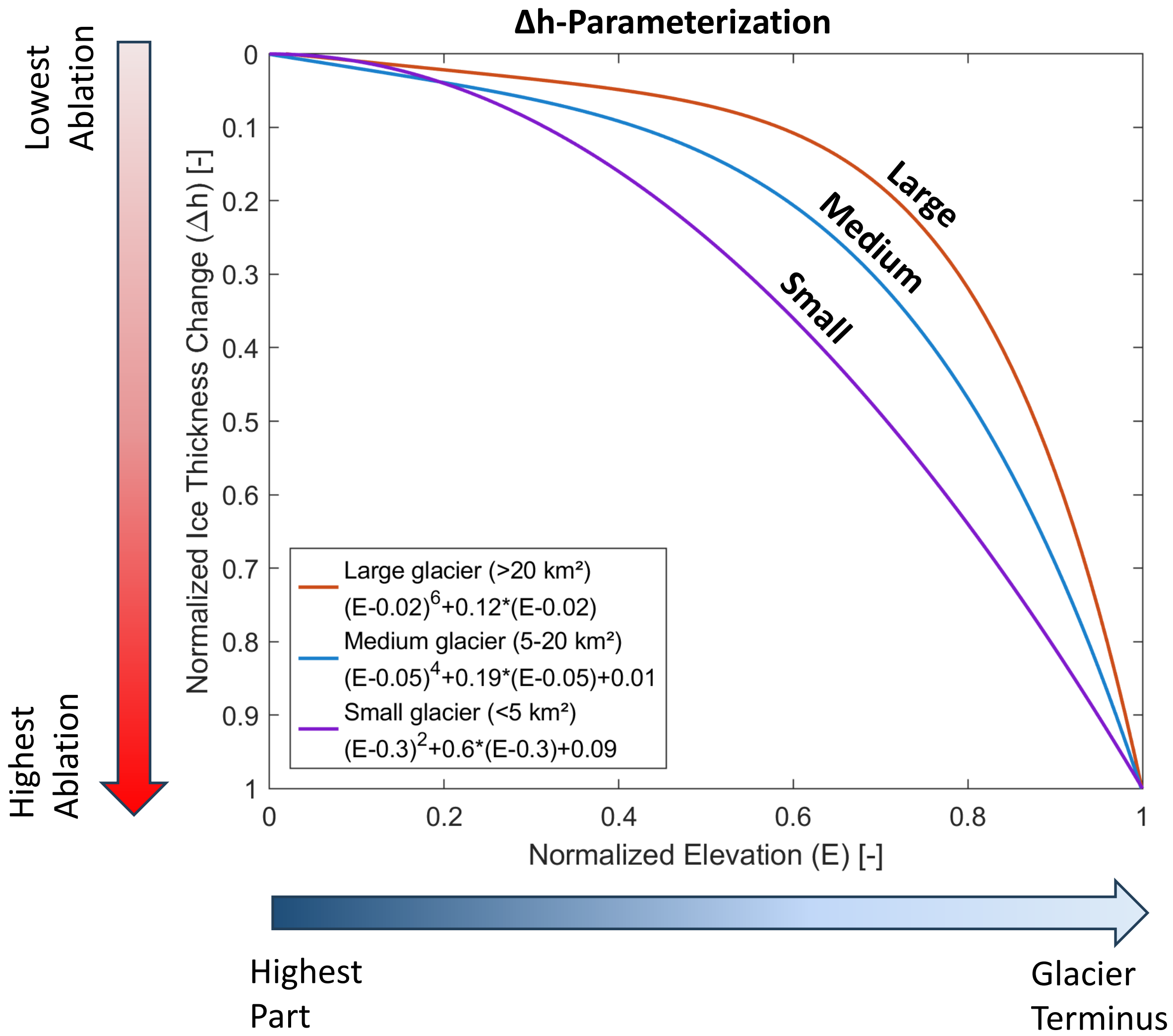
Δh_2 ⟷ Elevation 2

… …

Δh_n ⟷ Elevation n



- Relationship depends on glacier size
- Glacier is split in Elevation Sections (ES)
- If $h_{i,1} \leq 0$ then not glacierized anymore (= **recession**)



SWAT-GL: Requirements & Application

3 New Input Files

- gl_hru_par.txt
- swat_gles_full.txt
- swatgl_control.txt

1 New & 1 Modified Output File

- gl_mb_aa.txt
- output.hru

Preprocessing & New Data

- Define ES
- Modify Land Use Map
- Define Initial Glacier Thickness & Area

New Input Data!

Snow Module

SWAT-GL: Snow Module Extension

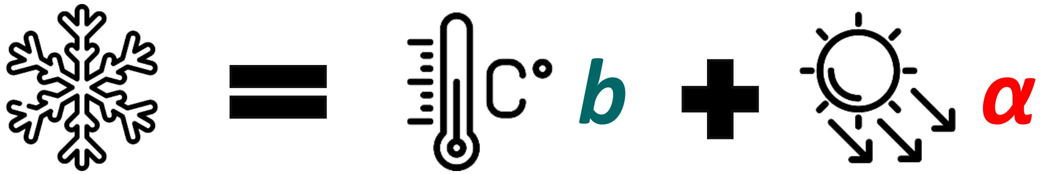
Snowmelt:

I. Wet Degree-Day Model (Rain on Snow)

II. Temperature-Index (TI) after *Hock et al. 1999* **(HTI)**

III. Enhanced TI after *Pelicciotti et al. 2017* **(ETI)**

IV. Exponential TI after *Magnusson et al. 2014* **(ExpTI)**



$$Melt_{default} = b(T - T_{melt})$$

$$Melt_{HTI} = (b + \alpha \cdot Rad)(T - T_{melt})$$

$$Melt_{ETI} = b(T - T_{melt}) + \alpha \cdot Rad$$

Precipitation:

I. Mixed Precipitation (Rain & Snow)

II. Seasonally Varying Lapse Rate

III. Snow Redistribution

SWAT-GL: Snow Module Extension

Snowmelt:

I. Wet Degree-Day Model (Rain on Snow)
II. Temperature-Index (TI) after *Hock et al. 1999* **(HTI)**
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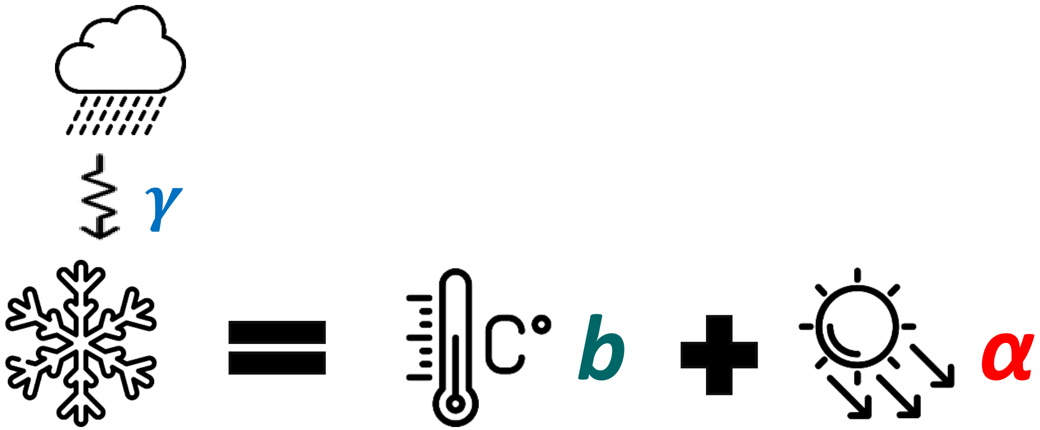


$$Melt_{default} = b(T - T_{melt})$$

$$Melt_{HTI} = (b + \alpha \cdot Rad)(T - T_{melt})$$

$$Melt_{ETI} = b(T - T_{melt}) + \alpha \cdot Rad$$

$$b_{wet} = b + \gamma(P - P_{thr})$$

Precipitation:

I. Mixed Precipitation (Rain & Snow)
II. Seasonally Varying Lapse Rate
III. Snow Redistribution

II. SWAT-GL: Evaluation

USGS Glacier Benchmark Project

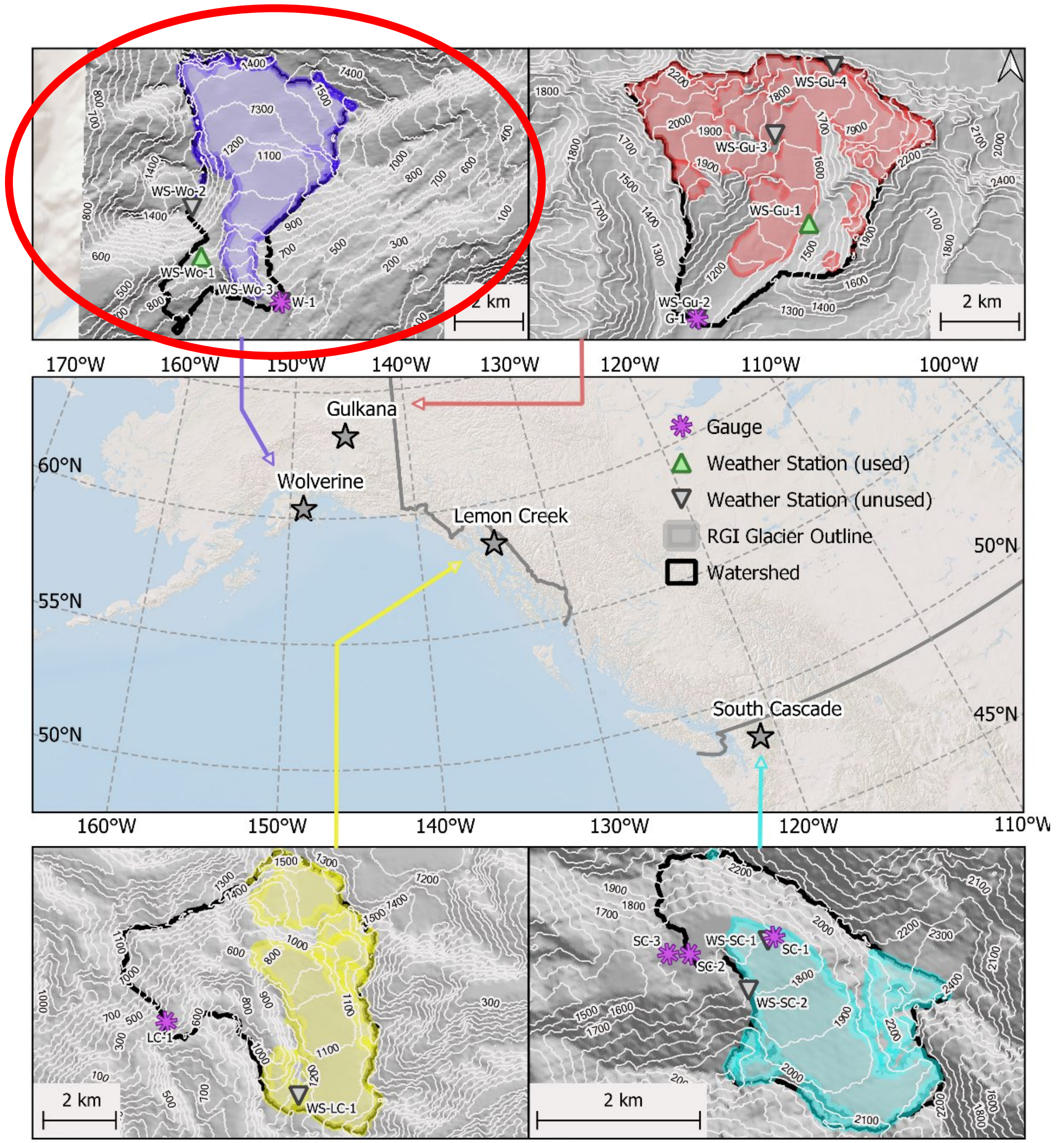
Glaciers of the project:

- Wolverine (WG)
- Gulkana (GG)
- Lemon Creek (LCG)
- South Cascade (SCG)

…mass balance, glacier area, hypsometry, discharge, precipitation, temperature, snow depth data **since 1950s**

Glacier	Gl. Area [km²]*	Basin Area [km²]	Observation Start	Elevation [m]
Gulkana	17.97	28.4 (64%)	1966	1,185 - 2420
Wolverine	16.69	23.9 (69%)	1966	466 - 1,653
Lemon Creek	14.92	29.3 (50%)	1953	543 - 1,550
South Cascade	3.46	5.9 (58%)	1959	1,619 - 2,439

**based on Randolph Glacier Inventory not USGS Outlines*



SWAT-GL: Methodology

1. Sensitivity Analysis (SA)

- **Morris/ Elementary Effects**
  - Also as TVSA (time-varying per variable)
- **Sampling:**
  - Radial Design:
    r = 500 (Latin Hypercube Points)
    M = 14 (Parameters/Factors)

2. Multi-Objective Optimization (MOO)

- **NSGA-II**
- **Variables**:
  - Snow Cover (SC)
  - Glacier Mass Balance (MB)
  - Glacier Hypsometry
- **Objective Function:**
  - NRMSE for all variables

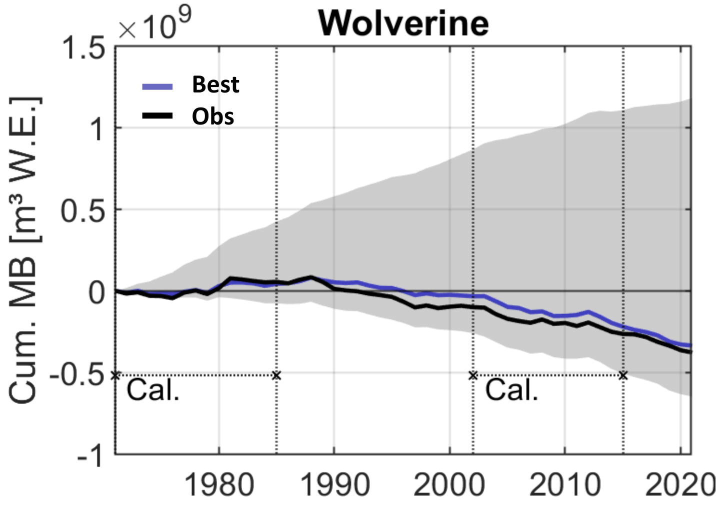
?

What about discharge?

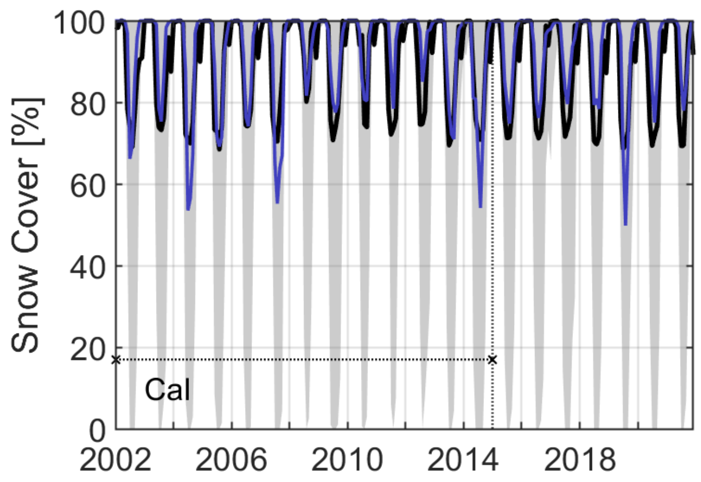
- Only cross-validation
- We don‘t think that a discharge-centric evaluation is evidence enough that glacier routine works

SWAT-GL: Wolverine Glacier Calibration

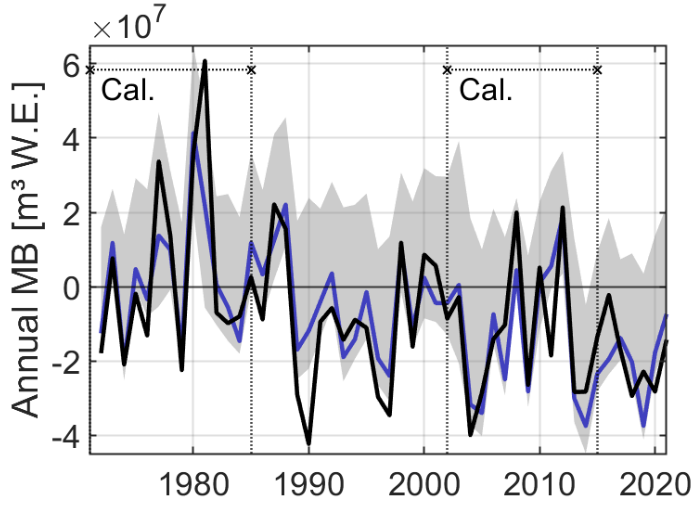
Cumulative Mass Balance



Snow Cover



Net Mass Balance



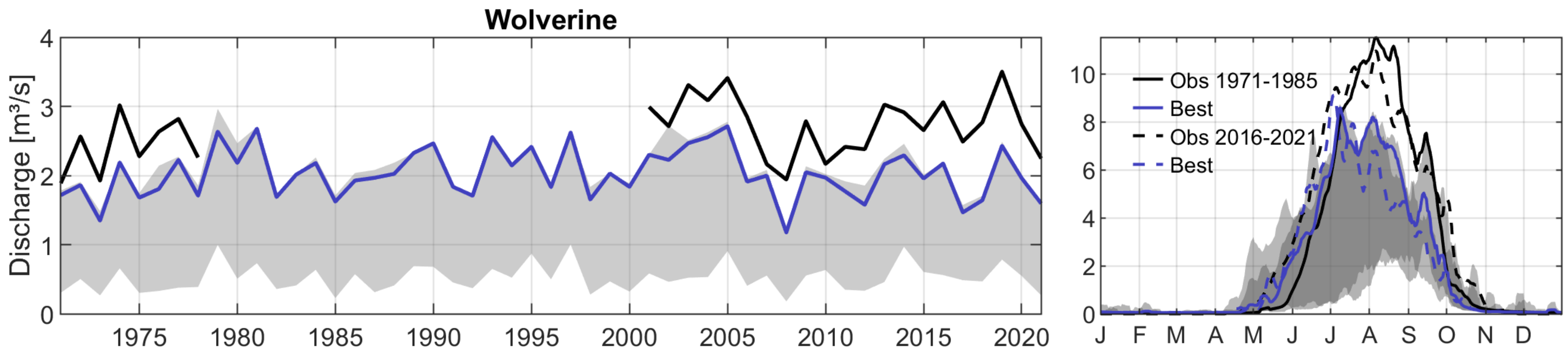
- Long nonstationary time series
- Qualitatively all variables look pretty ok!
  - Also statistically (not shown)
- 3 of 4 glaciers look satisfying

Hypothesis:
"A good representation of snow and glaciers in a 70% glaciated catchment produces satisfying discharge."

SWAT-GL: What About Discharge?

<u>Let’s see how annual discharge looks!</u>

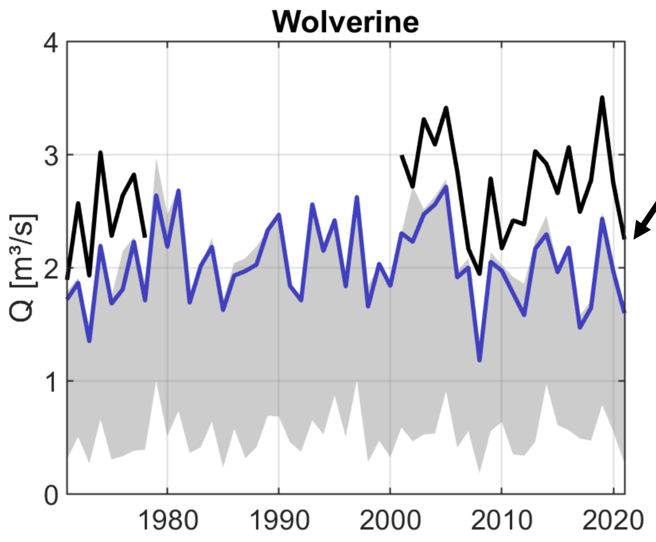
- Same Generation as before



- A little bit (much) of water missing ☹
  - KGE = 0.64 (for daily discharge)

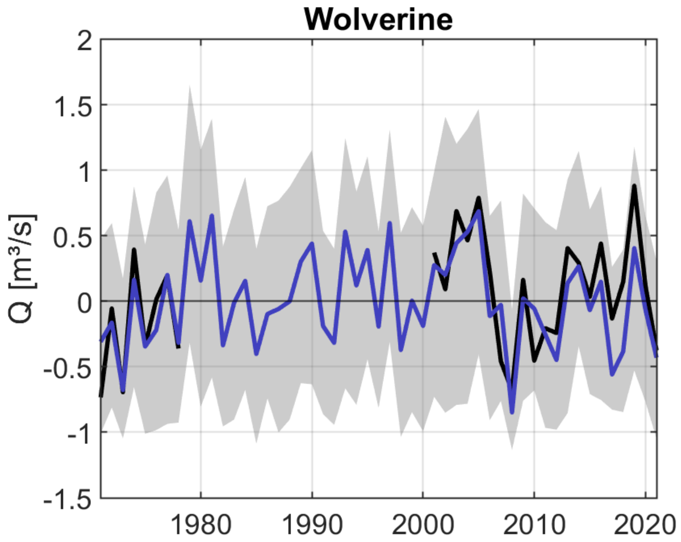
SWAT-GL: What About Discharge?

But how about the annual pattern itself?



Same as slide before!

Centered Discharge



- Pattern shows something I can live with
  - ☺!

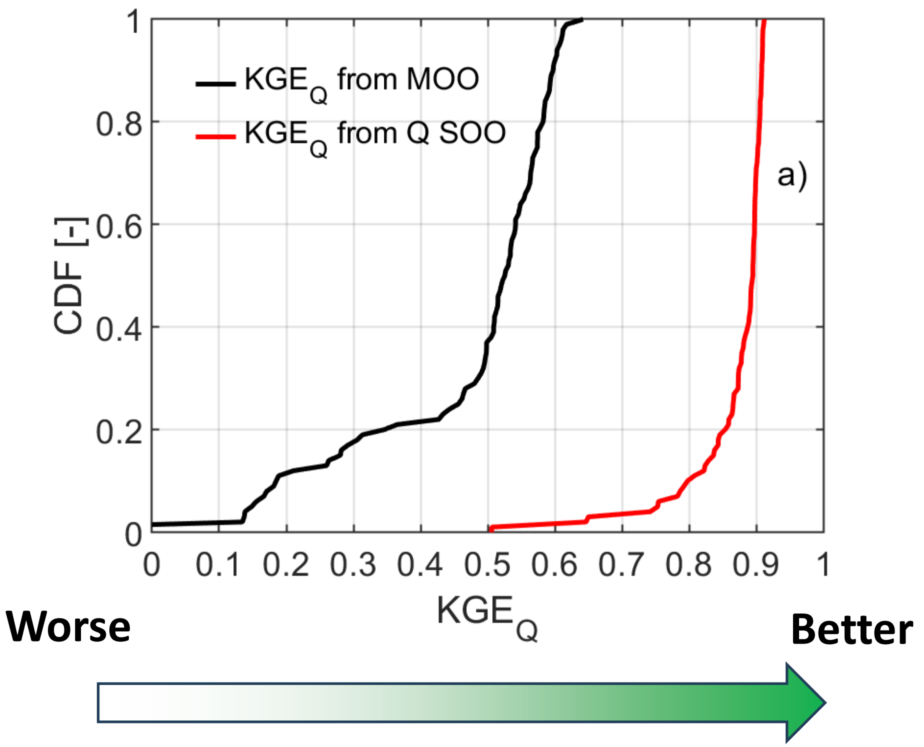
SWAT-GL: What About Discharge?

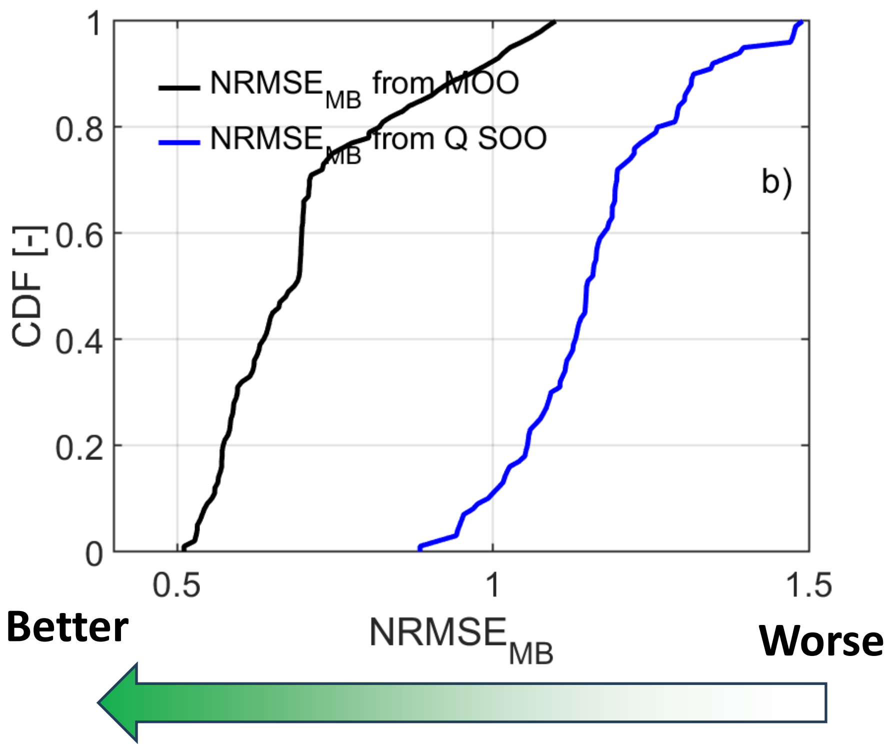
<u>What if we calibrate for discharge only?</u>

- Optimize for Q using a Differential Evolution
  - Single-objective optimization (SOO)
- Compare last Generation of SOO with results from before (MOO)

!

- If you go all in of course your discharge looks good.
- However, the price might be high





Conclusions & Further Infos

SWAT-GL offers flexiibility in **snow** & **glacier** dominated basins
...with a minimum of input & processing requirements

Easily & openly accessible!
...encourage community to make code available & to foster model development

Current demonstrations indicate **promising capabilities**!
...However, every study helps, so we need you!

Please be careful using SWAT/SWAT+ (standard) in **highly glaciated catchments** ☺

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SWAT-GL Online Resources
Download & Manual

GitLab

I. **Technical Note**
Schaffhauser et al. (2024a)
SWAT-GL: A new glacier routine for the hydrological model SWAT

II. **Evaluation Paper**
Schaffhauser et al. (2024b)
Merits and Limits of SWAT-GL: Application in Contrasting Glaciated Catchments

SWAT-GL:
Benefits, Challenges & the Way Forward

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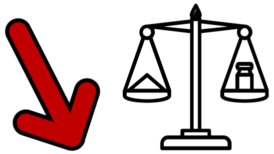
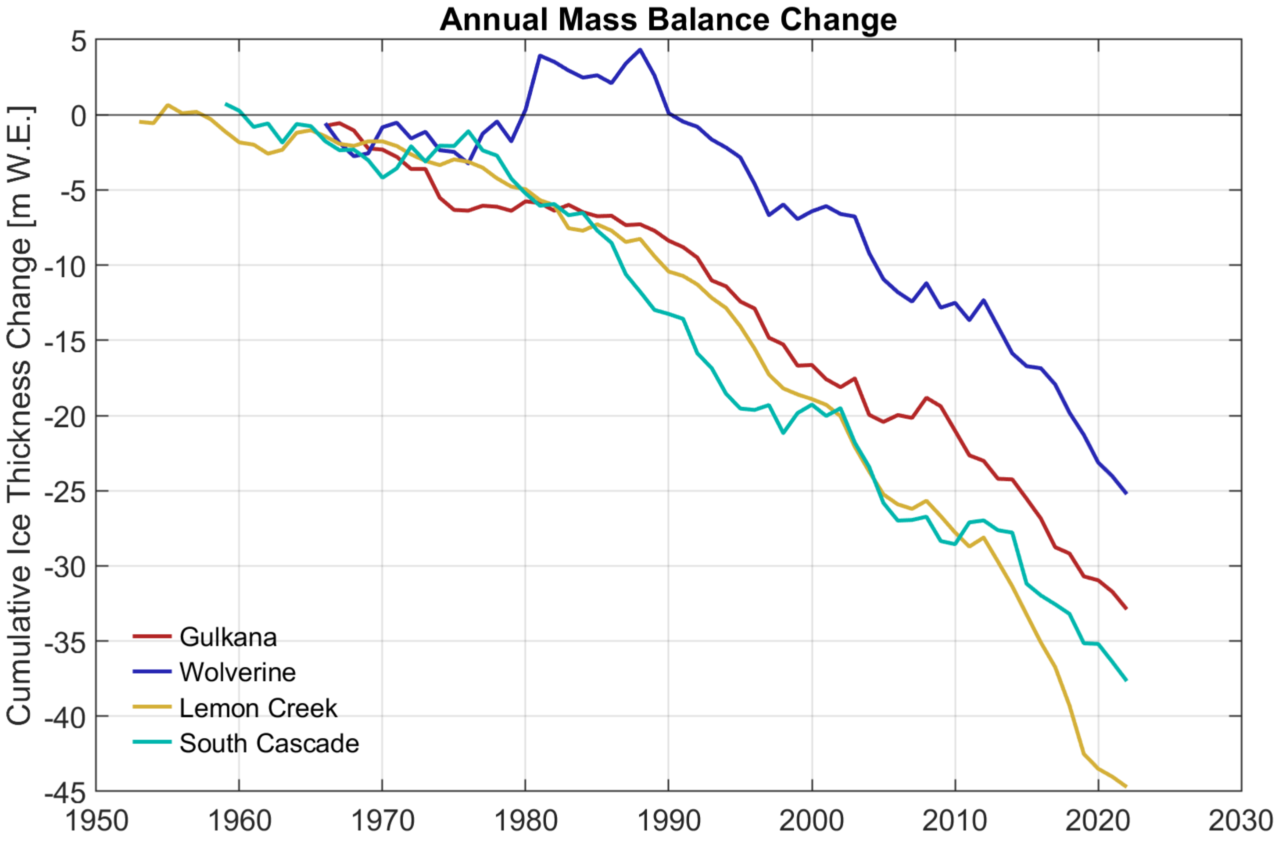
USGS Benchmark Glaciers – Mass Balance





Can SWAT-GL represent this?

Sensitivity Analysis - Parameters

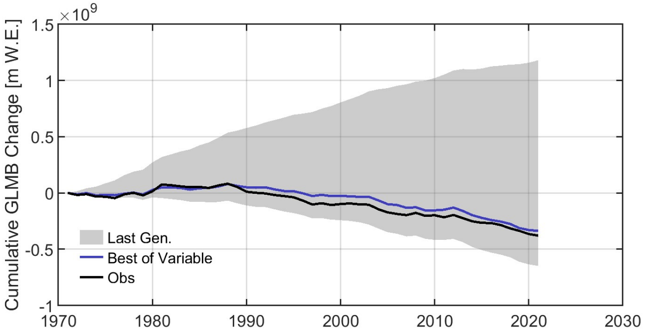
Table 2
Parameters used for the benchmarking of SWAT-GL.

Parameter	Description	Minimum	Maximum
SFTMP	Snowfall temperature [°C]	0	4.5
SMTMP	Snowmelt temperature [°C]	0	4.5
SMFMX	Melt factor for snow on June 21 [mm H_2O/(°C·day)]	0.1	7
SMFMN	Melt factor for snow on December 21 [mm H_2O/(°C·day)]	0.1	7
TIMP	Snow temperature lag factor [-]	0	0.5
SNOCOVMX	Threshold snow water equivalent where 100% snow cover occur [mm]	2	75
SNO50COV	Fraction of SNOCOVMX at which 50% snow cover occur [-]	0.1	0.9
TLAPS	Temperature Lapse Rate [°C/km]	-9	-5
PLAPS	Precipitation Lapse Rate [mm/km]	550	1800
GLMLTMP	Threshold temperature for glacier melt [°C]	0	4.5
GLMFMX	Melt factor for ice on June 21 [mm H_2O/(°C·day)]	3.5	13
GLMFMN	Melt factor for ice on December 21 [mm H_2O/(°C·day)]	3.5	10
β_f	Refreezing factor of glacier melt [-]	0.001	0.01
f_{acc}	Conversion factor of snow to firn and ice [-]	0.1	0.6

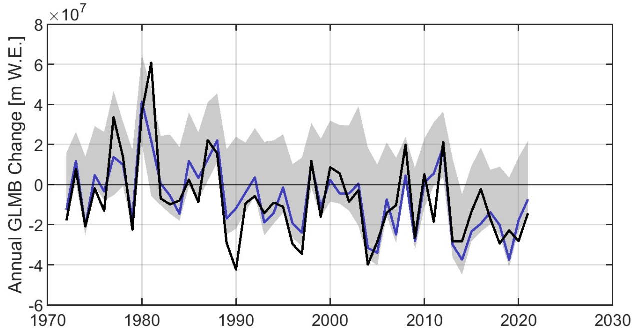
Preliminary Optimization Results – WG & SCG

Wolverine

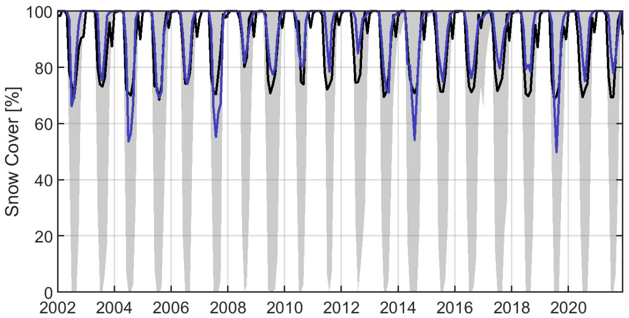
Cum. MB



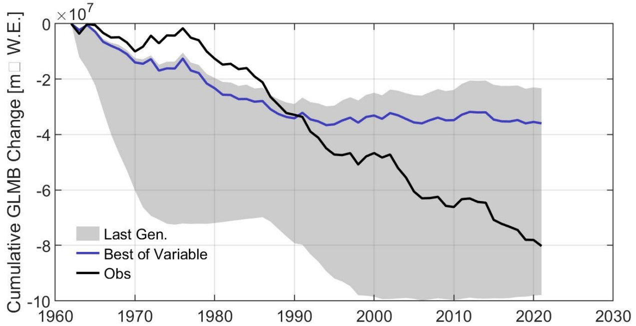
MB

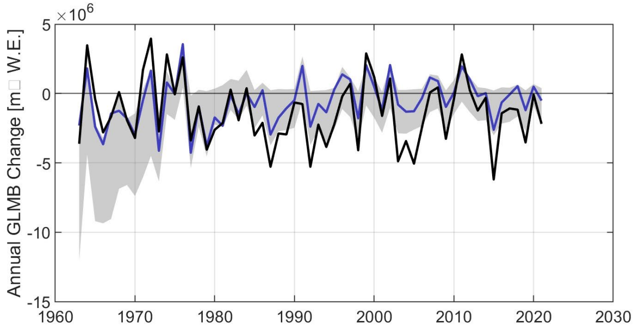


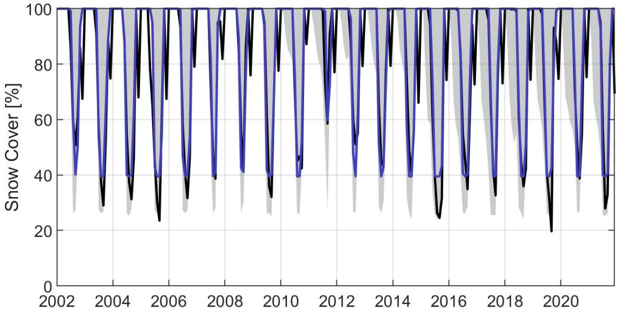
SC



South Cascade







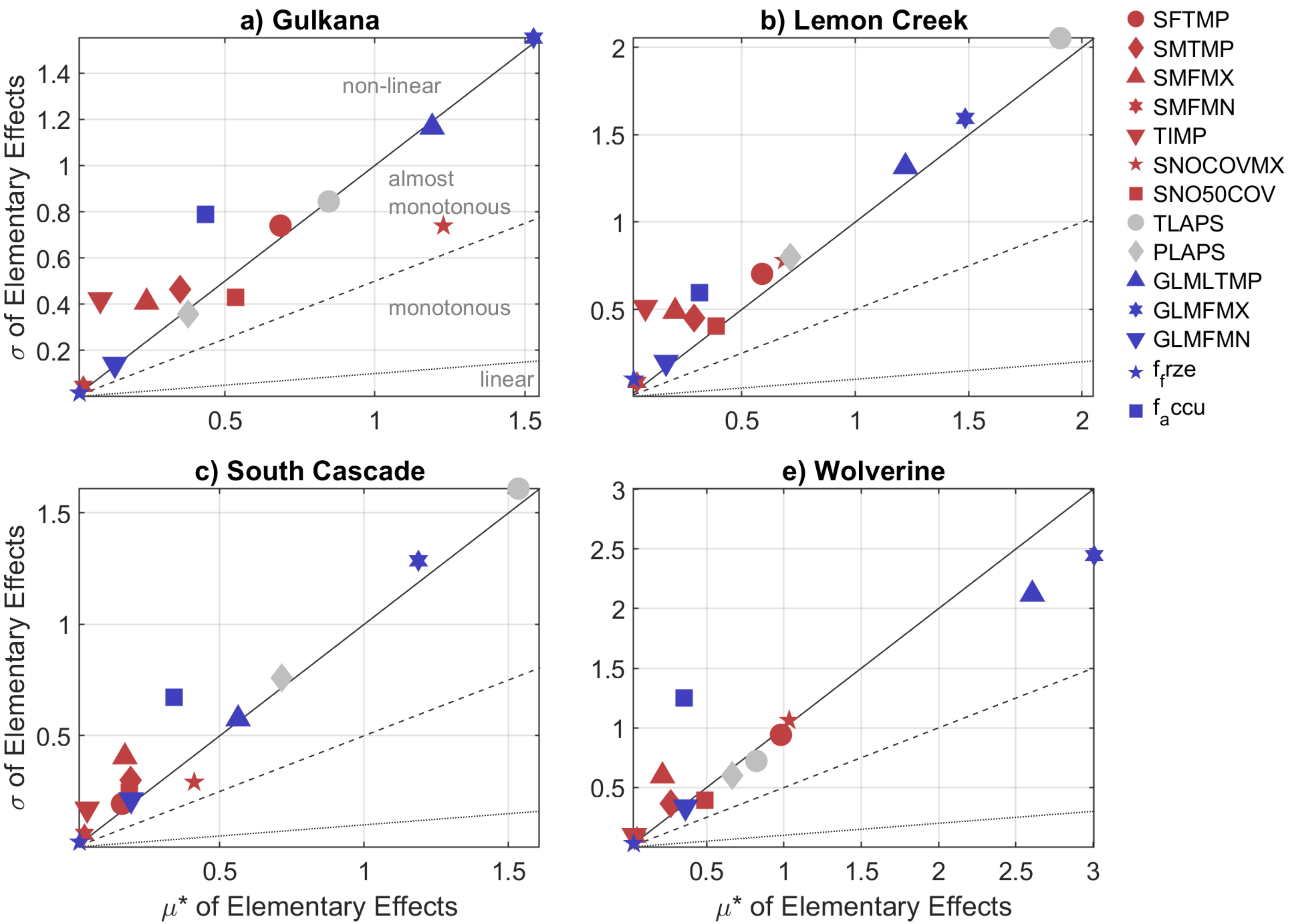
But let's take a closer look!

Wolverine

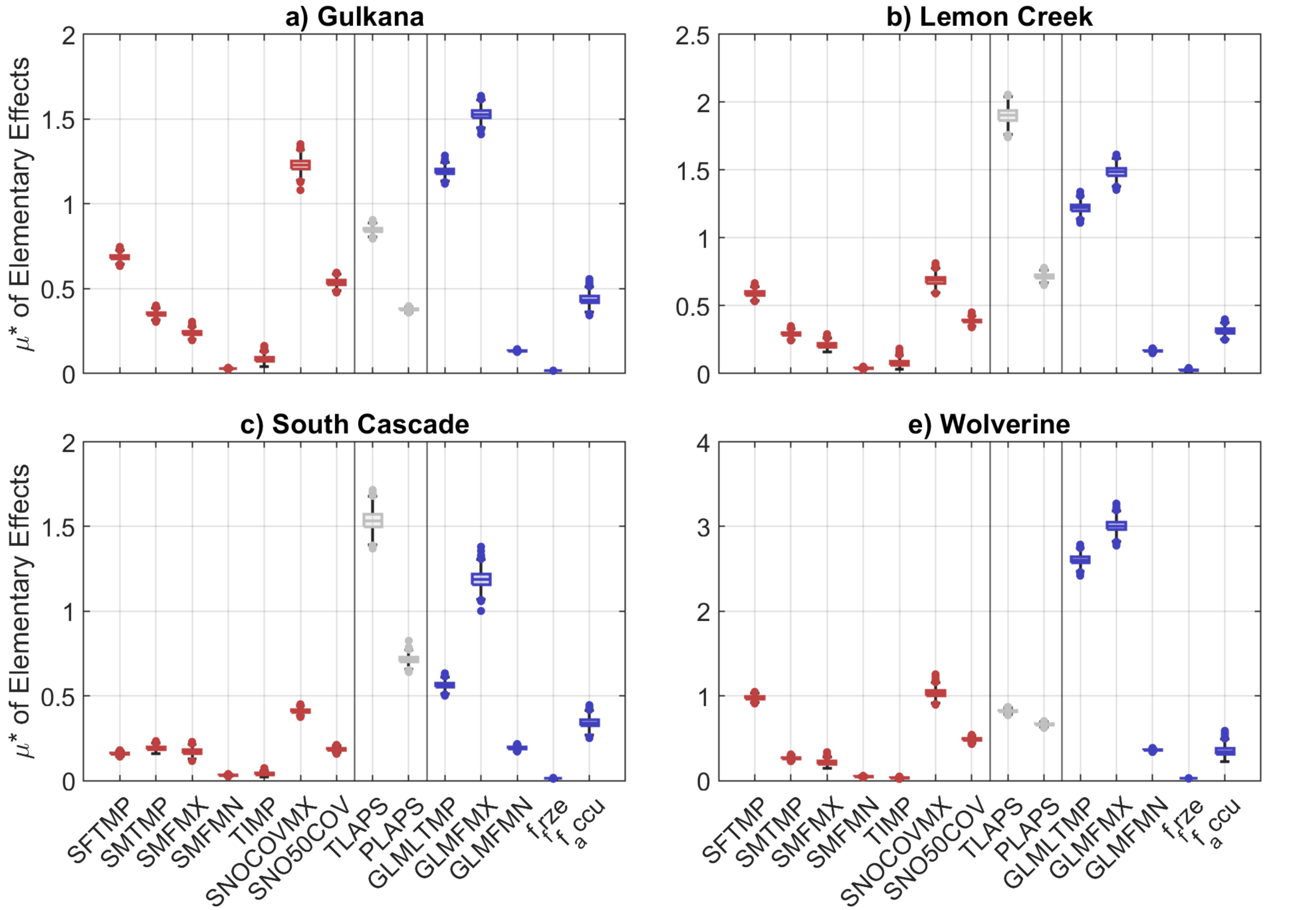
- Tendency of too high accumulation in last N
  Reason: the strong accumulation subperiod in calibration phase 1
- Generally catches instationary conditions (T increase)
- Kind of overfitting in calibration phases & underestimation of ablation in validation
- Last N contains extreme summer SC drops

South Cascade

- End Boss
- Huge troubles with SC's instationarities
- Troubles with SC's "post"-melt events (SC drop)
- Solutions with stronger melt tend to substantially overestimate ablation at simulation start

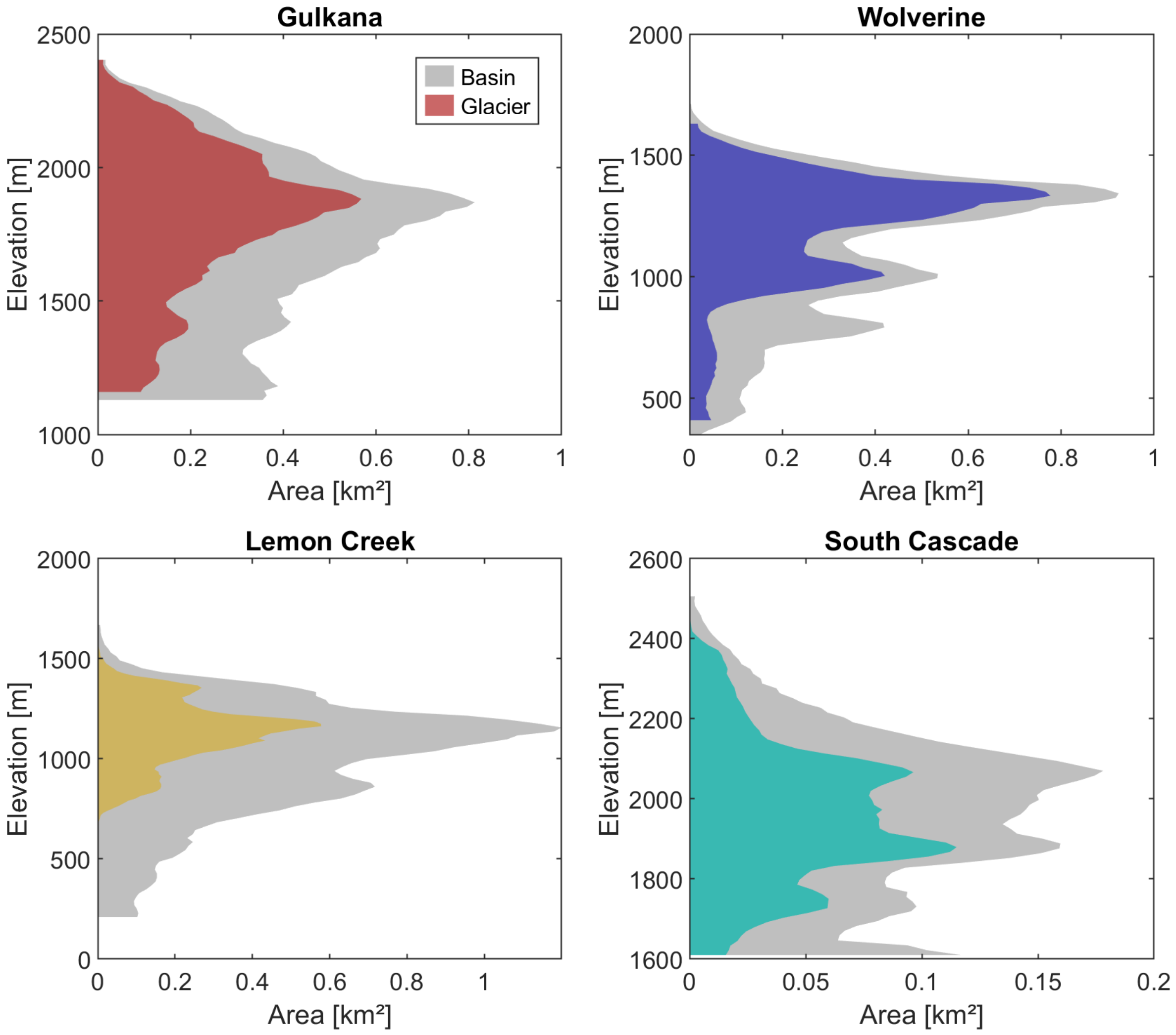


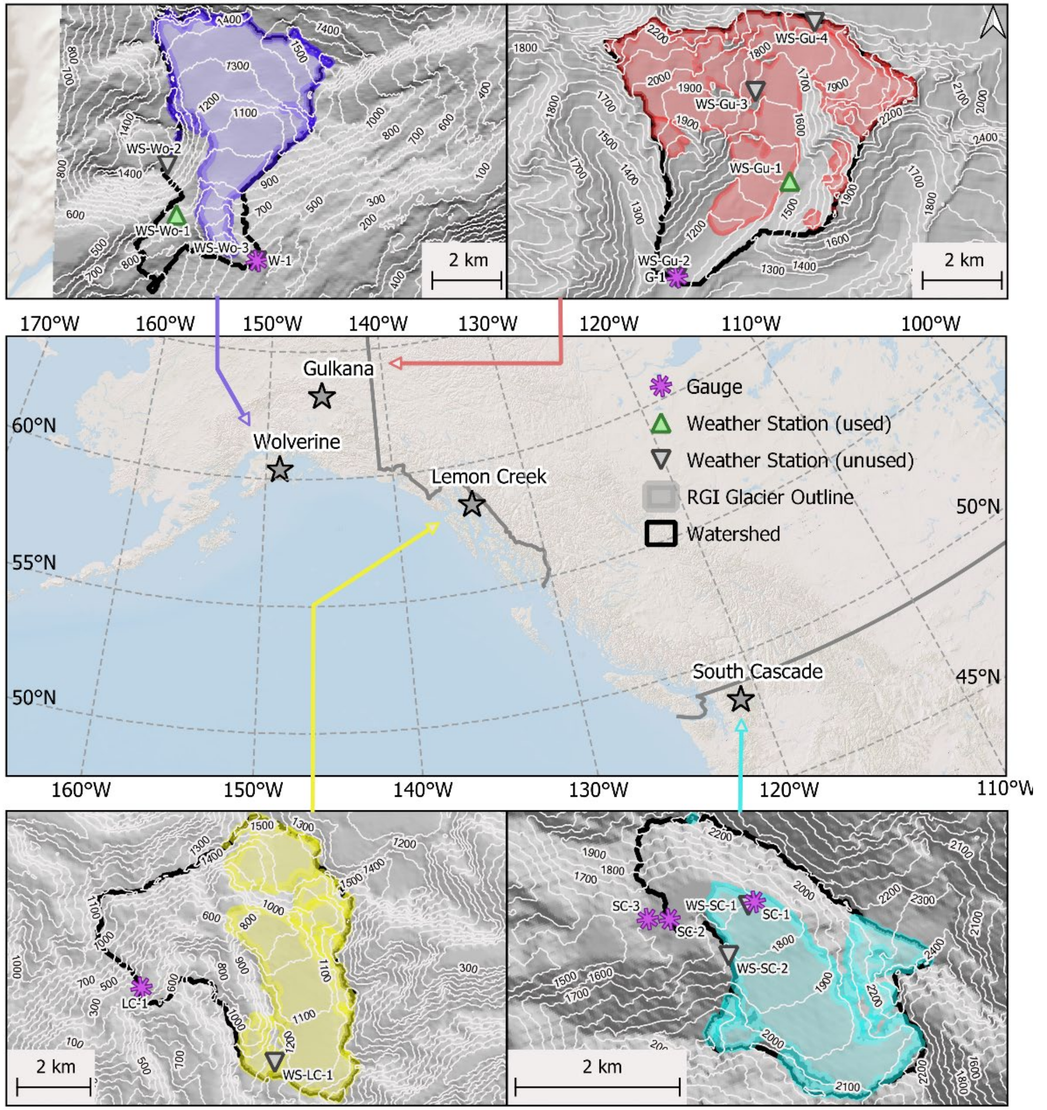
a) Gulkana
b) Lemon Creek
c) South Cascade
e) Wolverine
σ of Elementary Effects
μ* of Elementary Effects
non-linear
almost monotonous
monotonous
linear
SFTMP
SMTMP
SMFMX
SMFMN
TIMP
SNOCOVMX
SNO50COV
TLAPS
PLAPS
GLMLTMP
GLMFMX
GLMFMN
f_frze
f_accu



a) Gulkana
b) Lemon Creek
c) South Cascade
e) Wolverine
μ* of Elementary Effects
0
0.5
1
1.5
2
2.5
3
4
SFTMP
SMTMP
SMFMX
SMFMN
TIMP
SNOCOVMX
SNO50COV
TLAPS
PLAPS
GLMLTMP
GLMFMX
GLMFMN
f_frze
f_accu

USGS Glacier Benchmark Project



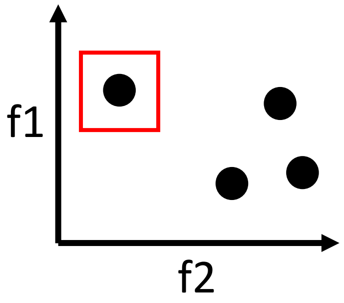


Excursus: NSGA-II

NSGA-II:

Non-dominated Sorting Genetic Algorithm

- Evolutionary Algorithm -> MOEA (Multi-objective Evolutionary Algorithm)
- Elitism, fast & no sharing parameter required
  - Elitism = preservation of best solutions (at least for crossover)
- Diversity preservation (via CD)
- Crossover: SBC – Simulated Binary Crossover
- Mutation: Polynomial
- Crowding Distance:



Initialization

Repetitive

Steps:

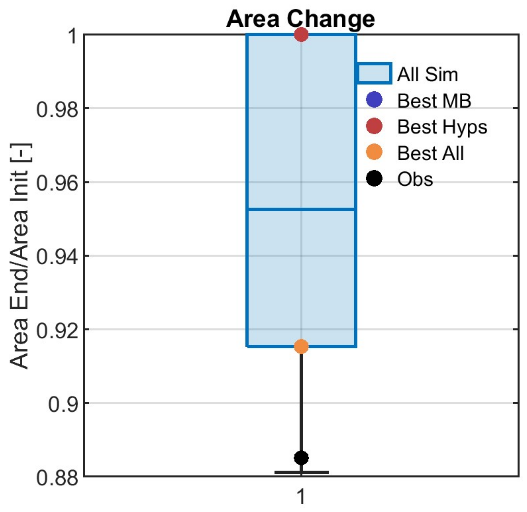
1. Initialization of Parent Solution (N)
2. Non-domination Sorting
3. Crowding Distance (CD) (Diversity Preservation)
4. Tournament Selection
5. Crossover & Mutation
   Create Offspring & Evaluate
6. Non-domination Sorting
   Offspring & Parent
7. CD
8. Select Parent for New Generation

Non-domination: A solution is superior in <u>all</u> performance criteria than another solution

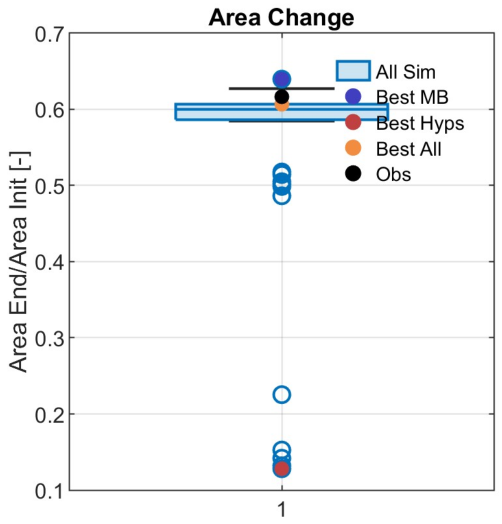
Preliminary Optimization Results – WG & SCG Hypsometry

What about Areal Changes?

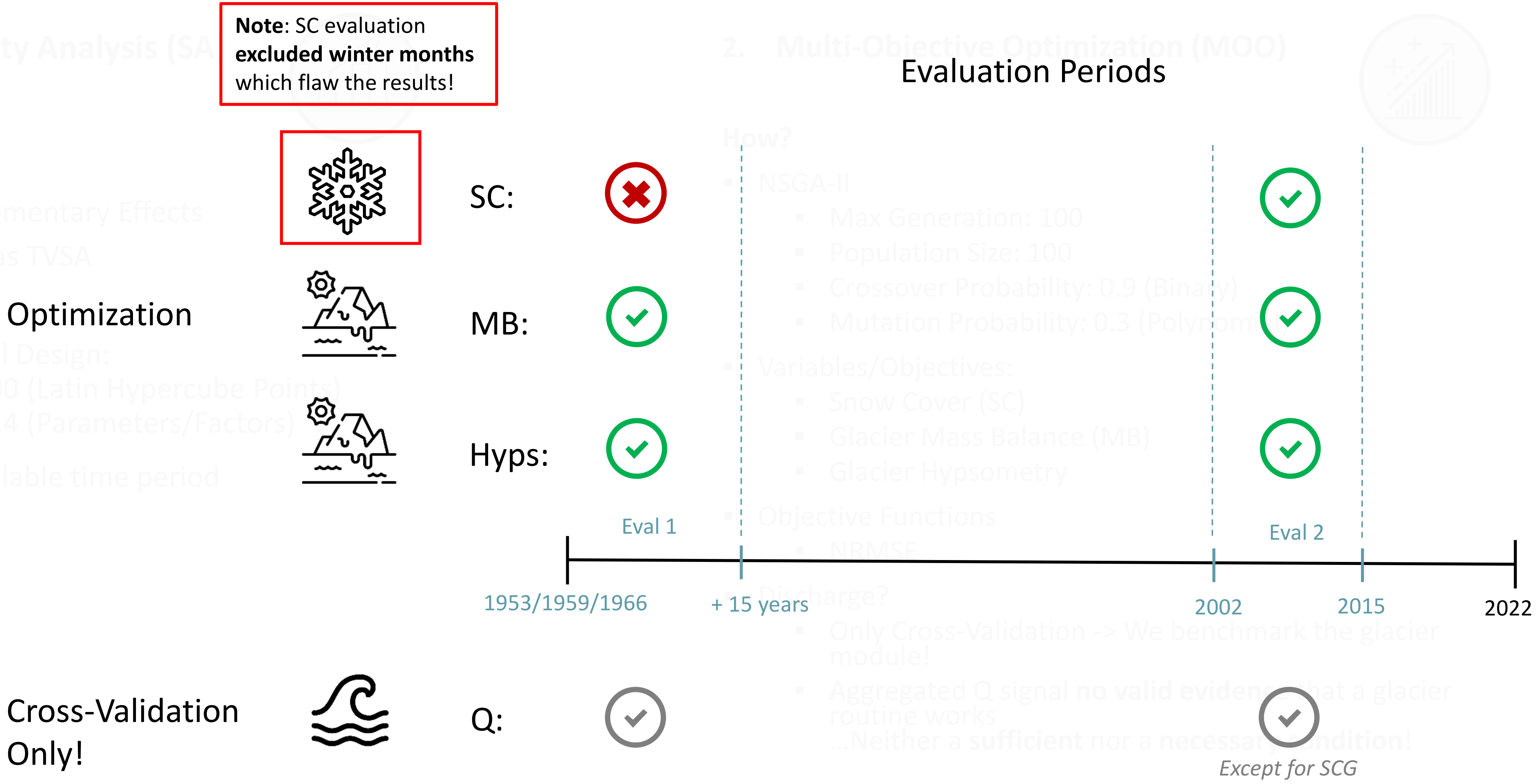
Wolverine



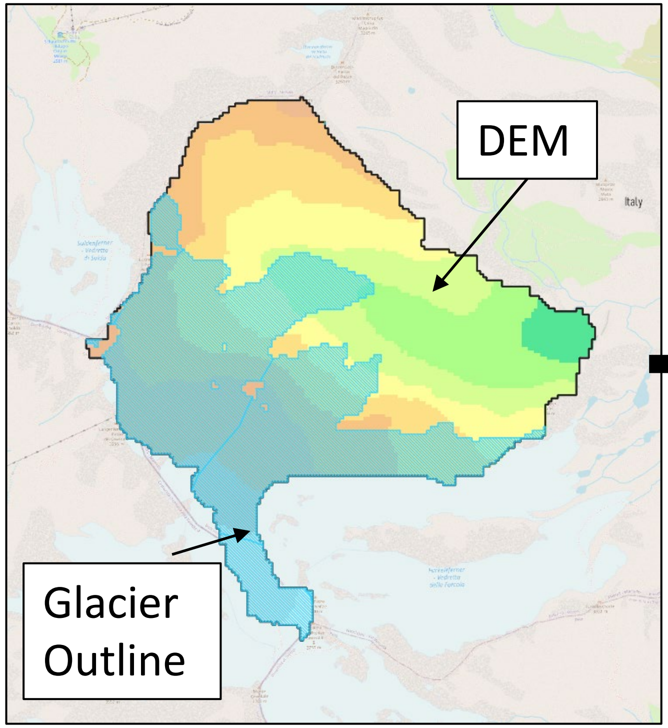
South Cascade



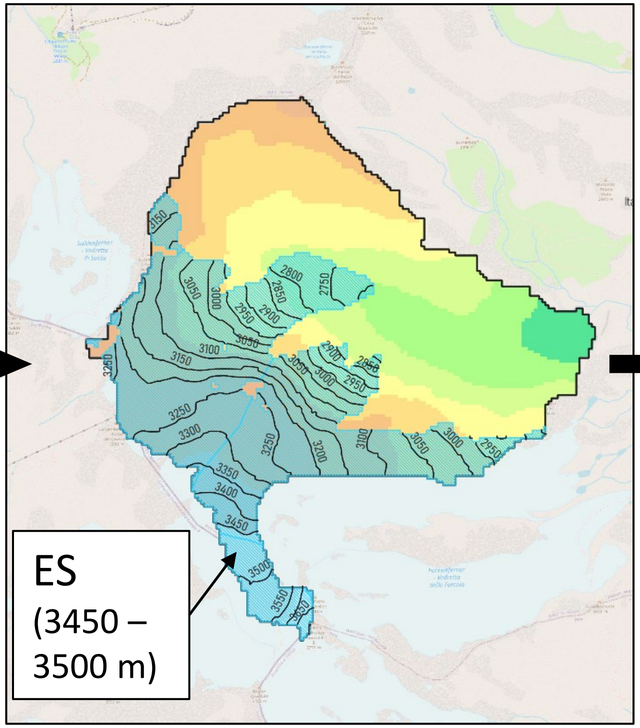
Benchmarking SWAT-GL: Methodology



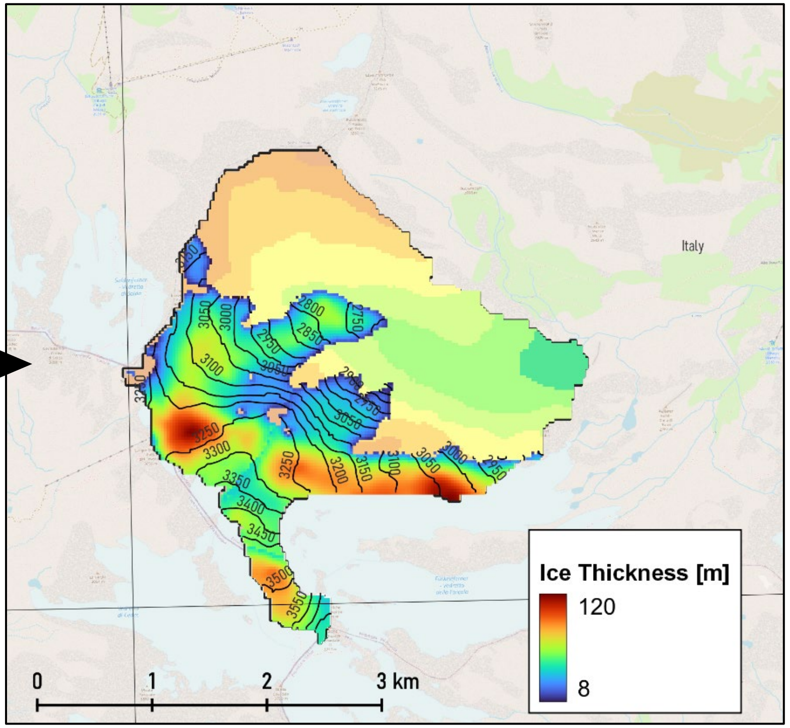
SWAT-GL: Requirements & Application



- Define ES spacing: 50 m



- Results in 20 ES
  2700 m – 3700 m

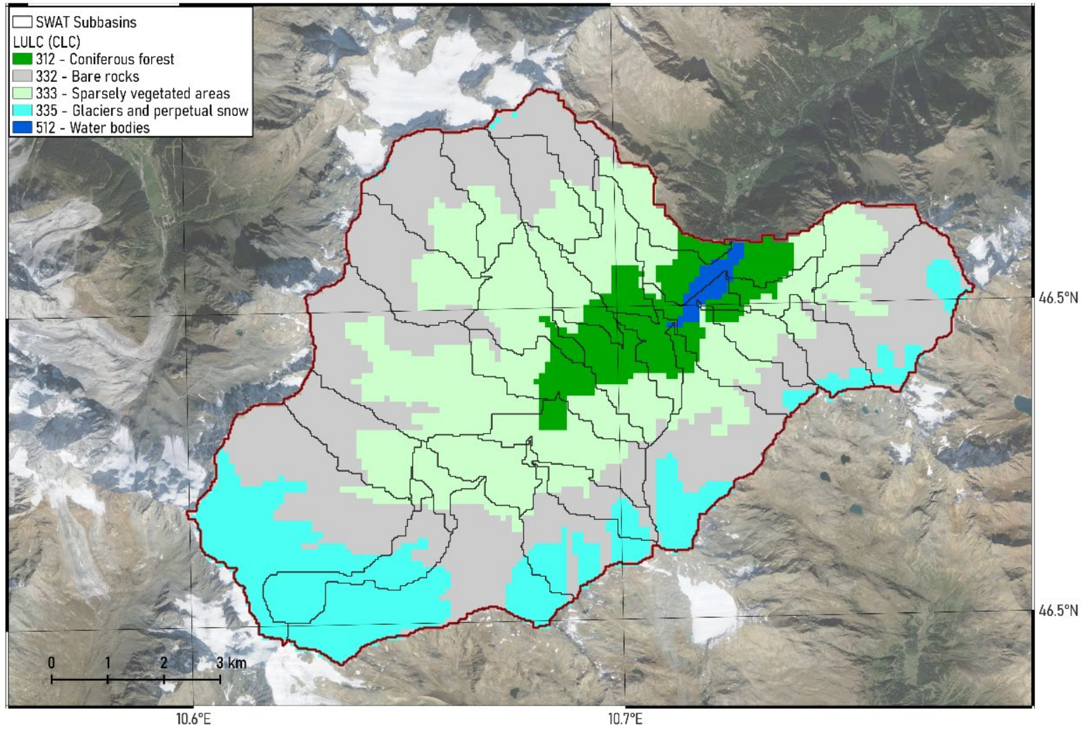


- Extract ice thickness & glacier area for each ES

Note:
Glacier Initialization on the subbasin scale

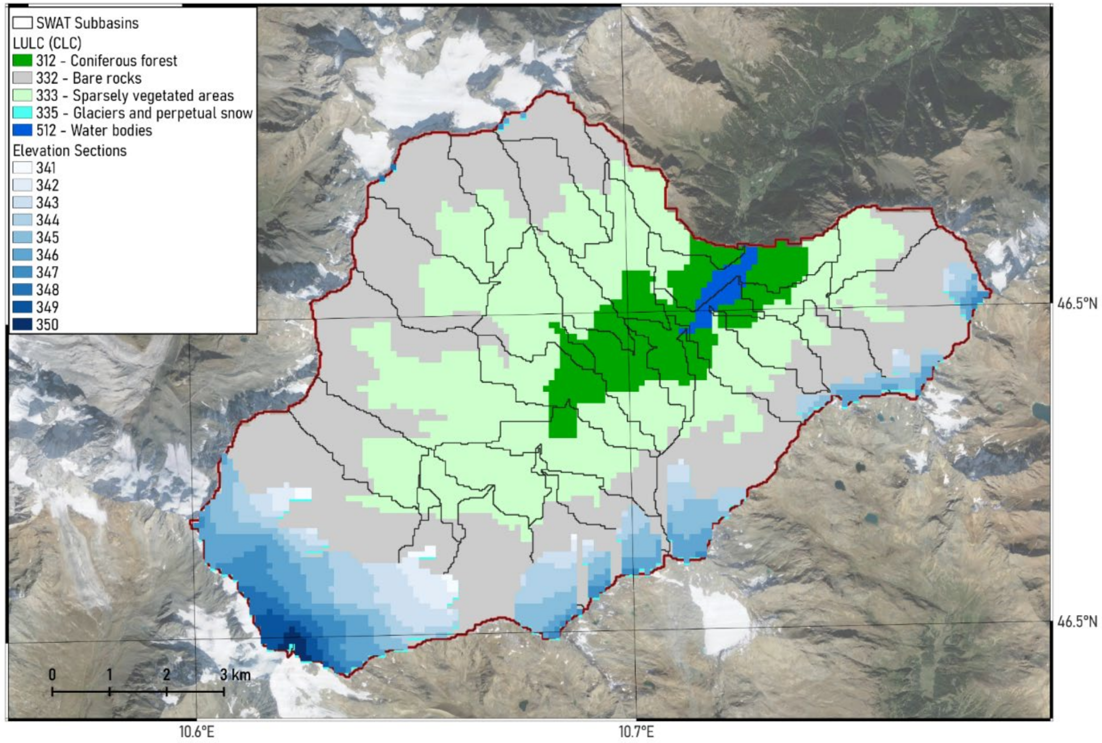
Preprocessing: Land Use Modification

Status Quo



Standard Land Use Map

What we Need

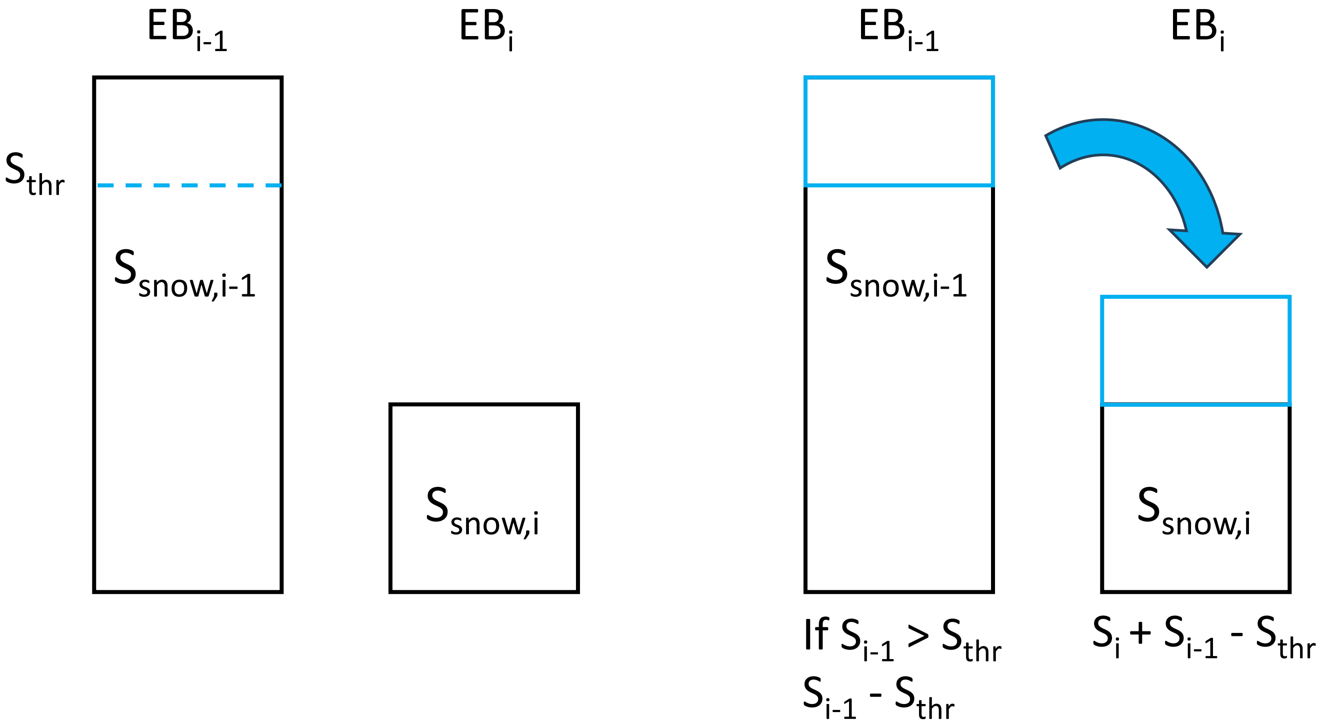


Modified Land Use Map
Considering N Sections of Glacier Elevation
= Elevation Sections

What Did We Do So Far?

Done

- Expansion of SWAT Standard Degree-Day Model:
  - Wet Degree-Day Model
  - Temperature-Index after *Hock et al. 1999* (HTI)
  - Enhanced Tem.-Ind. after *Pelicciotti et al. 2017* (ETI)
- Snow Redistribution



Mass Balance Components: Melt

$$EW_t = EW_{t-1} - M_t \cdot (1 - \beta_f) - S_t + C_t$$

$$M_t = \begin{cases} (T_{mx,t} - T_{gmlt}) \cdot b_{gmlt}, & if\ T_{mx,t} > T_{gmlt}\ and\ A_{sc} < A_{gc} \\ 0, & if\ T_{mx,t} \leq T_{gmlt}\ or\ A_{sc} \leq A_{gc} \end{cases}$$

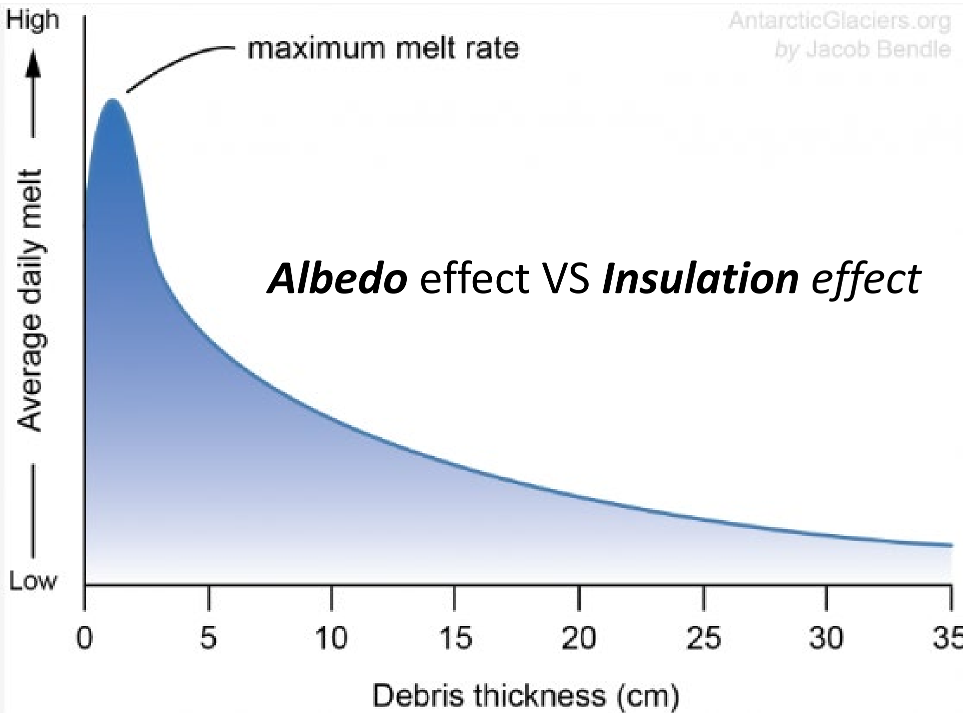
Tmx:	*Max. Daily Temp. [°C]*
Tgmlt:	*Threshold Temp of Glacier Melt [°C]*
bgmlt:	*Ice Melt Factor [mm/(d*°C)]*
Asc:	*Snow Cover Fraction of Subbasin [-]*
Agc:	*Glaciated Fraction of Subbasin [-]*

$$b_{gmlt} = \frac{(b_{gmlt,mx} + b_{gmlt,mn})}{2} + \frac{(b_{gmlt,mx} - b_{gmlt,mn})}{2} \cdot \sin\left[\frac{2\pi}{365}(t - 81)\right]$$

bgmlt,mx:	*Melt factor June 21 [mm/(d*C°)]*
bgmlt,mn:	*Melt factor December 21 [mm/(d*C°)]*
T:	*Day of year [-]*

- **Degree-Day Approach**
- Occurs when **HRU snow-free** & $\boldsymbol{T_{gmlt}}$ **exceeded**
- **Snow cover (SC)** & **Glacier cover (GC)** comparison
  - E.g.: 70% SC and 80% GC
  - 10% of glacier area can generate melt
- **Albedo** of ice < albedo of snow
  - Thus: $b_{gmlt} > b_{smlt}$
  - If $b_{gmlt} < b_{smlt}$ then $b_{gmlt} = b_{smlt}$
- **Refreezing factor β_f** to control high melt rates
  - 0-30% of glacier melt able to refreeze

What Comes Next – Snow & Glacier?



Albedo effect VS ***Insulation*** *effect*

Reference: https://www.antarcticglaciers.org/glacier-processes/mass-balance/the-role-of-debris-cover-on-glacier-ablation/

Melt Factor Adjustment Example:

$$\delta_d = \delta_i \cdot e^{-0.0572 \cdot H_d}$$

What Comes Next – Snow & Glacier?

Done

- Expansion of SWAT Standard Degree-Day Model:
  - Wet Degree-Day Model
  - Degree-Day with Radiation Term
  - „Classical“ Degree-Day
- Snow Redistribution

To be done

- Glacier Melt Lag
- Debris Cover
- New PLAPS

SWAT/SWAT+ PLAPS

$$R_{band} = R_{day} + (EL_{band} - EL_{gage}) \cdot \frac{plaps}{days_{pcp,yr} \cdot 1000} \quad \text{when } R_{day} > 0.01$$

PLAPS = fixed in time

Alternatives

- *Immerzeel et al. 2012*

➔ Correction by two linear functions for dZ & dL

- *Wortmann et al. 2016*

➔ Exponential function based with max. correction & decrease at high altitudes

- Monthly varying PLAPS
- Glaciological Half Year varying PLAPS

What Comes Next – Snow & Glacier?

Done

- Expansion of SWAT Standard Degree-Day Model:
  - Wet Degree-Day Model
  - Degree-Day with Radiation Term
  - „Classical“ Degree-Day
- Snow Redistribution

To be done

- Glacier Melt Lag
- Debris Cover
- New PLAPS
- SC

SWAT-GL: Methodology

1. Sensitivity Analysis (SA)

How?

- Morris/ Elementary Effects
  - Also as TVSA (time-varying per variable)
- Sampling:
  - Radial Design:
    r = 500 (Latin Hypercube Points)
    M = 14 (Parameters/Factors)
- Whole available time period

2. Multi-Objective Optimization (MOO)

How?

- NSGA-II
  - Max Generation: 100
  - Population Size: 100
  - Crossover Probability: 0.9 (Binary)
  - Mutation Probability: 0.3 (Polynomial)
- Variables/Objectives:
  - Snow Cover (SC)
  - Glacier Mass Balance (MB)
  - Glacier Hypsometry
- Objective Functions:
  - NRMSE