Detection and Explanation of Shifts in the Climatic Controls of Norwegian Glaciers

An Empirical-Statistical Approach

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With the support of the Erasmus+ Programme of the European Union

Okstindbreen Glacier
Image credits: Visit Norway

01 Introduction

Background

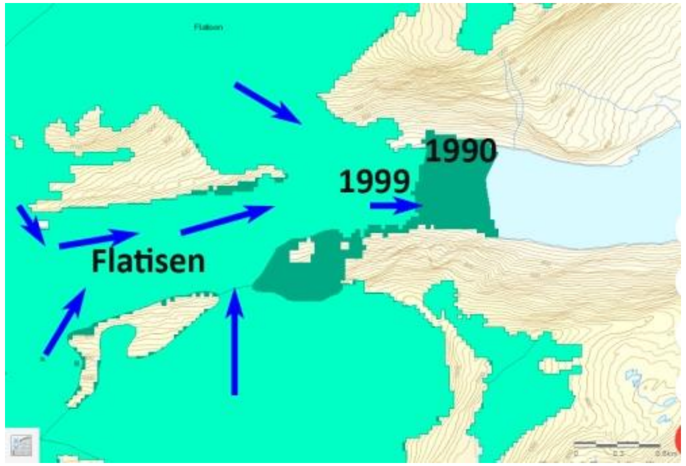
- Norway– largest share of ice-covered land in mainland Europe. [1]
- Glaciers occupy ~0.8–0.9 % (mainland Norway) ≈ to 2,692 ± 81 km^2 (±3 % uncertainty). [2, 3]
- 2,534 glaciers have been identified in the latest inventories. [3]
- Proportionately high glacier coverage than rest of Europe. [4, 5]
- Substantial economic potential: hydroelectric power generation ~92% of the total power production in April 2025. [6]

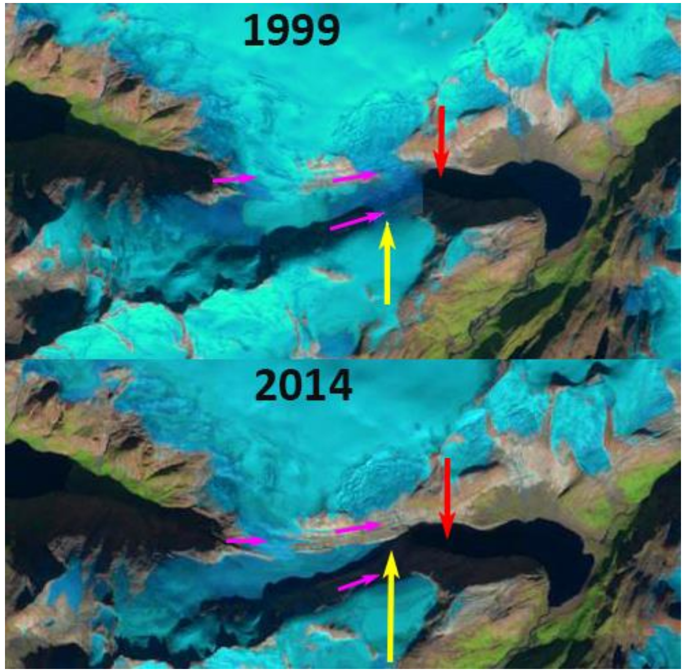
Austdalsbreen on 31 August 2023.
Picture source: Hallgeir Elvehøy

Impacts of Glacier Mass Loss

- 27 ± 22 mm global mean sea-level rise (1961–2016). Glaciers in Scandinavia contributed to SLR by +0.47 ± 0.23 m w.e. [7]

- Severe consequences for river runoff, water temperature, sediment transport regimes, etc. [8]

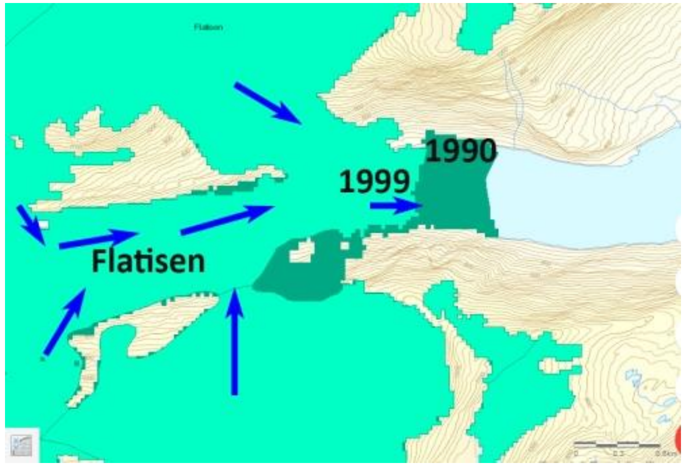


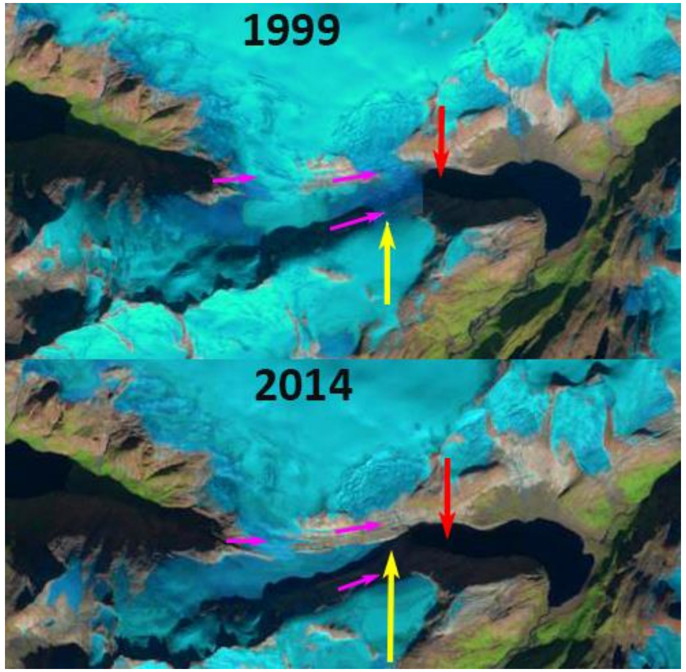


Flatisen Glacier, Norway (1999 vs 2014)
Figure credits: Prof. Mauri Pelto

Impacts of Glacier Mass Loss

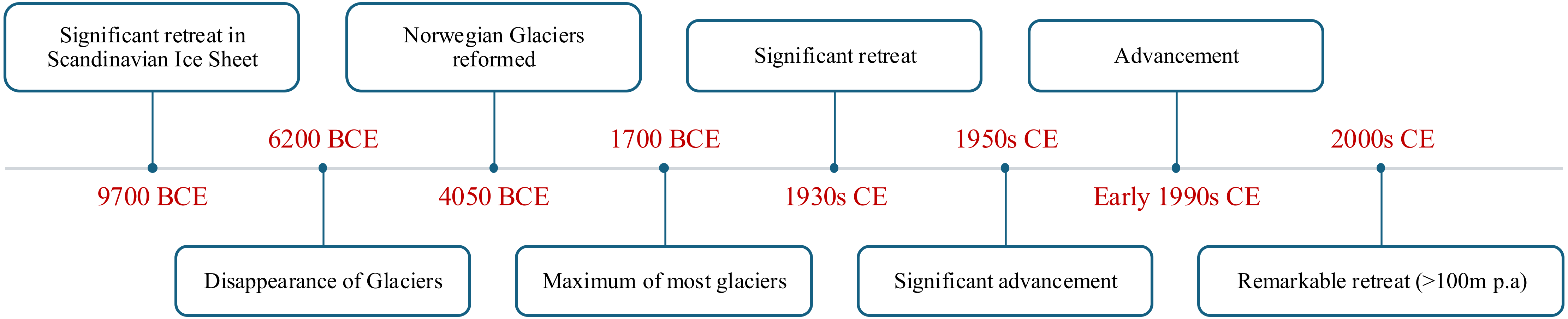
- 27 ± 22 mm global mean sea-level rise (1961–2016). Glaciers in Scandinavia contributed to SLR by +0.47 ± 0.23 m w.e. [7]
- Severe consequences for river runoff, water temperature, sediment transport regimes, etc. [8]
- Sudden outburst floods (jökulhlaups) due to destabilization of ice or glacio-fluvially dammed water bodies. Example: Søndre Folgefonna in 2002 & at Flatbreen in Fjærland in 2004. [8]
- Meltwater can be a potential source of anthropogenic contaminants like POPs, black carbon, trace elements, etc. [8, 9, 10]





Flatisen Glacier, Norway (1999 vs 2014)
Figure credits: Prof. Mauri Pelto

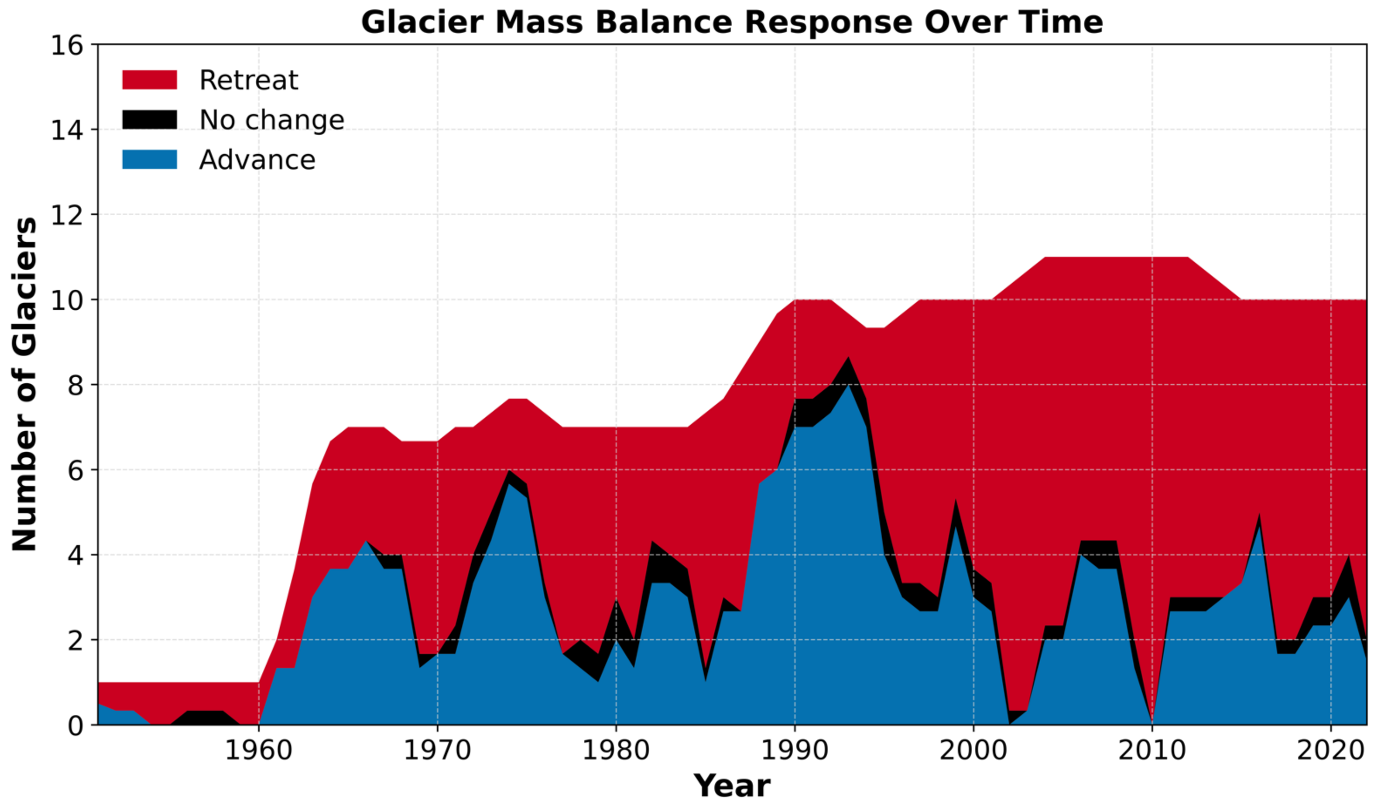
Historical Context



- A ‘regime shift’ has been reported; all Norwegian glaciers exhibiting remarkable mass-balance deficits.[11, 12]
- This shift–most negative mass balance period on record due to accelerated retreat rates, driven by increased summer temperatures. [13]

Hypothesis

A Regime Shift in the Climatic Controls on Norwegian Glaciers in 2000…?

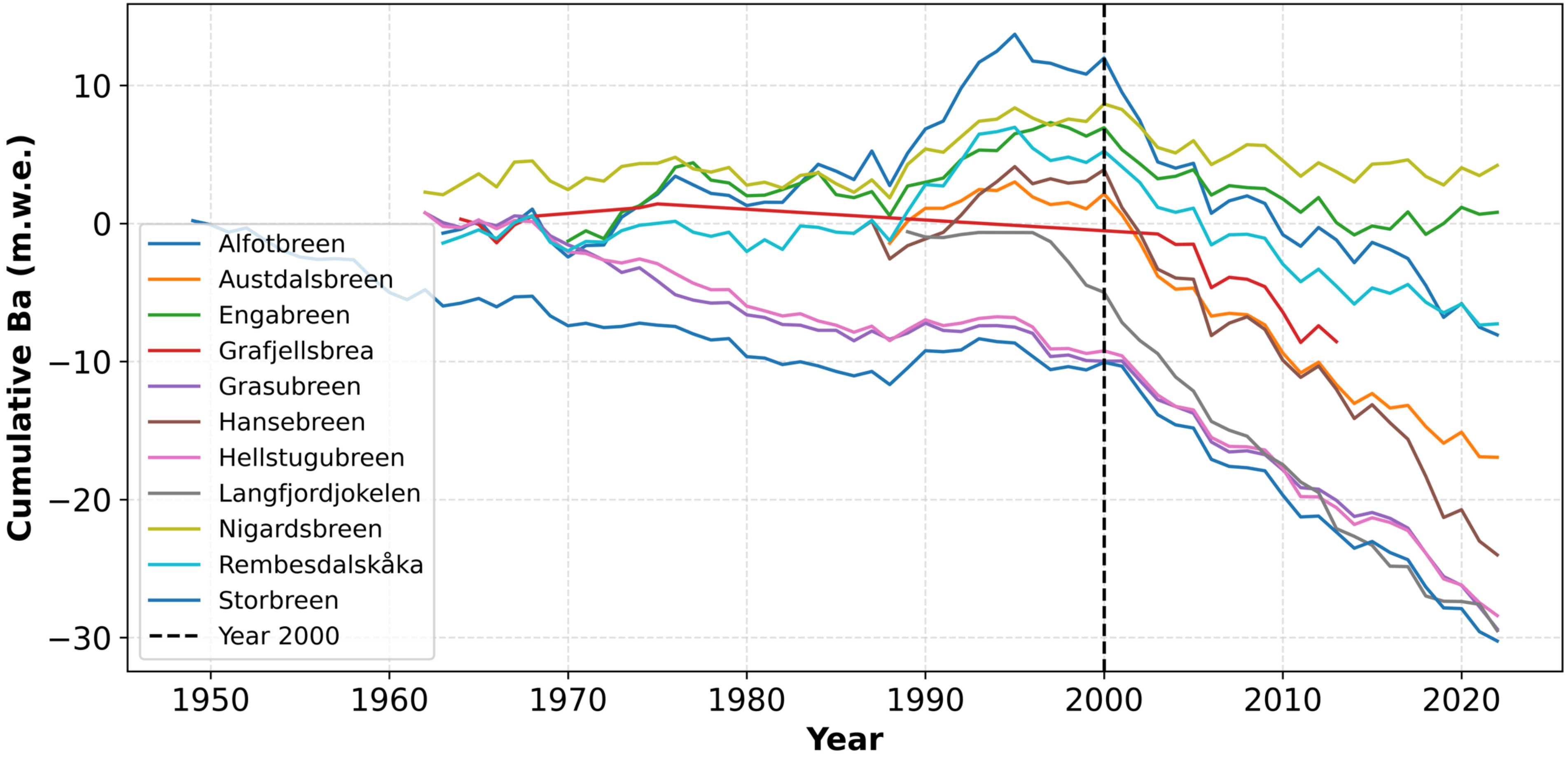


- Stacked area plot showing the response of Norwegian glaciers between 1950 and 2023.
- Glaciers are categorized as:
  - Advance (blue): *ba* > +0.05 m w.e.
  - No change (black): -0.05 ≤ *ba* ≤ +0.05 m w.e.
  - Retreat (red): *ba* < -0.05 m w.e.
- Distinct advance phases in the early 1960s, 1970s, and early 1990s.
- Periods of dominant retreat are visible post 2000.

Data Source: NVE

Hypothesis

A Regime Shift in the Climatic Controls on Norwegian Glaciers in 2000…?



Data Source: NVE

Aims

1. Detect & explain regime shifts in glacier–climate relationships (pre-2000 vs post-2000).

&

2. Develop an empirical-statistical model framework for glacier mass balance.

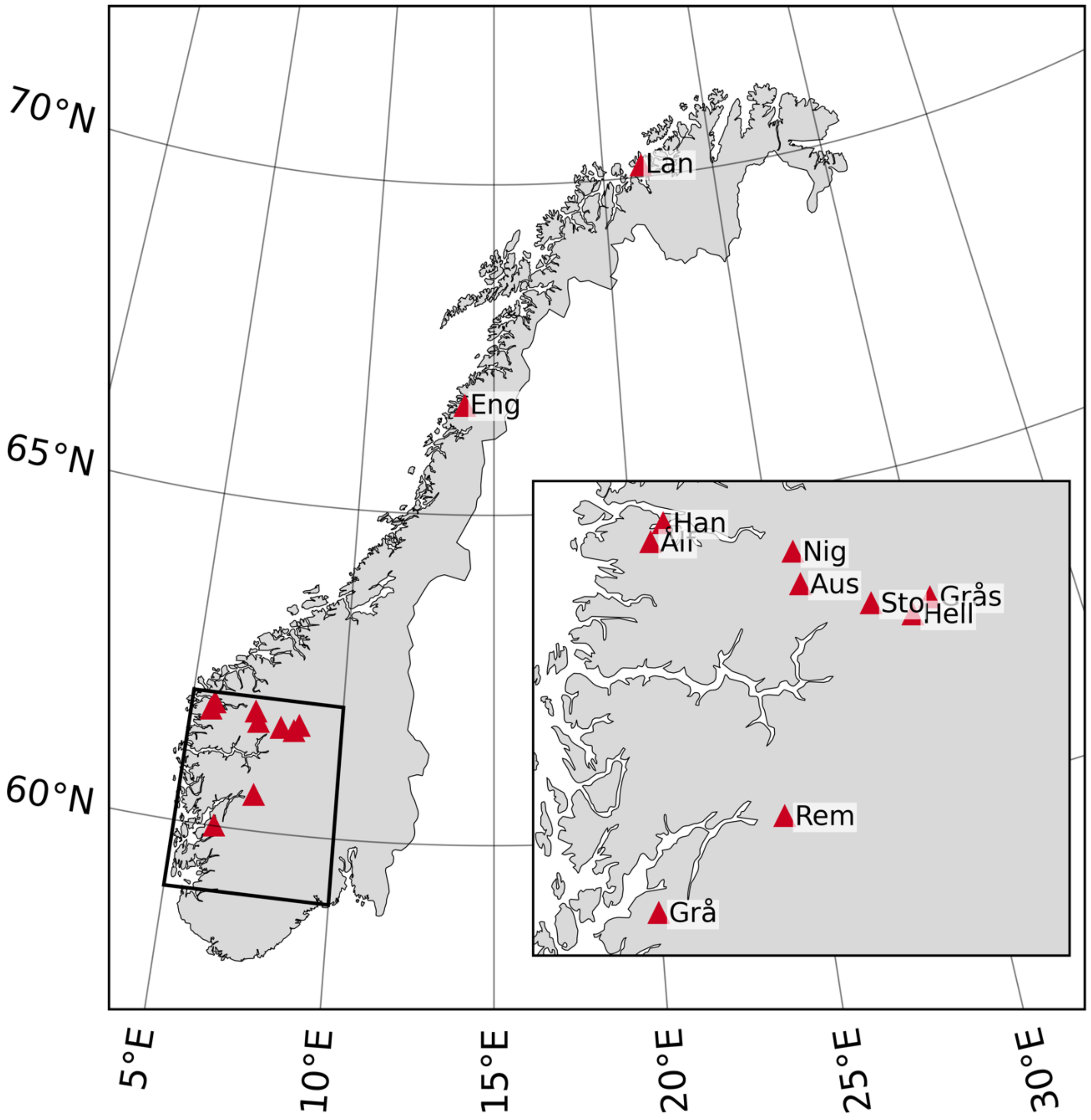
Okstindbreen Glacier
Image credits: Visit Norway

02 Methodology

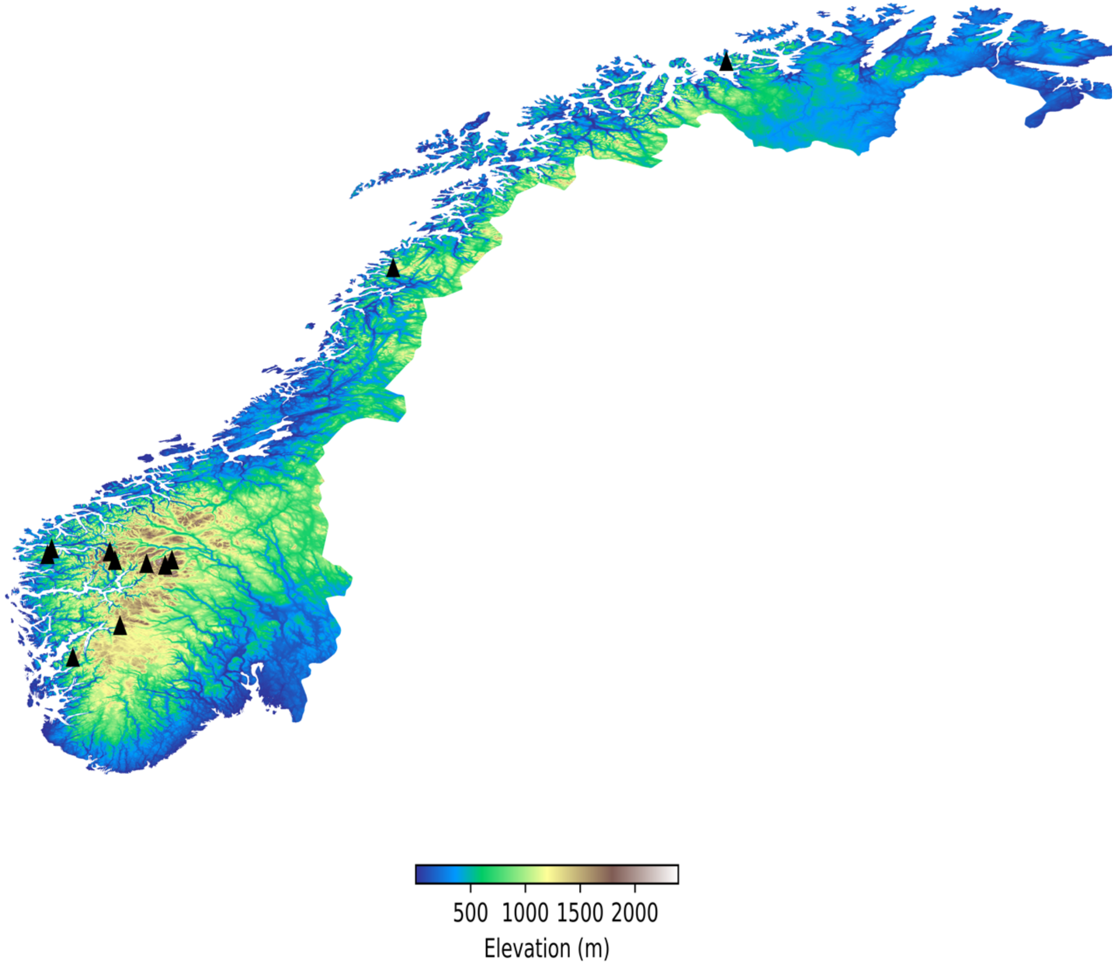
Study Sites

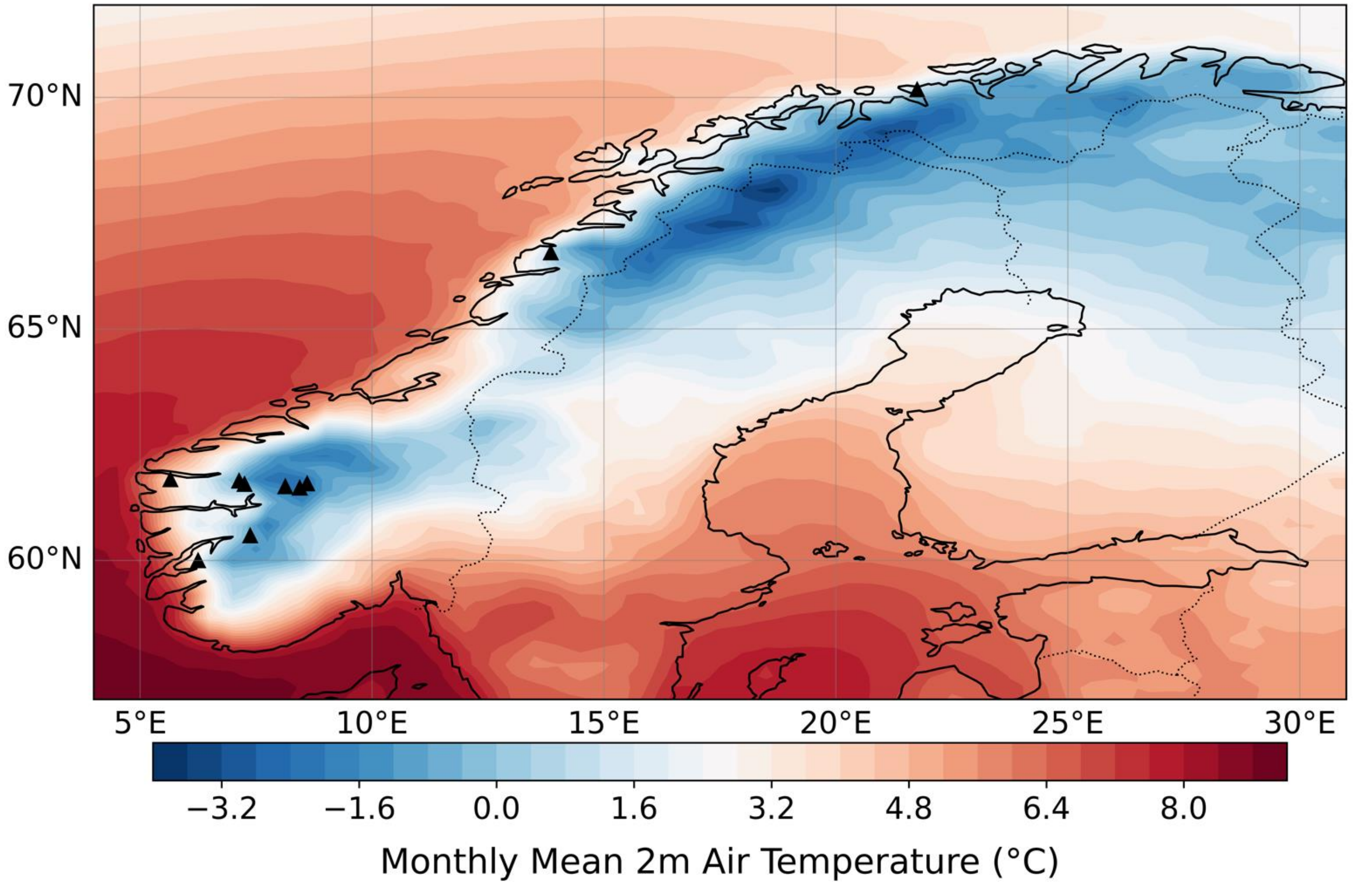
- Ålf- Ålfotbreen *(S)*
- Aus- Austdalsbreen *(S)*
- Eng- Engabreen *(N)*
- Gråf- Gråfjellsbrea *(S)*
- Grås- Gråsubreen *(S)*
- Han- Hansebreen *(S)*
- Hell- Hellstugubreen *(S)*
- Lan- Langfjordjøkelen *(N)*
- Nig- Nigardsbreen *(S)*
- Rem- Rembesdalskåka *(S)*
- Sto- Storbreen *(S)*

N- North, S- South



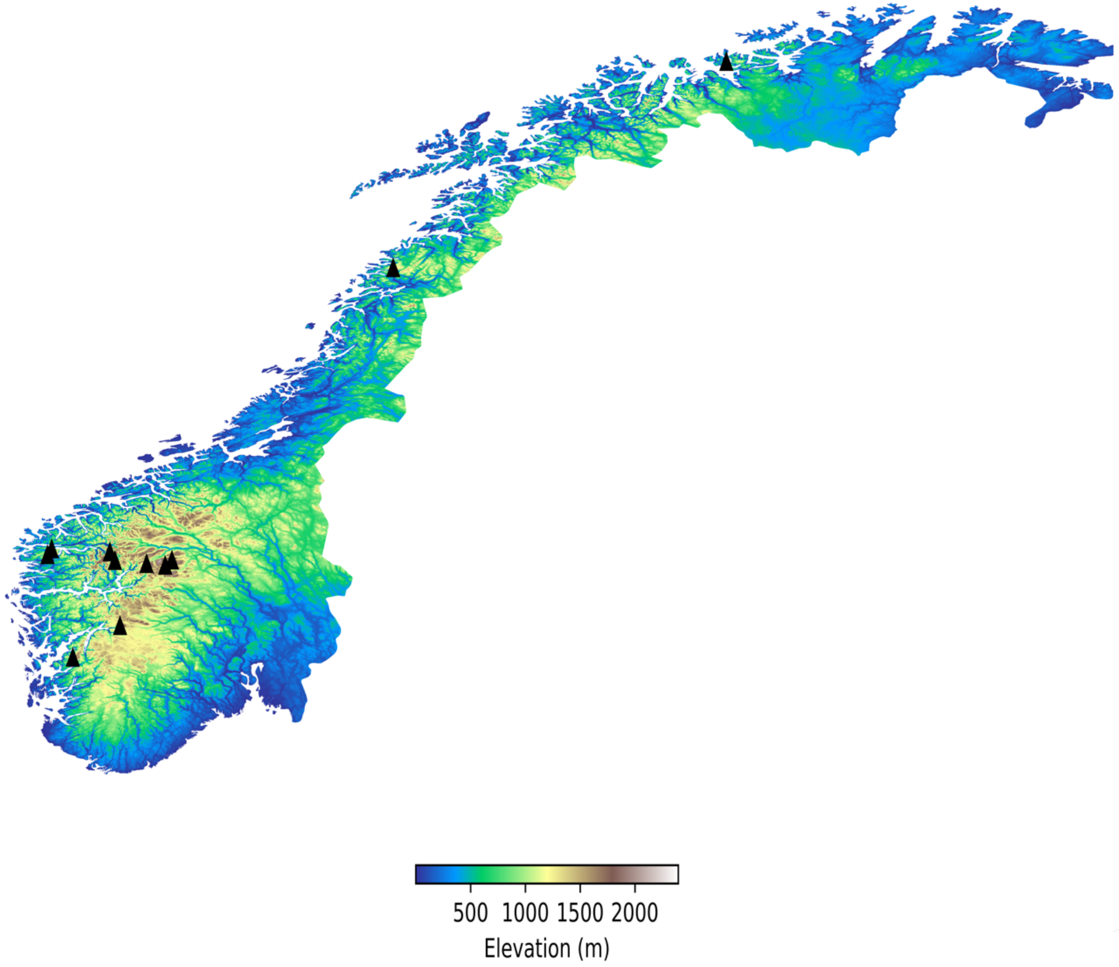
Climatic Context

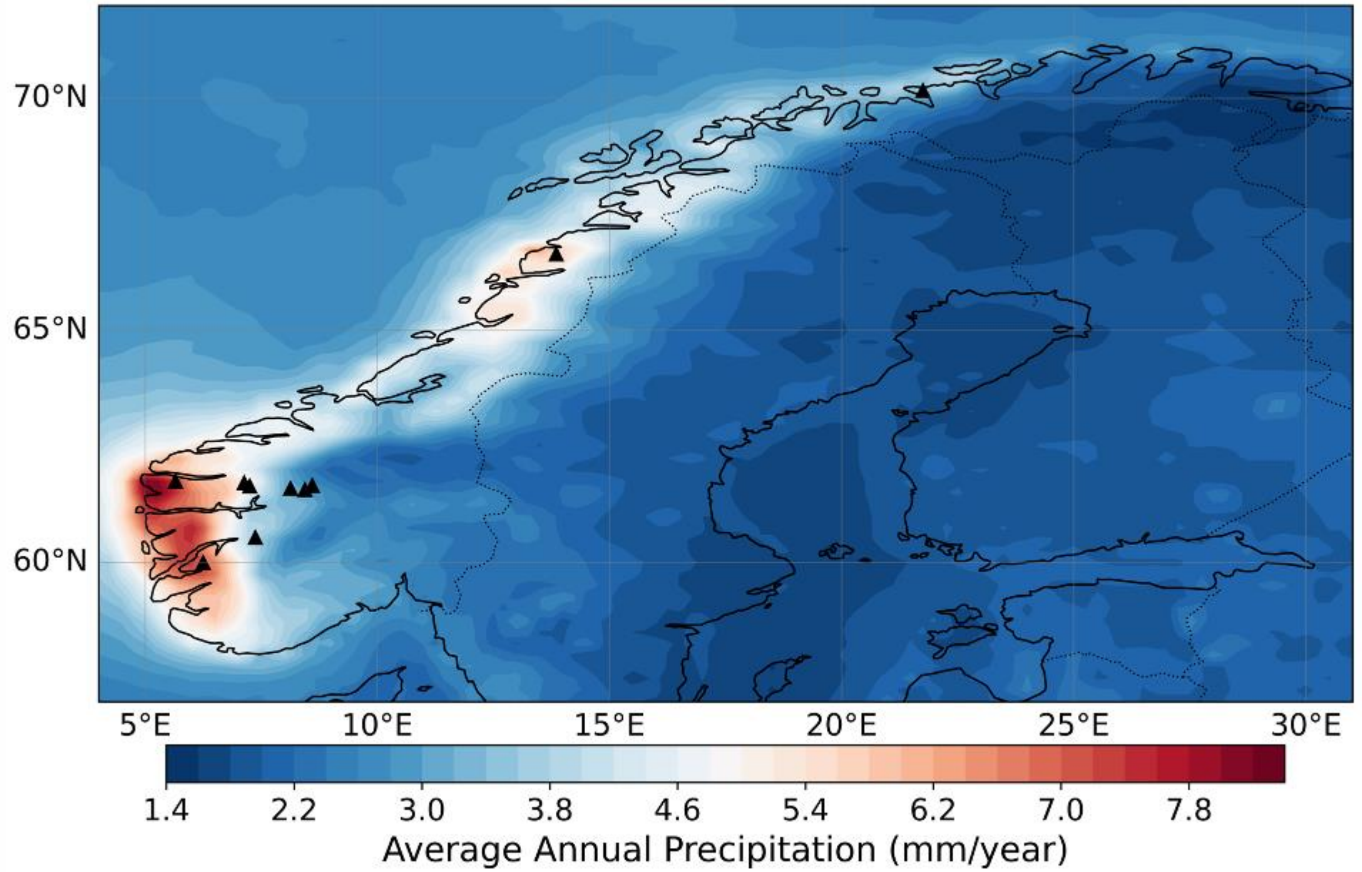




Data Source: ECMWF

Climatic Context





Data Source: ECMWF

Mass Balance ‘Regime’

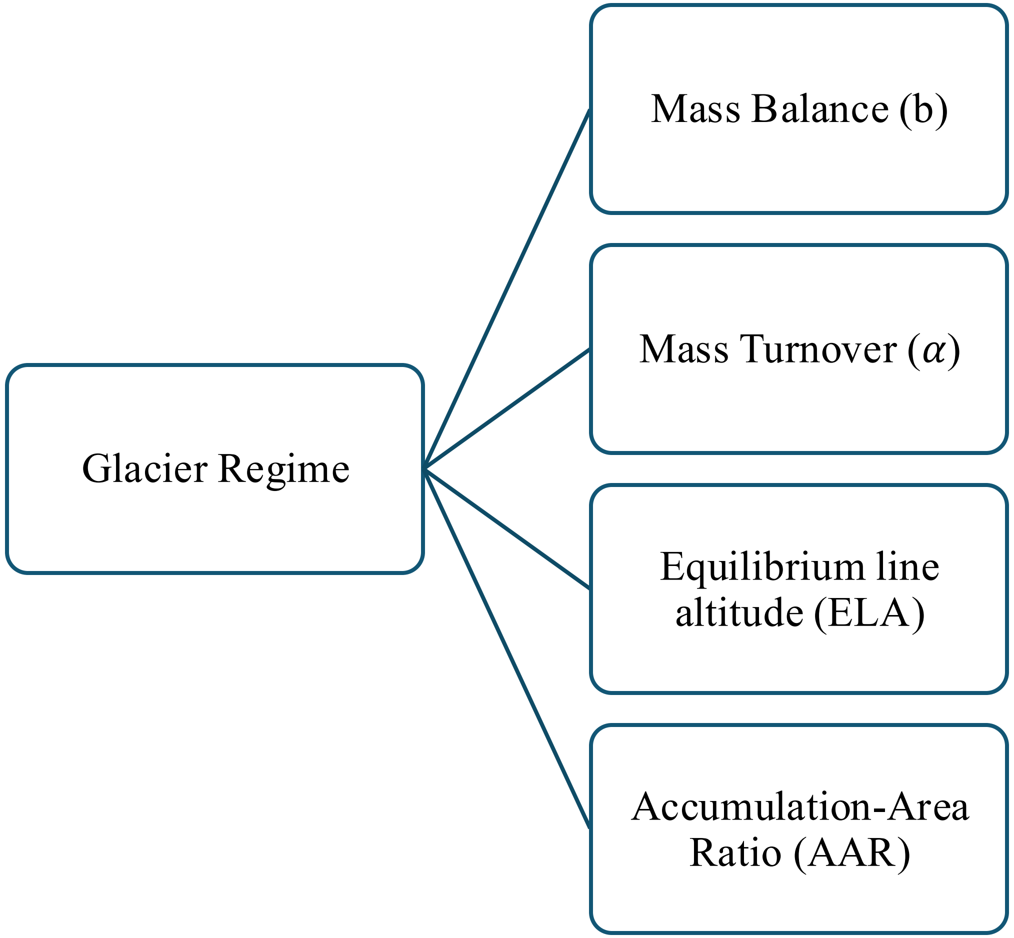
- Mass balance measurements comprise of accumulated snow (winter balance: *bw*) and measurements of snow and ice removed by ablation (summer balance: *bs*). [2, 14]

- The net balance: ***ba* = *bw* + *bs***

- *Generally, bs < 0* and *bw > 0*
  - *ba > 0* if *bw > bs*

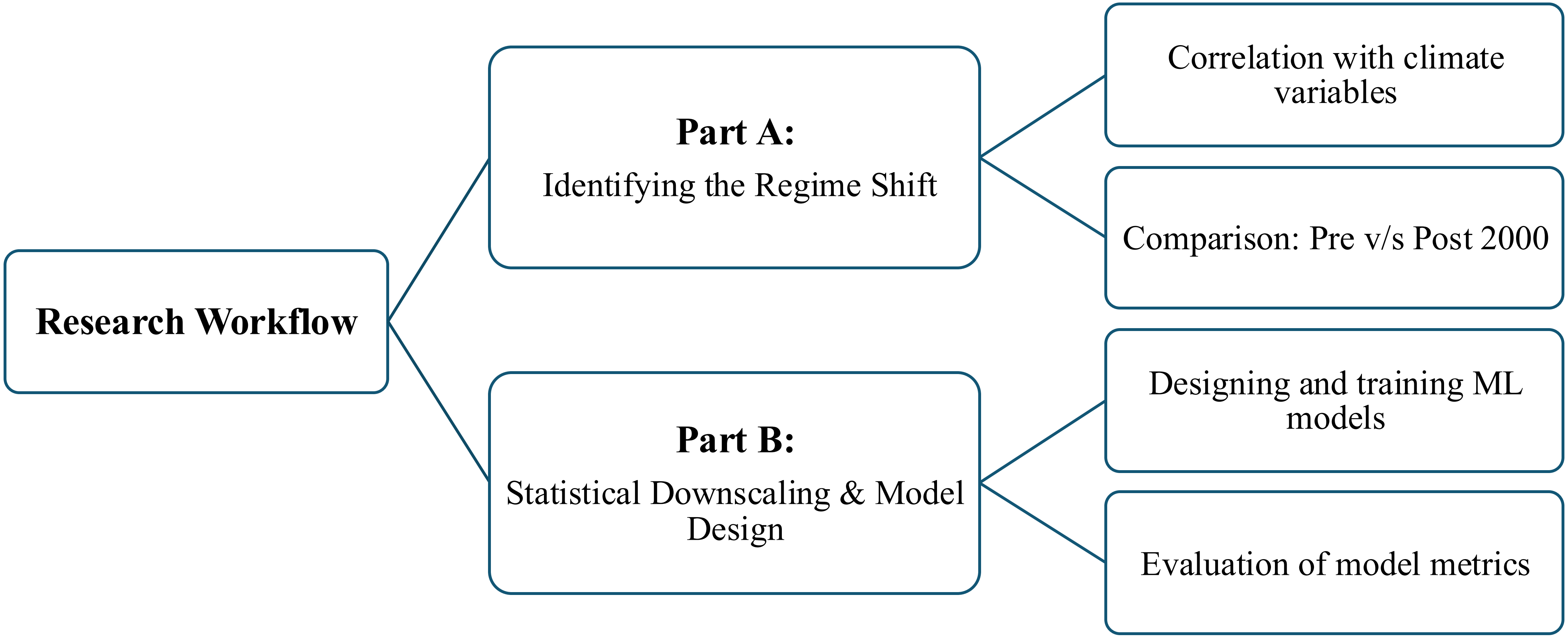
- Unit used: metres water equivalent (m w.e.)

- Glacier loss of 0.5 m w.e. = ice loss equivalent to loss of 50 cm thick sheet of water spread evenly across its surface.



Classification from: M. Dyurgerov (2003)

Methodology Overview



Overview: Part A

Data Extraction → Regional Subsetting → Seasonal Aggregation (DJF/MJJAS) → Period Split (Pre-/Post-2000) → Correlation Testing (Pearson r) → Significance Testing ($p < 0.05$)

Key Climate Drivers: chosen based on known physical relevance to glacier mass balance dynamics:

- 2m Air Temperature *(t2m)*
- Total Precipitation *(tp)*
- 10m Wind Components *(u10, v10)*
- Surface Solar Radiation Downwelling *(ssrd)*
- Large-scale Teleconnections:
  - North Atlantic Oscillation (NAO)
  - Arctic Oscillation (AO)

Analysis Design: correlated climate variables with mass balance components (B_w, B_s, B_a) over two distinct periods:

- Pre-2000 (historical/regime-1)
- Post-2000 (recent/regime-2)

Overview: Part B

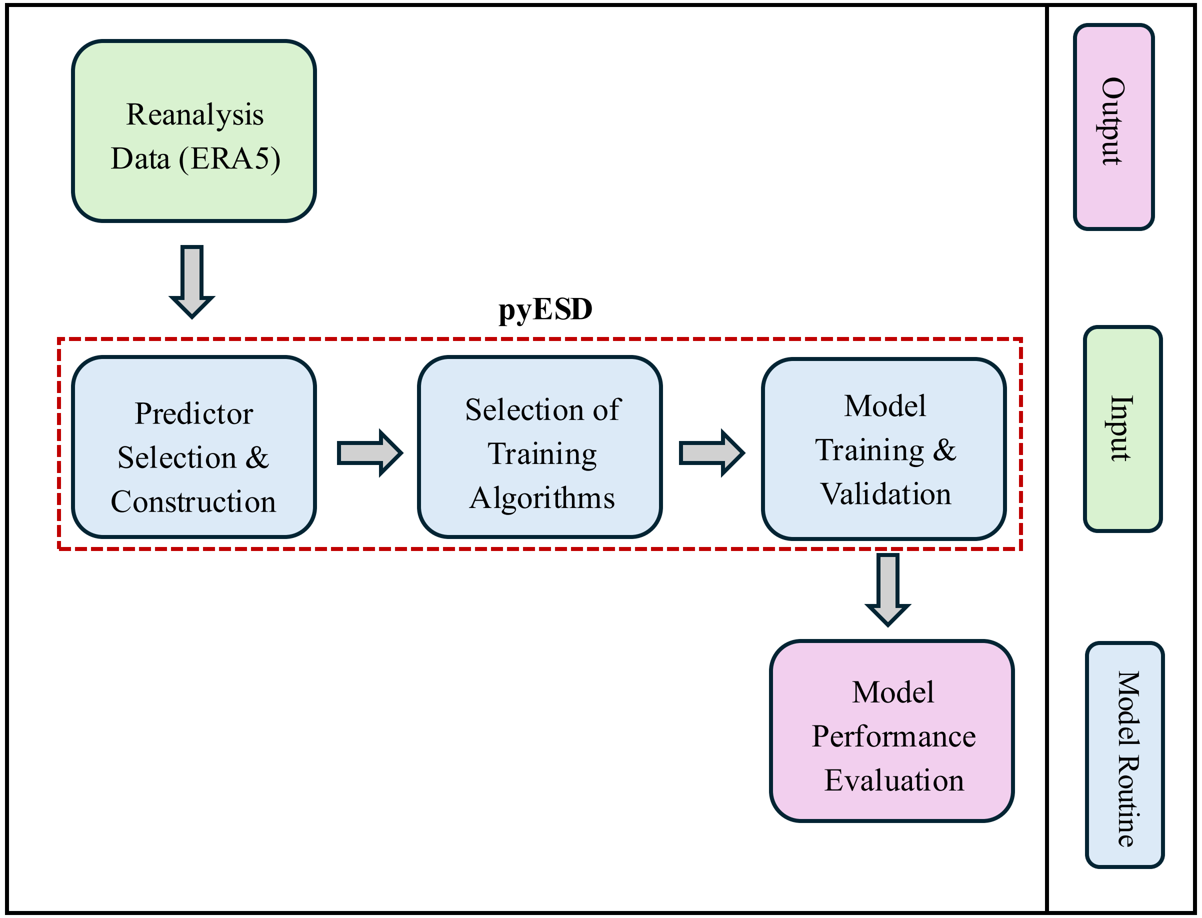
Objective: Develop an empirical-statistical model framework to predict individual mass balance components (B_w, B_s, B_a).

Model Setup:

- Regressors (6):
  - RidgeCV, Bagging, ARD, Random Forest, XGBoost, & Bayesian Ridge.
- Feature Selectors (3):
  - Recursive, Tree-Based, Sequential.

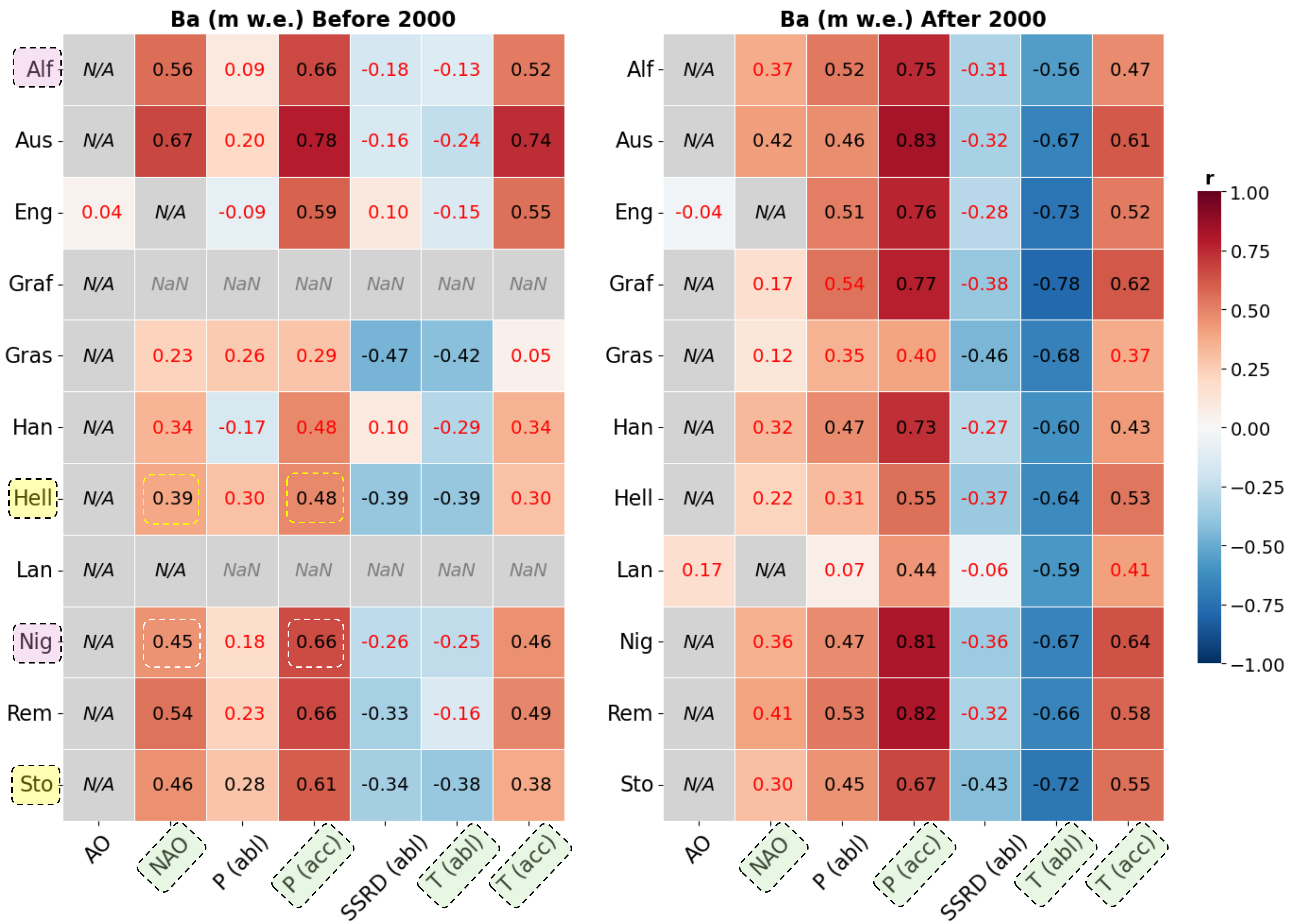
Evaluation Metrics:

- R^2 & RMSE used to assess prediction skill across glaciers and models.

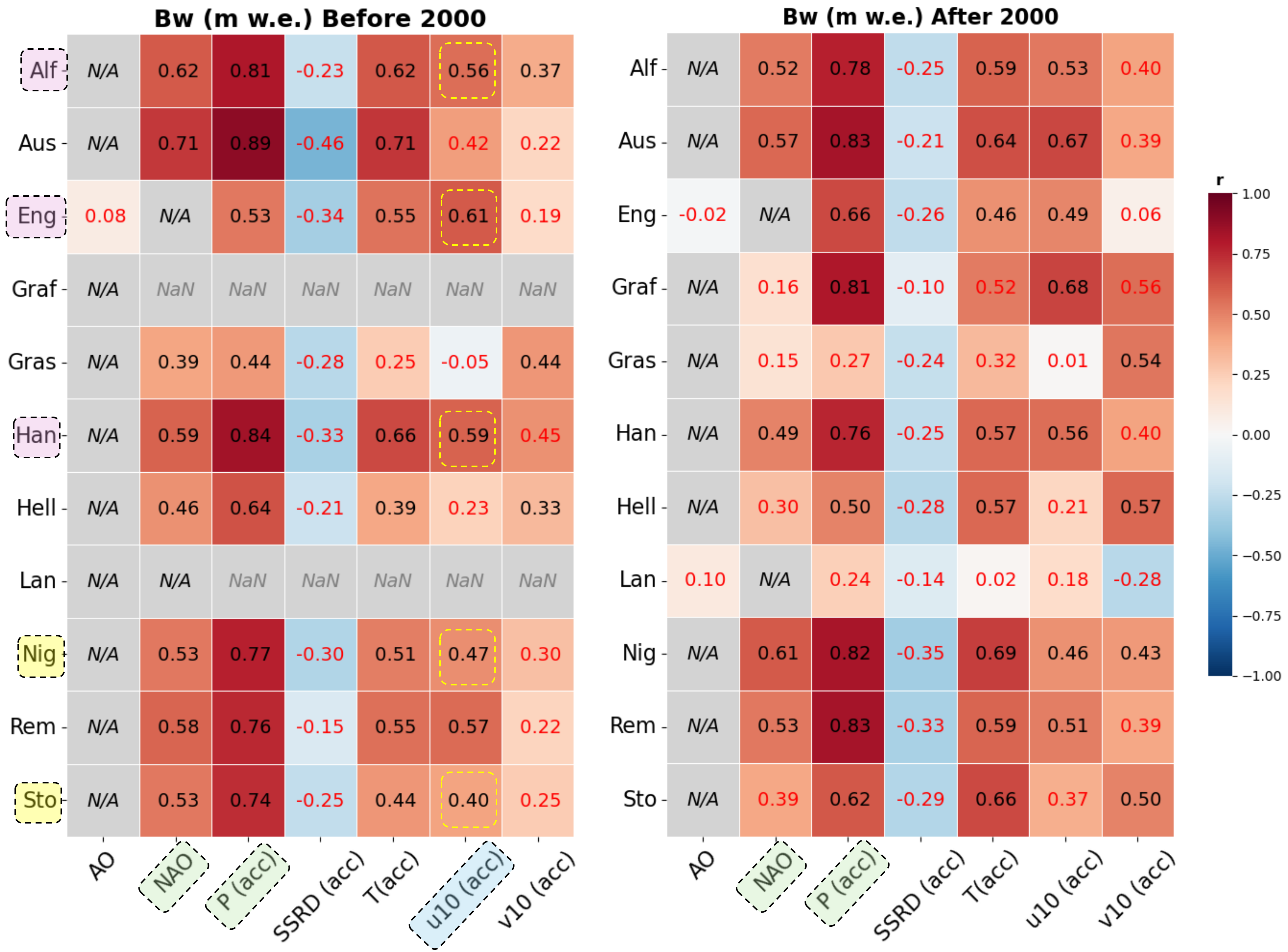


Okstindbreen Glacier
Image credits: Visit Norway

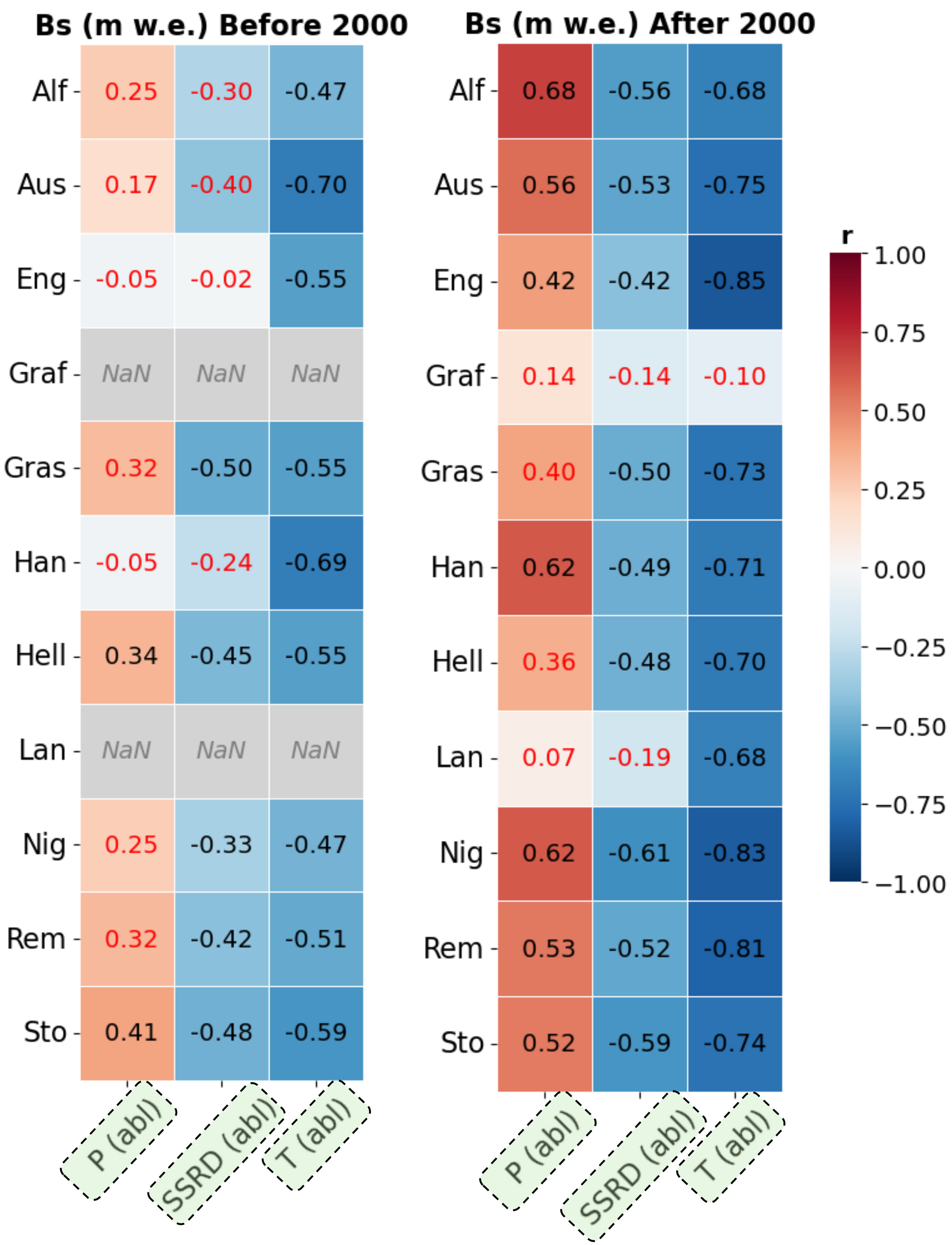
03
Results & Discussion
A. Glacier–Climate Correlation Analysis



- Strong influence of NAO + P(acc). [12, 14]
- Maritime–westerly airflow; continental –low-pressure systems. [8]
- Post-2000 mass loss = low P(acc) + high T(abl). [12]
- Post-2000 = Negative NAO phase, low P(acc) & high T(acc) = retreat. [3]

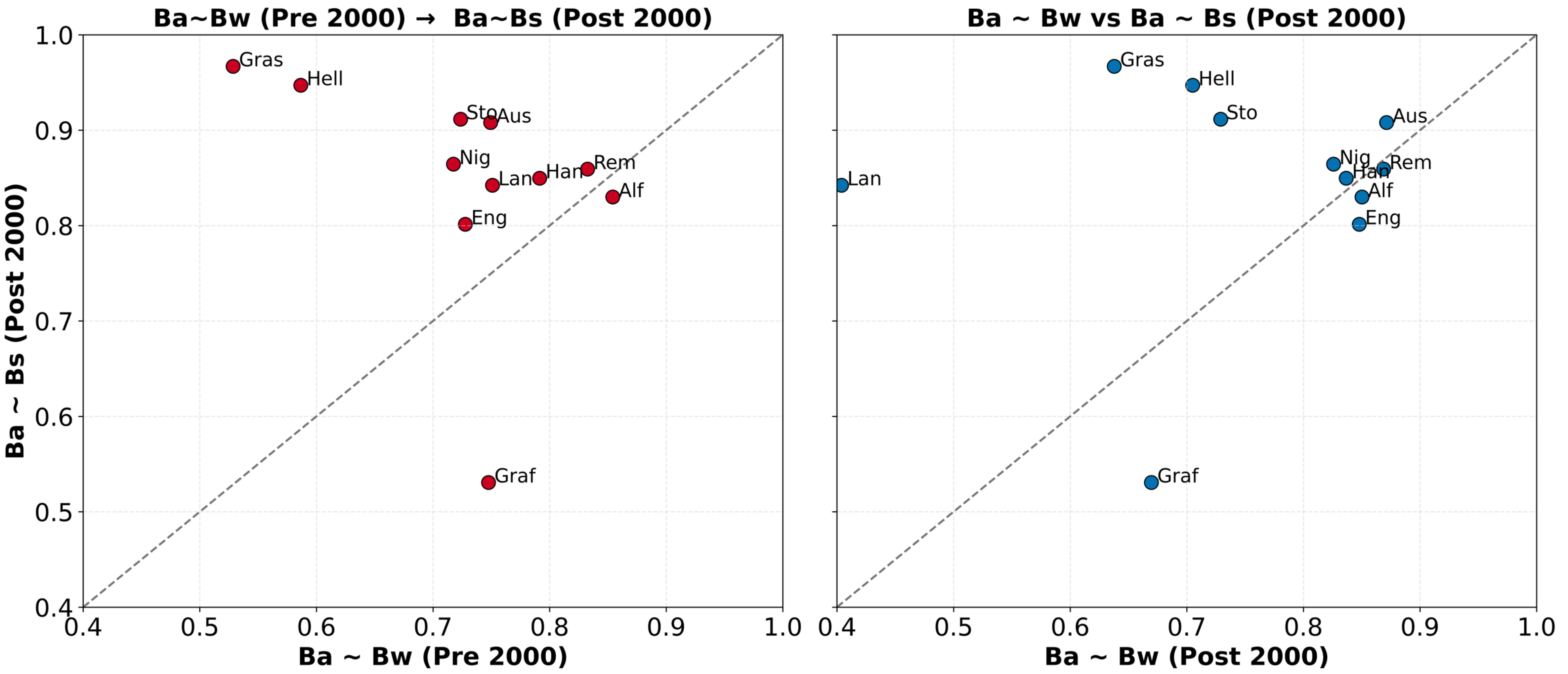


- Strong influence of NAO + P(acc). [12, 14]
- NAO & P(acc) = Maritime (↑ Corr.); continental (↓ Corr.)
- Wind Comp. = Maritime (↑ Corr.); continental (↓ Corr.)



- Post-2000 = T(abl) (↑ Corr.)
- Post-2000 = P(abl) (↑ Corr.) → Precipitation ≠ Snowfall [3]
- Post-2000 = Surface Solar Radiation Downwelling (↑ Corr.)

Shift in Glacier–Climate Control



Okstindbreen Glacier
Image credits: Visit Norway

03
Results & Discussion
B. Model Metrics

Model Metrics

- **Prediction Errors (RMSE) Ranking:** *bw* < *ba* < *bs*
- **Predictive Skill (R^2) Ranking:** *ba* > *bw* > *bs*
- **Spatial gradient:** maritime glaciers (↓ RMSE) & continental glaciers (↑ RMSE). [8, 12]
- **Model Performance:** Linear (↑ median R^2) ≥ non-linear models (↓ median R^2)
- **Dataset Size:** Longer records (>15 years) → lower RMSE values → better predictive skill. [16]
- **This study (Norway):** *ba* models (mean): $R^2 \approx 0.55$; RMSE ≈ 0.64 m w.e., comparable to reported values. (e.g., *ba* R^2 from 0.82 at Ålf to 0.30 at Grås). [17]
- **Other regions:** Similar values in Austria and the Andes (Mean $R^2 \approx 0.5$; RMSE ≈ 0.6 m w.e.). [18, 19]
- **Model type:** Physical ≥ statistical models. (e.g., Andes: $R^2 = 0.91$, RMSE = 0.47 m w.e.). [20]

Okstindbreen Glacier
Image credits: Visit Norway

04
Conclusion

Summary (Part A)

"A Post-2000 Regime Shift in the Controls on Norwegian Glaciers."

- **Post-2000 shift in regime:** from winter (*bw*) → summer (*bs*) dominated control.
- **Change in control:** from NAO driven P(acc) → an energy dominated regime (T(abl)).
- ***ba*~T(abl) correlation:** strong negative correlation for all 11 glaciers post-2000.
- **Spatial gradient:** maritime glaciers (↑ precipitation sensitive) & continental glaciers (↑ temperature sensitive). [8, 12]

Weaker NAO (↓ P(acc)) + higher T(abl) → ***MOST NEGATIVE BALANCE ON RECORD POST-2000!*** [3]

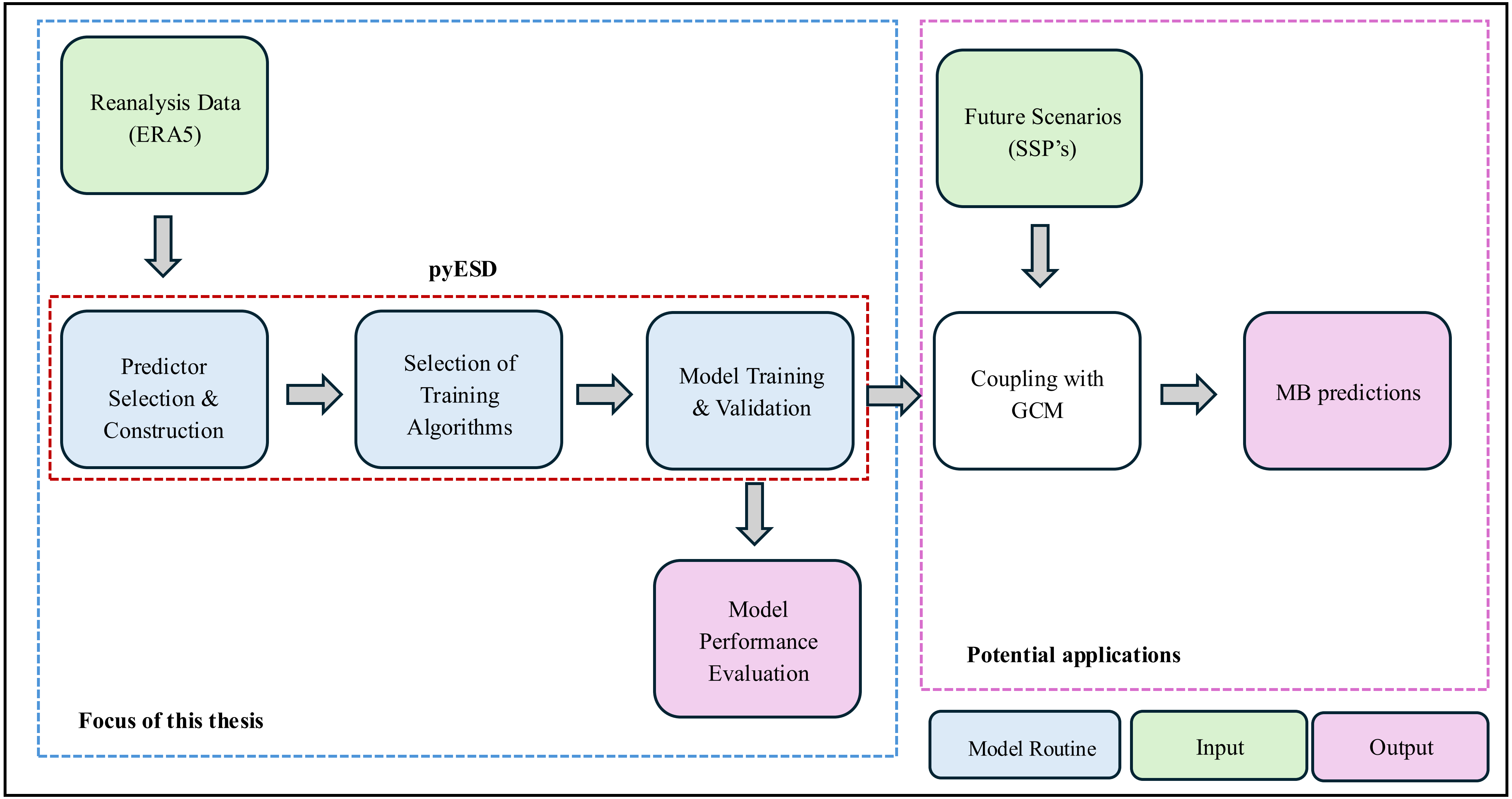
Summary (Part B)

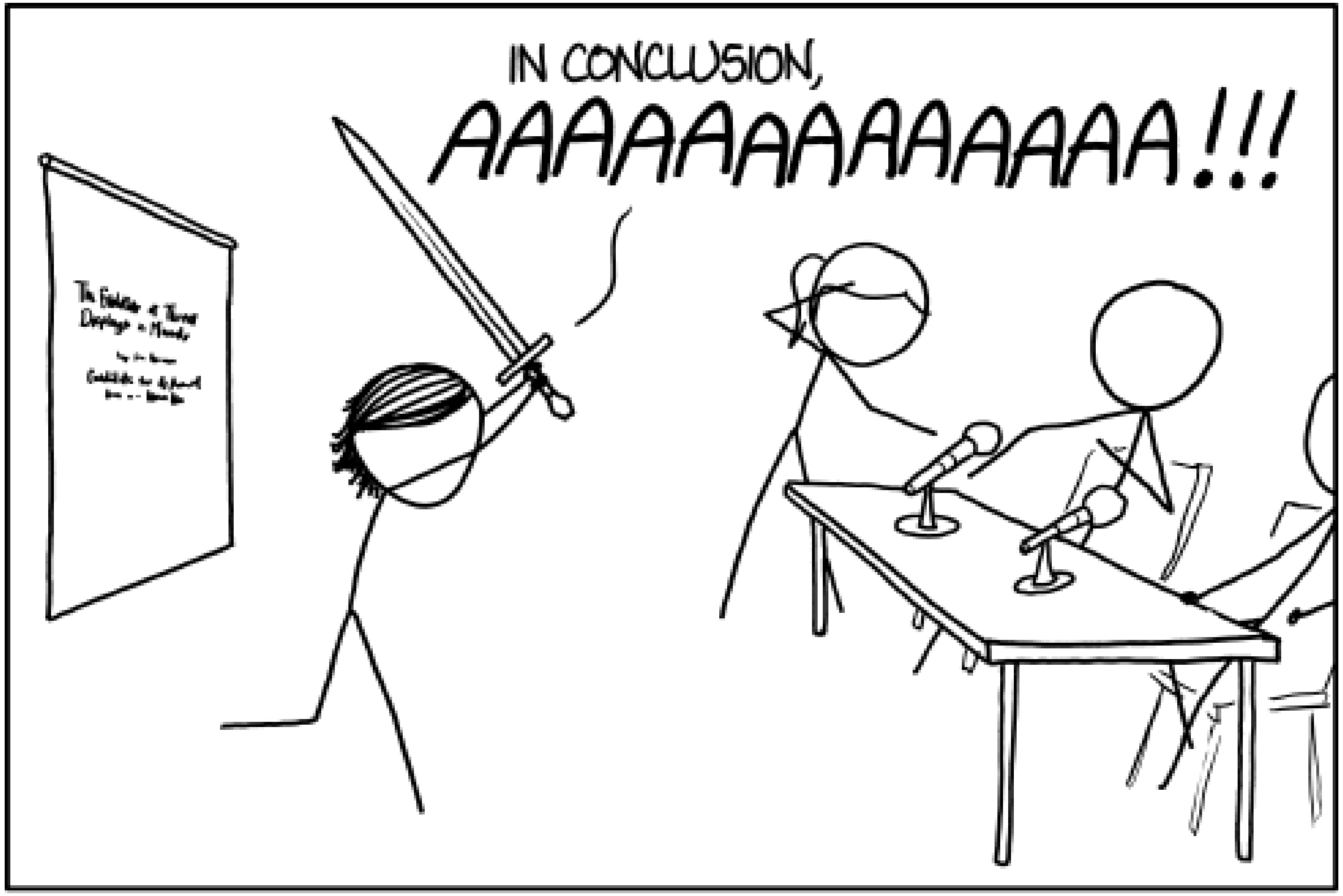
"A Post-2000 Regime Shift in the Controls on Norwegian Glaciers."

- **Model type:** Linear (ARD, RidgeCV, BYR) ≥ non-linear models (Bag, RF, XGBoost).
- **Dataset size:** More complete records pre-2000 → better predictive skill.
- **Spatial gradient:** maritime glaciers (↑ performance) & continental glaciers (↓ performance).

Incorporate proxy data + robust dataset → ***Improved model performance***

05
Future Applications


Reanalysis Data
(ERA5)
pyESD
Predictor
Selection &
Construction
Selection of
Training
Algorithms
Model Training
& Validation
Model
Performance
Evaluation
Focus of this thesis
Future Scenarios
(SSP’s)
Coupling with
GCM
MB predictions
Potential applications
Model Routine
Input
Output



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Thank you for your attention!

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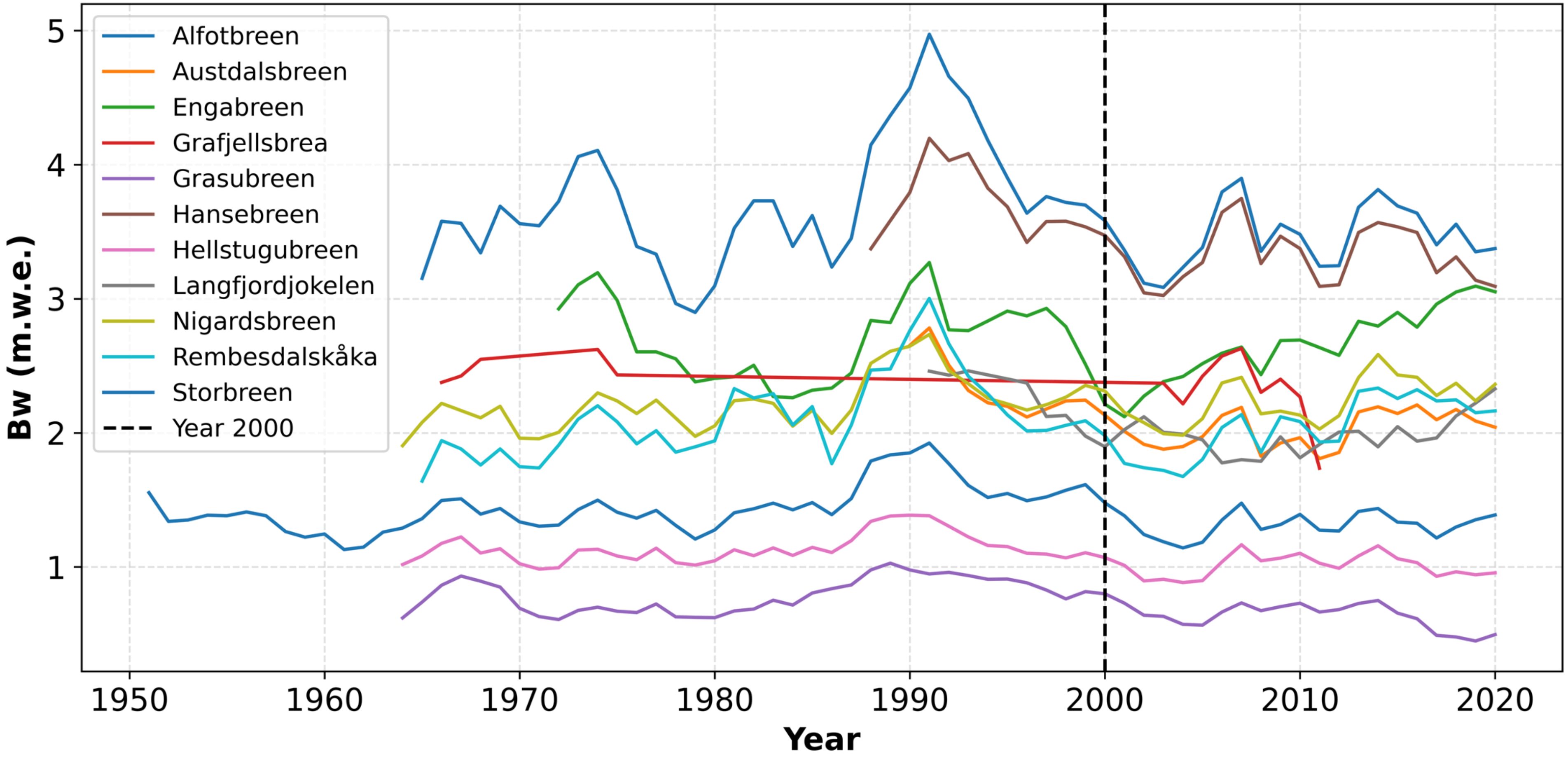
06
Appendix

Hypothesis

A Regime Shift in the Climatic Controls on Norwegian Glaciers in 2000…?



Data Source: NVE

Hypothesis

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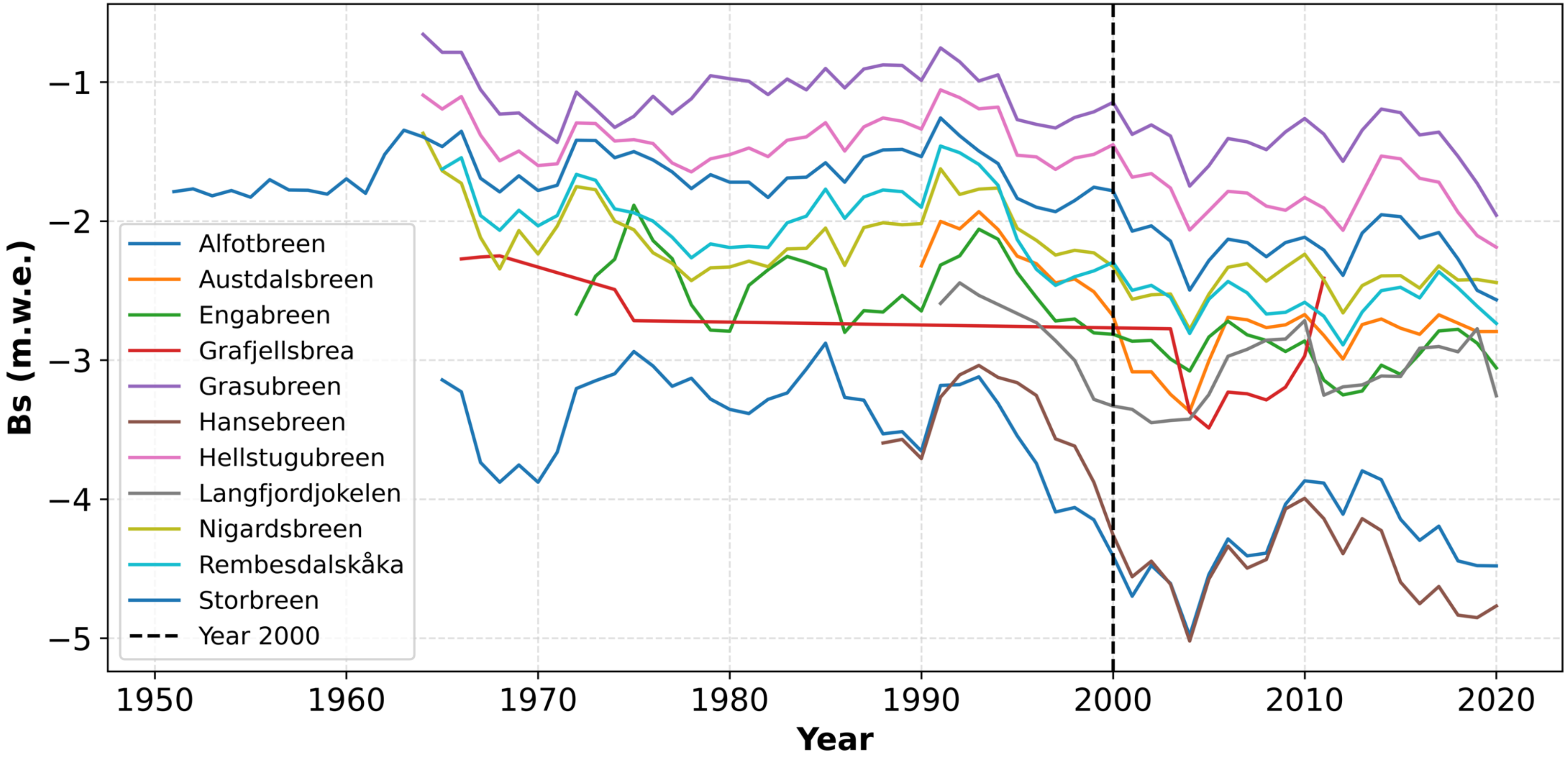

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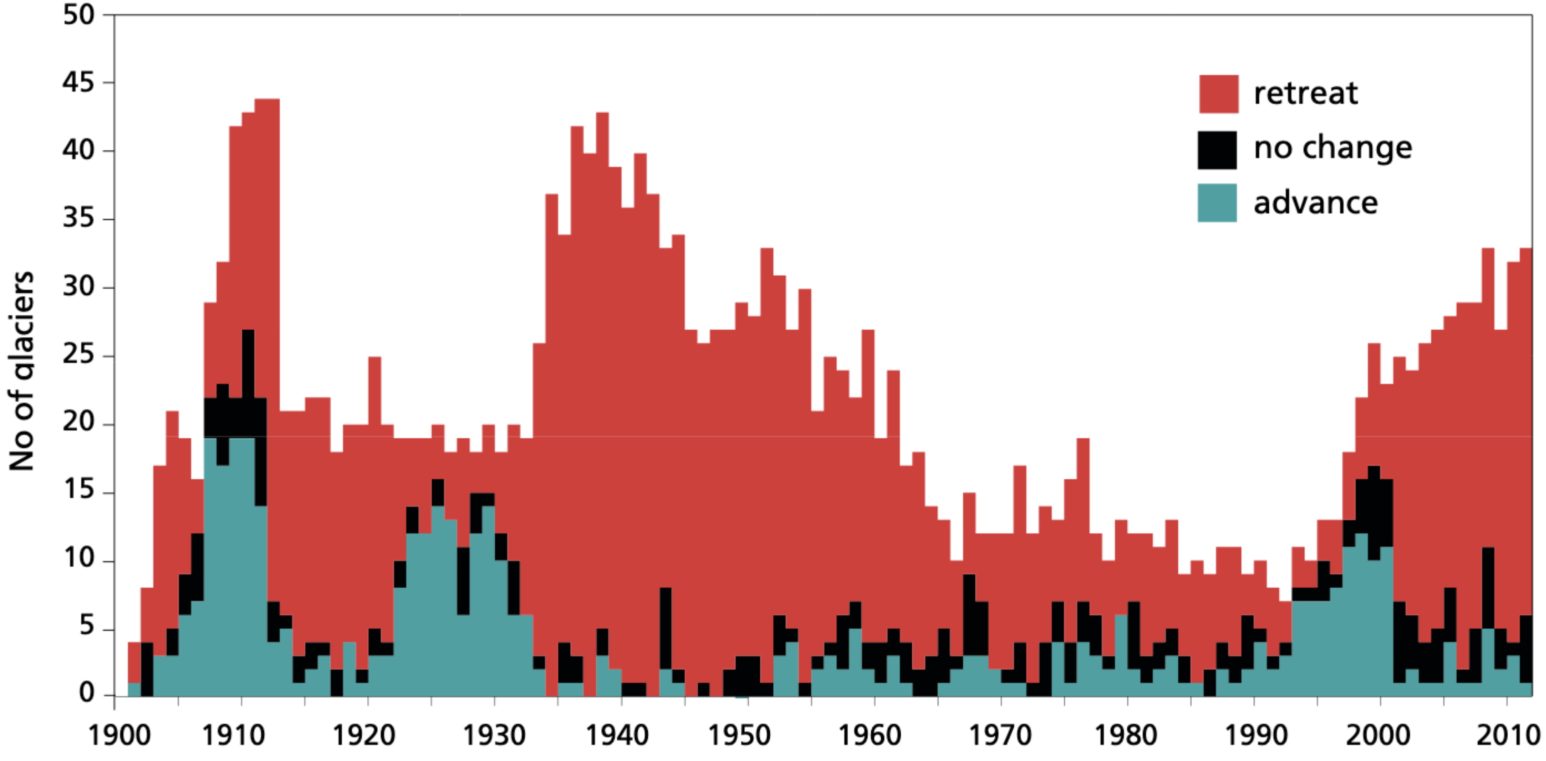
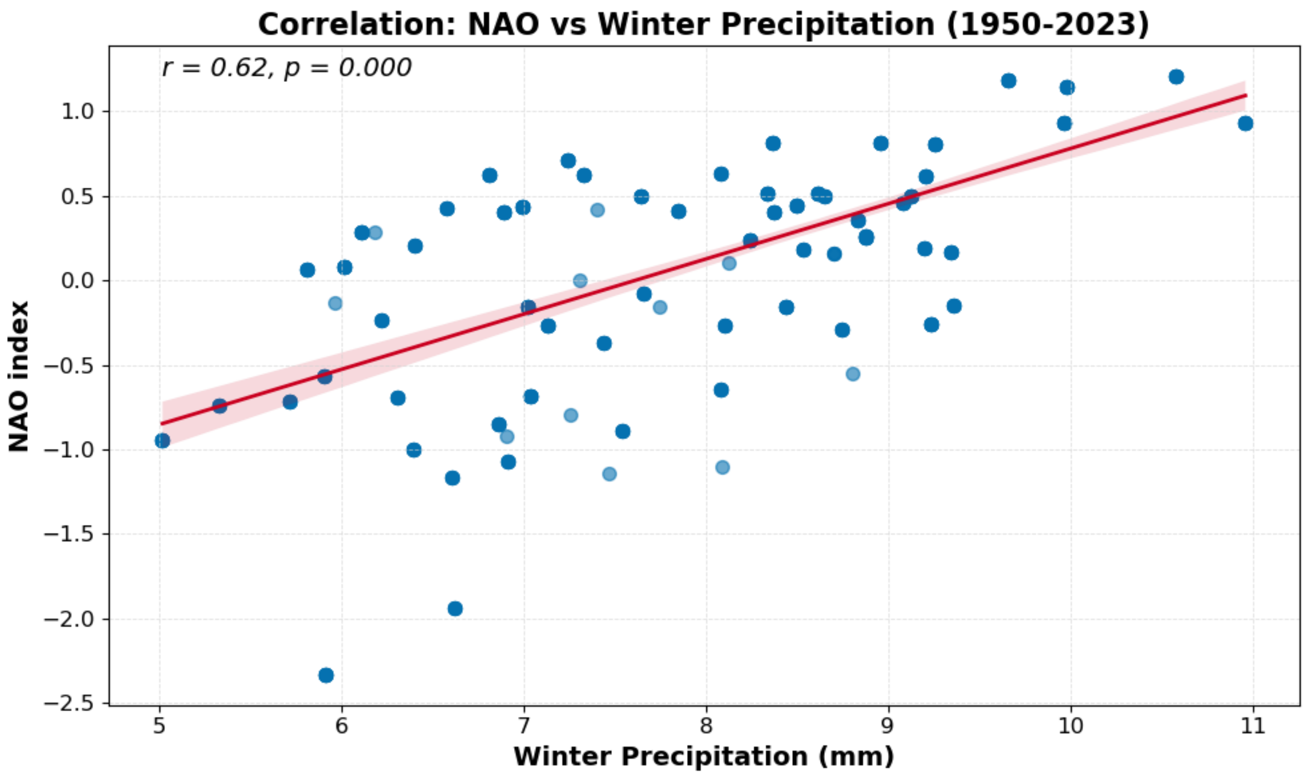


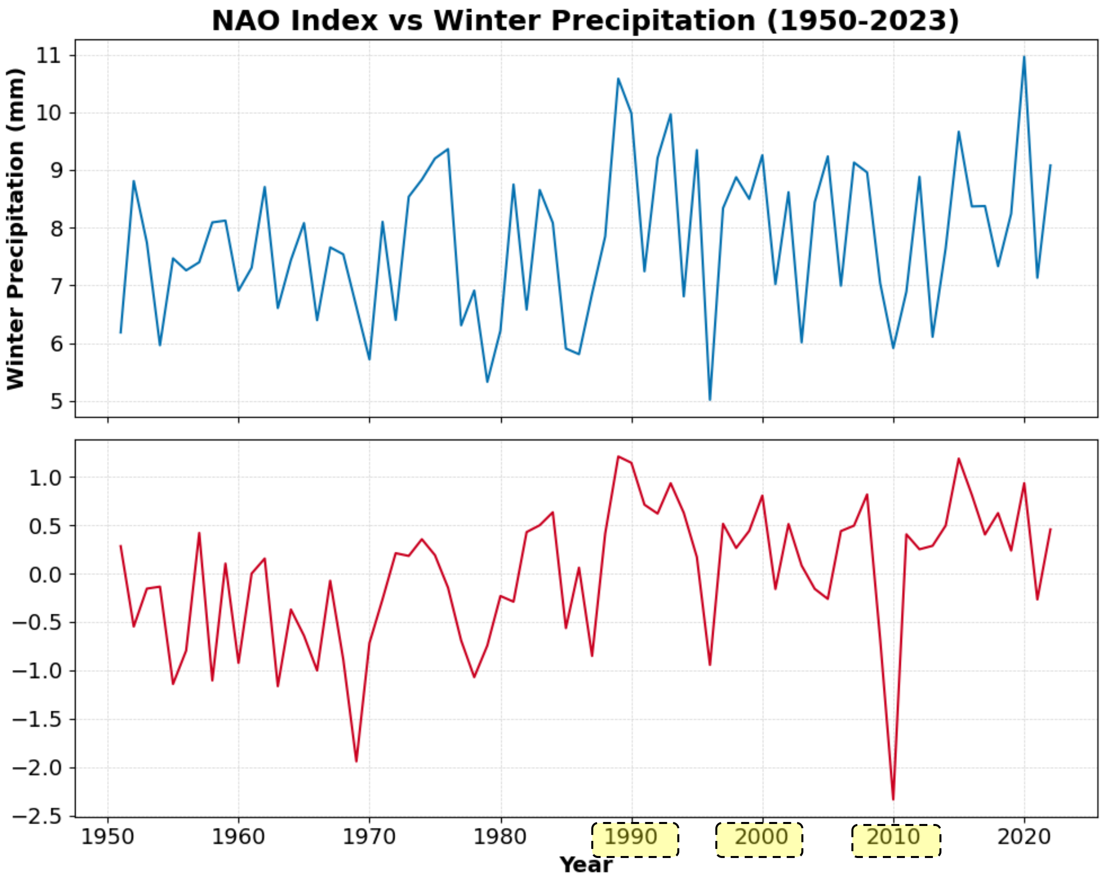
Figure from Andreassen & Winsvold (2012):

- Stacked histogram showing the number of Norwegian glaciers measured every year between 1900 and 2004.
- Red indicates part of total that retreated (more than 2 m), black indicates no change (+/- 2m), and green part of total that advanced (more than 2 m).
- Major advances occurred around 1910, 1930 and in the 1990s.

Data Source: NVE

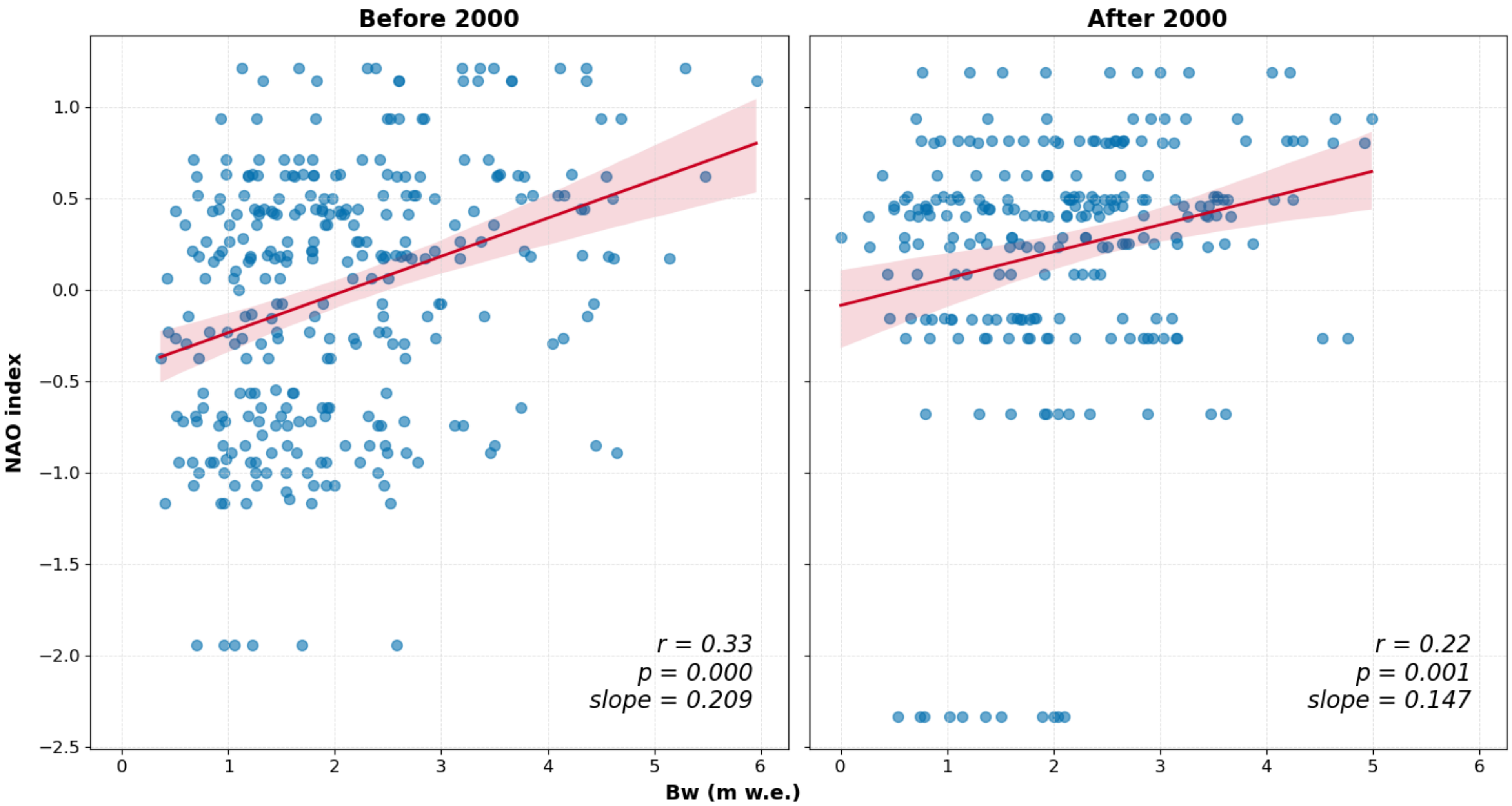


Scatterplot of correlation between P(acc) & NAO



Inter-annual variability of P(acc) *(top)* & NAO *(bottom)*

Data Source: NVE & ECWMF

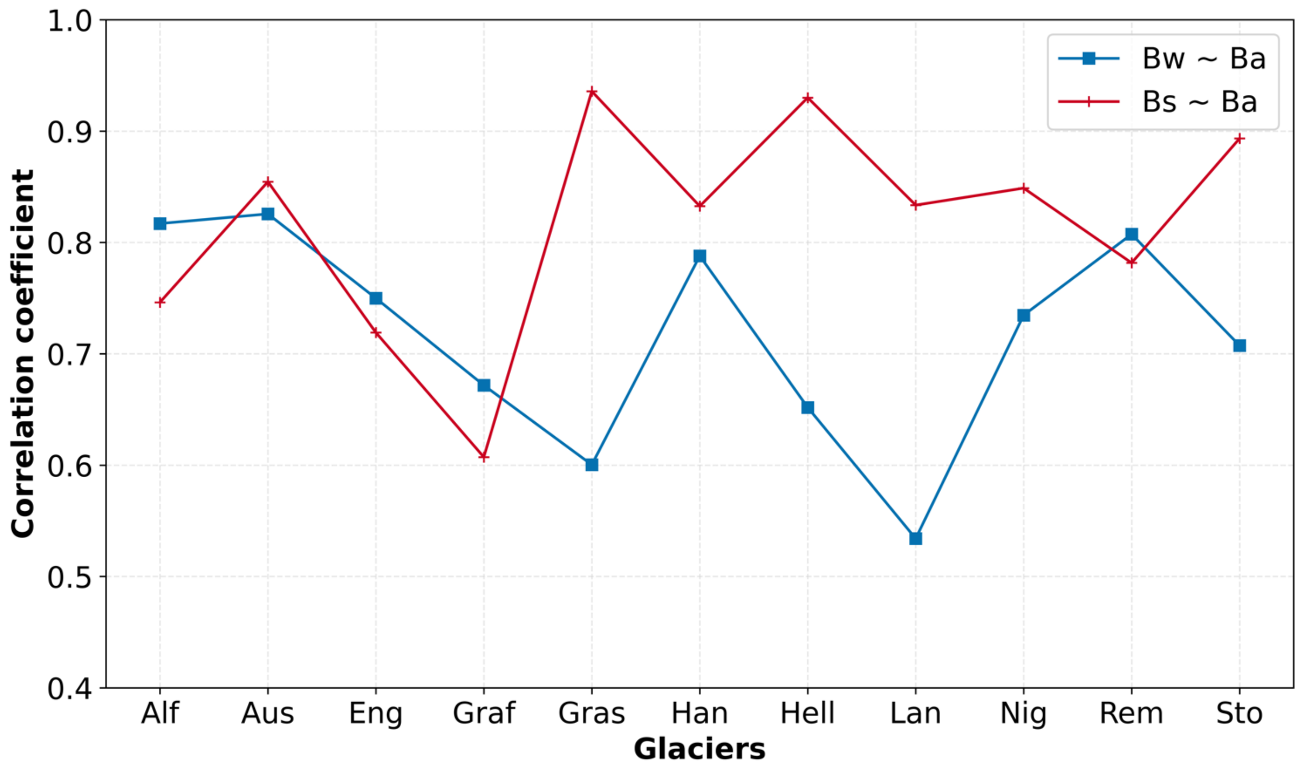


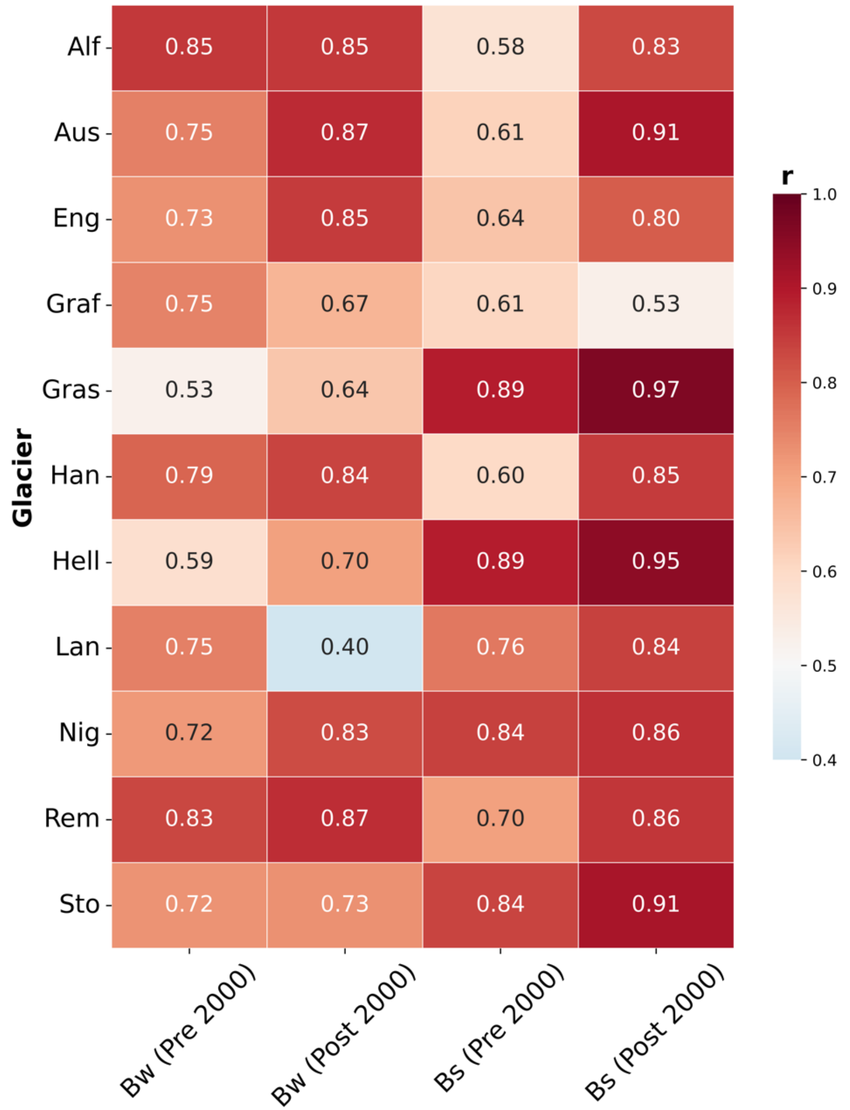
Slope change (After - Before): -0.062

Relationship weakened by 29.6%

Data Source: NVE & ECWMF

Shift in Glacier–Climate Control





Test R^2

Test R² Scores for Ba (1950 - 2023)
Test R²
Regressor
Ridge
Bag
ARD
RF
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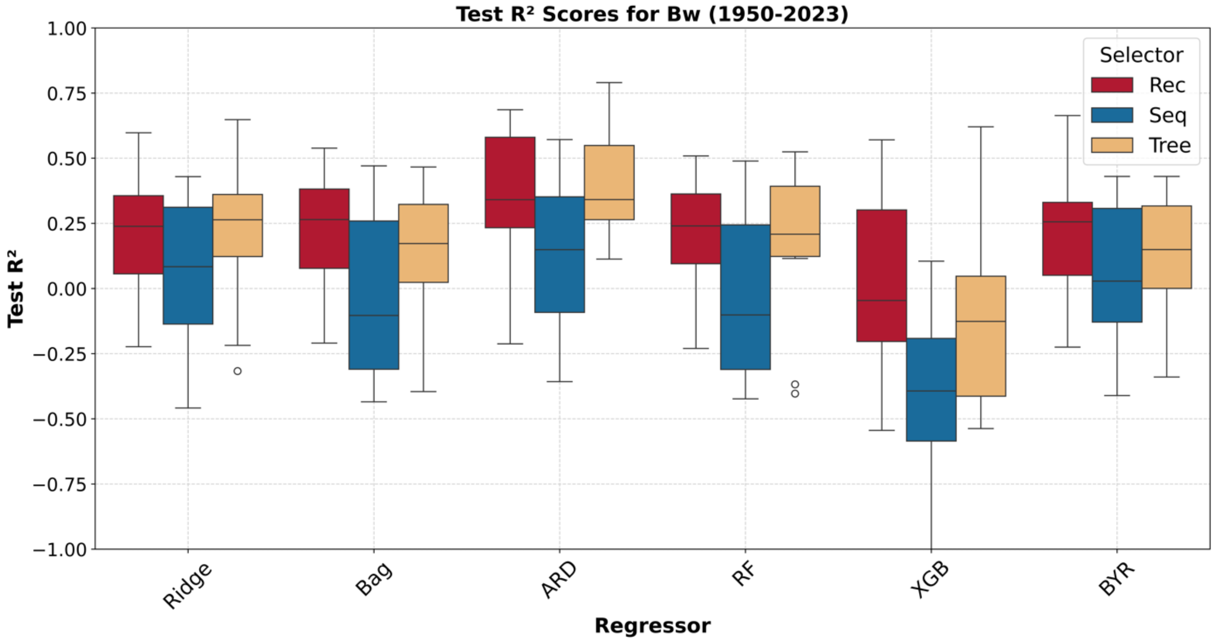

Test R² Scores for Bw (1950-2023)
Test R²
Regressor
Ridge
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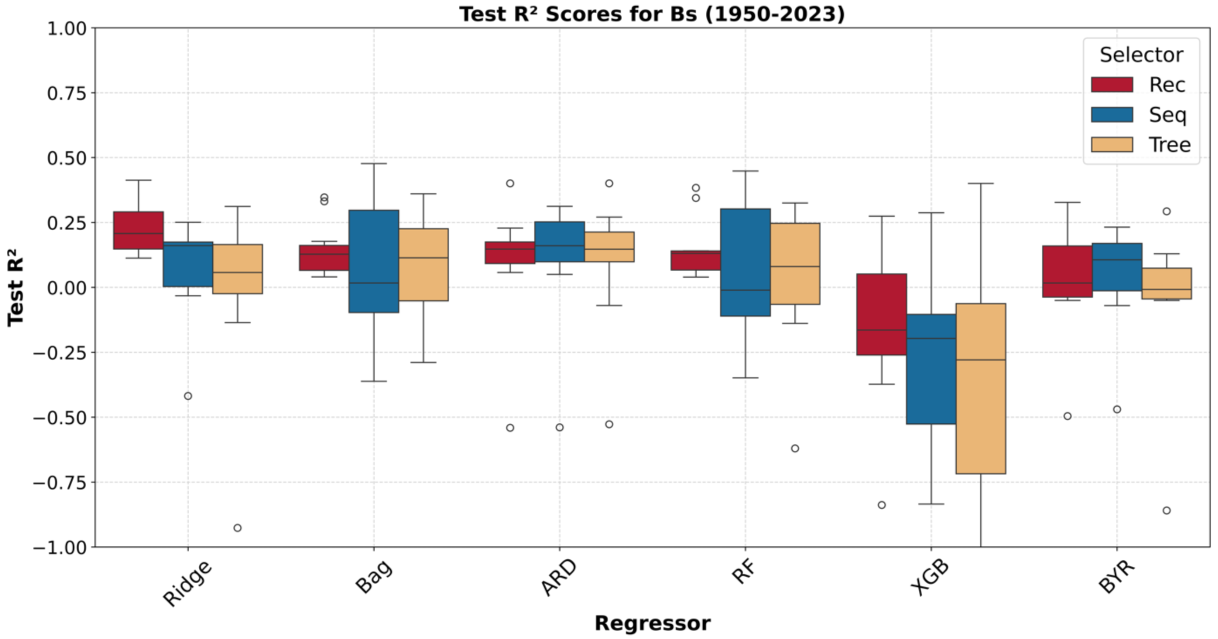

Test R² Scores for Bs (1950-2023)
Test R²
Regressor
Ridge
Bag
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Rec
Seq
Tree
1.00
0.75
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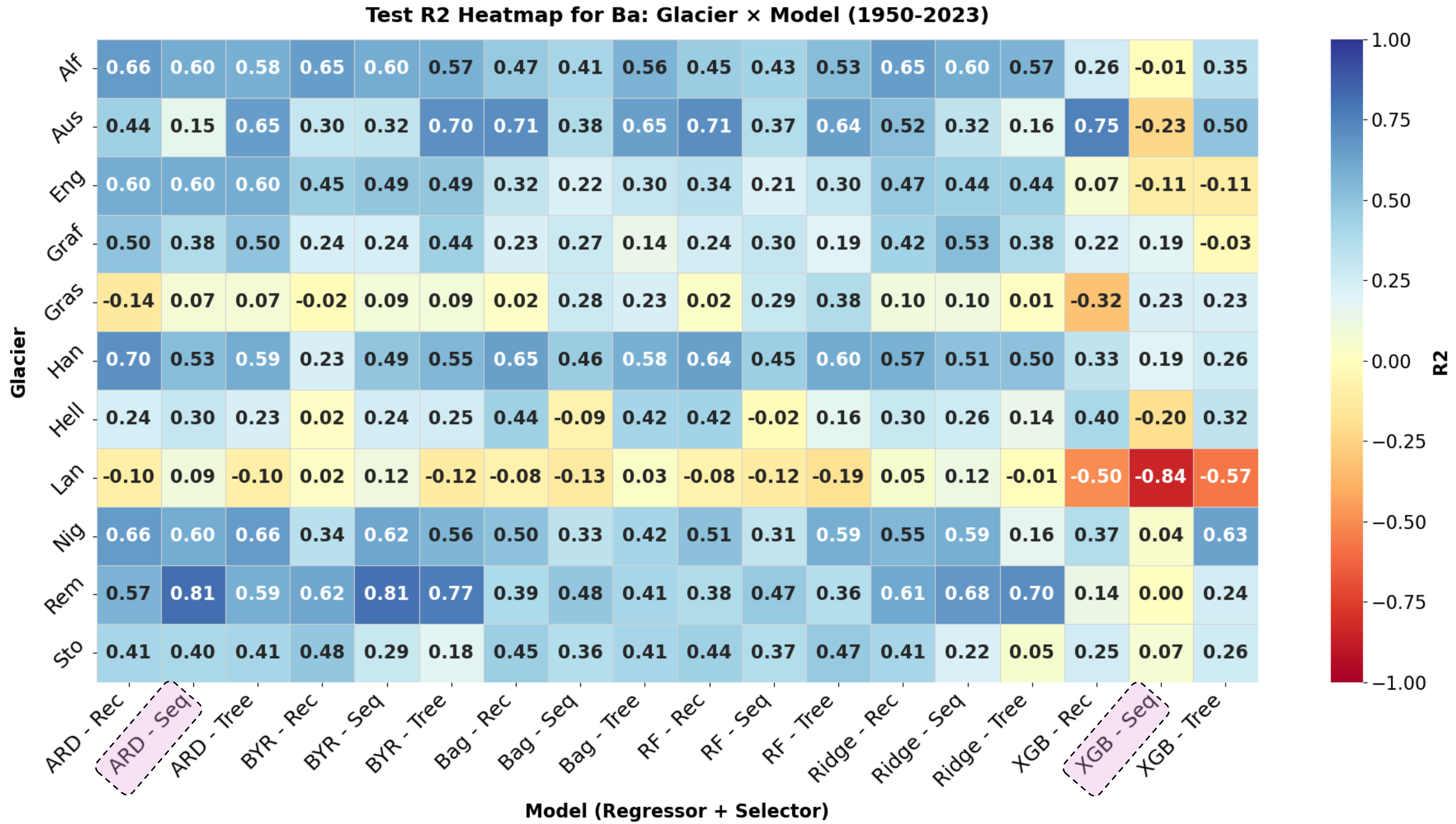
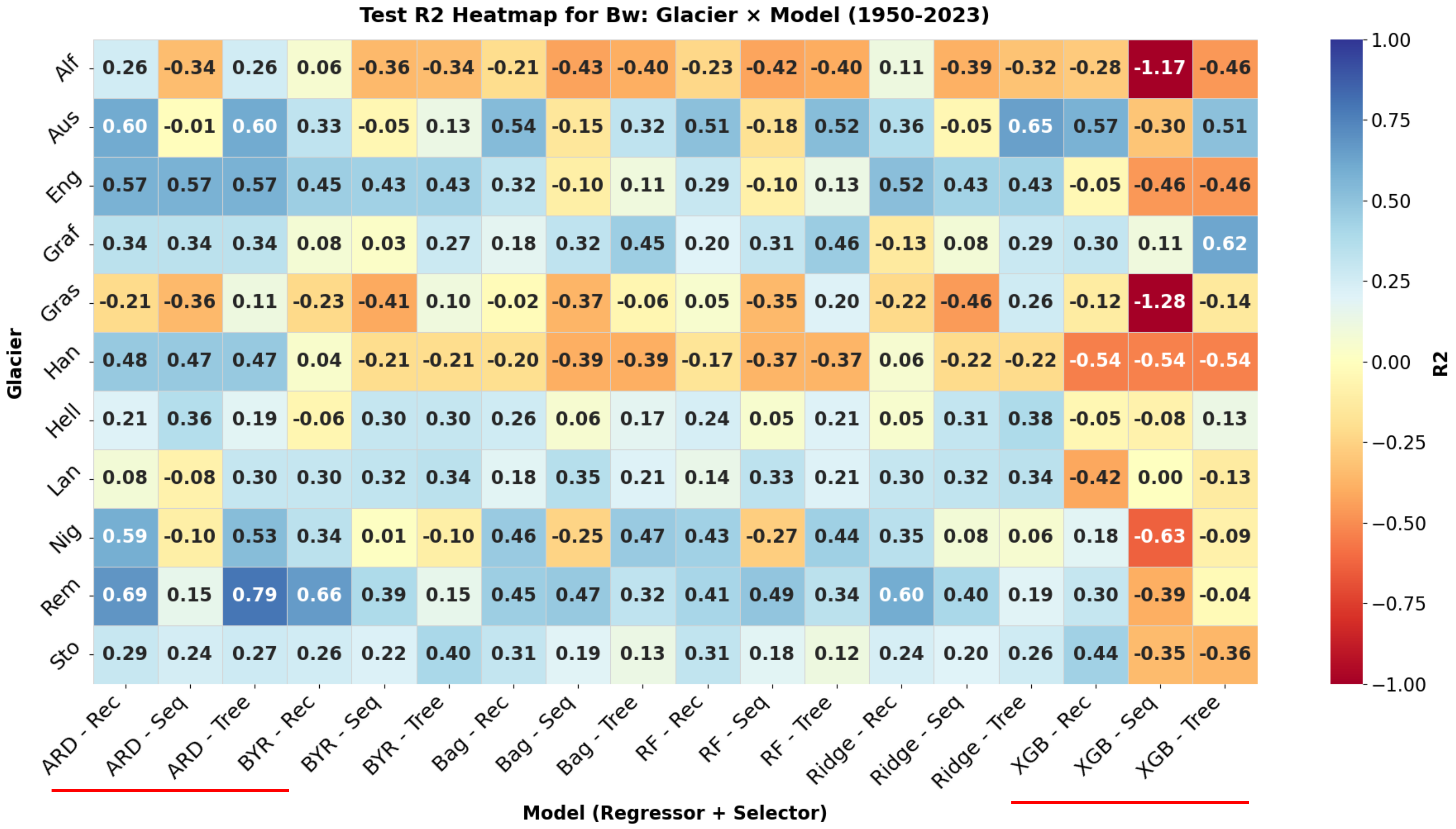
0.25
0.00
−0.25
−0.50
−0.75
−1.00

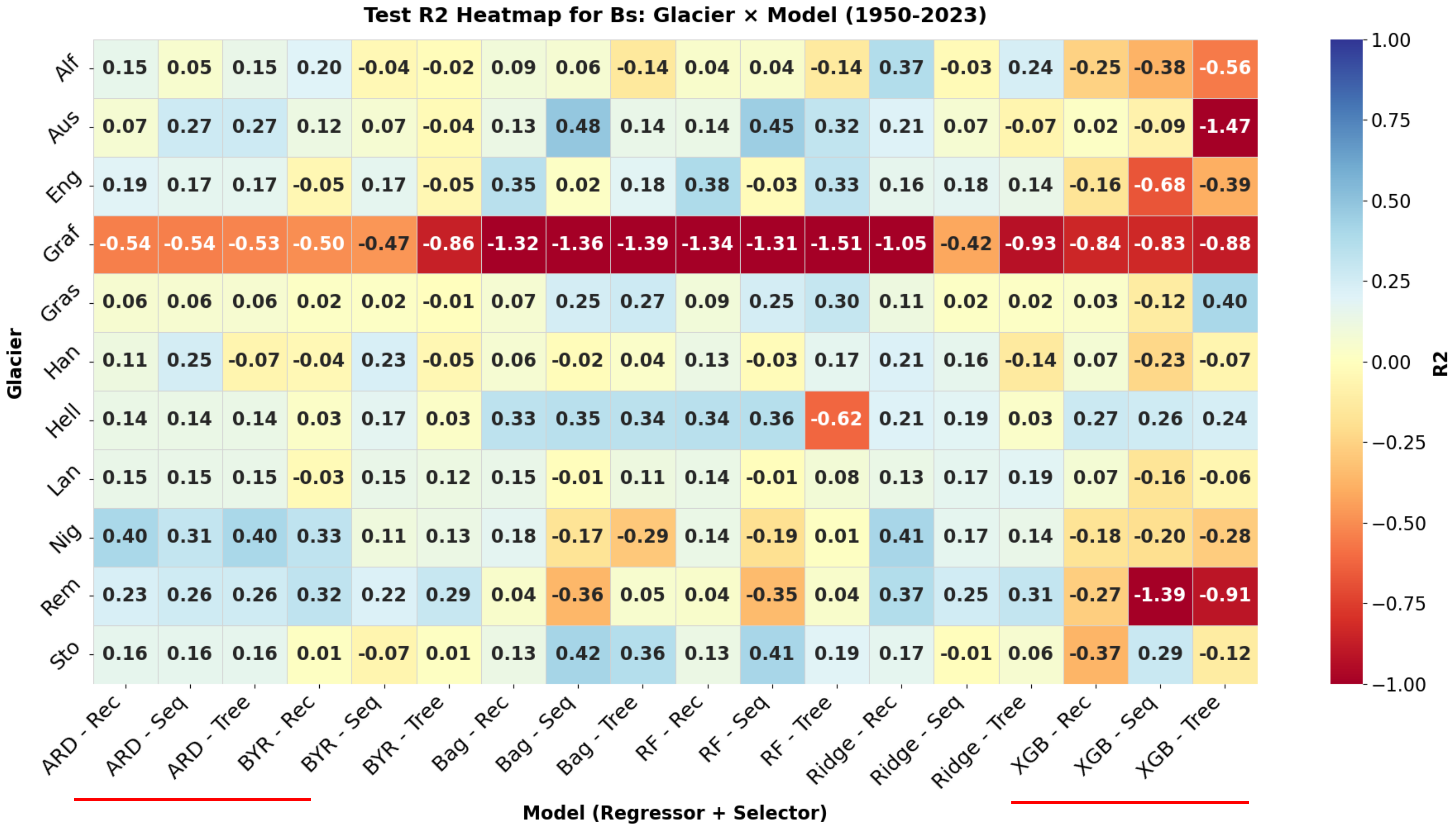
Test R^2


Test R2 Heatmap for Ba: Glacier × Model (1950-2023)
Alf 0.66 0.60 0.58 0.65 0.60 0.57 0.47 0.41 0.56 0.45 0.43 0.53 0.65 0.60 0.57 0.26 -0.01 0.35
Aus 0.44 0.15 0.65 0.30 0.32 0.70 0.71 0.38 0.65 0.71 0.37 0.64 0.52 0.32 0.16 0.75 -0.23 0.50
Eng 0.60 0.60 0.60 0.45 0.49 0.49 0.32 0.22 0.30 0.34 0.21 0.30 0.47 0.44 0.44 0.07 -0.11 -0.11
Graf 0.50 0.38 0.50 0.24 0.24 0.44 0.23 0.27 0.14 0.24 0.30 0.19 0.42 0.53 0.38 0.22 0.19 -0.03
Gras -0.14 0.07 0.07 -0.02 0.09 0.09 0.02 0.28 0.23 0.02 0.29 0.38 0.10 0.10 0.01 -0.32 0.23 0.23
Han 0.70 0.53 0.59 0.23 0.49 0.55 0.65 0.46 0.58 0.64 0.45 0.60 0.57 0.51 0.50 0.33 0.19 0.26
Hell 0.24 0.30 0.23 0.02 0.24 0.25 0.44 -0.09 0.42 0.42 -0.02 0.16 0.30 0.26 0.14 0.40 -0.20 0.32
Lan -0.10 0.09 -0.10 0.02 0.12 -0.12 -0.08 -0.13 0.03 -0.08 -0.12 -0.19 0.05 0.12 -0.01 -0.50 -0.84 -0.57
Nig 0.66 0.60 0.66 0.34 0.62 0.56 0.50 0.33 0.42 0.51 0.31 0.59 0.55 0.59 0.16 0.37 0.04 0.63
Rem 0.57 0.81 0.59 0.62 0.81 0.77 0.39 0.48 0.41 0.38 0.47 0.36 0.61 0.68 0.70 0.14 0.00 0.24
Sto 0.41 0.40 0.41 0.48 0.29 0.18 0.45 0.36 0.41 0.44 0.37 0.47 0.41 0.22 0.05 0.25 0.07 0.26
Glacier
ARD - Rec
ARD - Seq
ARD - Tree
BYR - Rec
BYR - Seq
BYR - Tree
Bag - Rec
Bag - Seq
Bag - Tree
RF - Rec
RF - Seq
RF - Tree
Ridge - Rec
Ridge - Seq
Ridge - Tree
XGB - Rec
XGB - Seq
XGB - Tree
Model (Regressor + Selector)
R2
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00

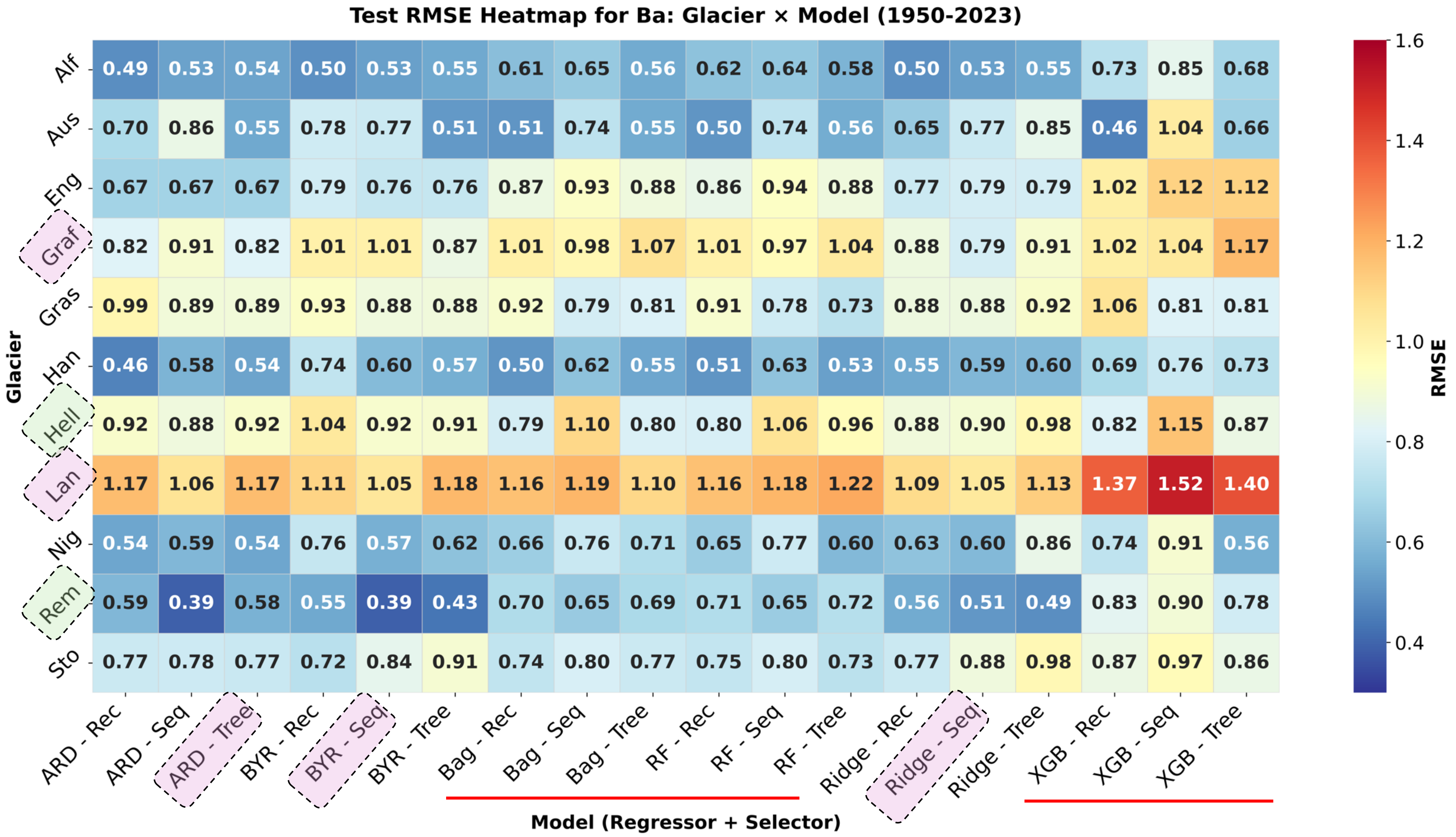
Test R^2


Test R2 Heatmap for Bw: Glacier × Model (1950-2023)
Glacier
Alf 0.26 -0.34 0.26 0.06 -0.36 -0.34 -0.21 -0.43 -0.40 -0.23 -0.42 -0.40 0.11 -0.39 -0.32 -0.28 -1.17 -0.46
Aus 0.60 -0.01 0.60 0.33 -0.05 0.13 0.54 -0.15 0.32 0.51 -0.18 0.52 0.36 -0.05 0.65 0.57 -0.30 0.51
Eng 0.57 0.57 0.57 0.45 0.43 0.43 0.32 -0.10 0.11 0.29 -0.10 0.13 0.52 0.43 0.43 -0.05 -0.46 -0.46
Graf 0.34 0.34 0.34 0.08 0.03 0.27 0.18 0.32 0.45 0.20 0.31 0.46 -0.13 0.08 0.29 0.30 0.11 0.62
Gras -0.21 -0.36 0.11 -0.23 -0.41 0.10 -0.02 -0.37 -0.06 0.05 -0.35 0.20 -0.22 -0.46 0.26 -0.12 -1.28 -0.14
Han 0.48 0.47 0.47 0.04 -0.21 -0.21 -0.20 -0.39 -0.39 -0.17 -0.37 -0.37 0.06 -0.22 -0.22 -0.54 -0.54 -0.54
Hell 0.21 0.36 0.19 -0.06 0.30 0.30 0.26 0.06 0.17 0.24 0.05 0.21 0.05 0.31 0.38 -0.05 -0.08 0.13
Lan 0.08 -0.08 0.30 0.30 0.32 0.34 0.18 0.35 0.21 0.14 0.33 0.21 0.30 0.32 0.34 -0.42 0.00 -0.13
Nig 0.59 -0.10 0.53 0.34 0.01 -0.10 0.46 -0.25 0.47 0.43 -0.27 0.44 0.35 0.08 0.06 0.18 -0.63 -0.09
Rem 0.69 0.15 0.79 0.66 0.39 0.15 0.45 0.47 0.32 0.41 0.49 0.34 0.60 0.40 0.19 0.30 -0.39 -0.04
Sto 0.29 0.24 0.27 0.26 0.22 0.40 0.31 0.19 0.13 0.31 0.18 0.12 0.24 0.20 0.26 0.44 -0.35 -0.36
ARD - Rec
ARD - Seq
ARD - Tree
BYR - Rec
BYR - Seq
BYR - Tree
Bag - Rec
Bag - Seq
Bag - Tree
RF - Rec
RF - Seq
RF - Tree
Ridge - Rec
Ridge - Seq
Ridge - Tree
XGB - Rec
XGB - Seq
XGB - Tree
Model (Regressor + Selector)
R2
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00

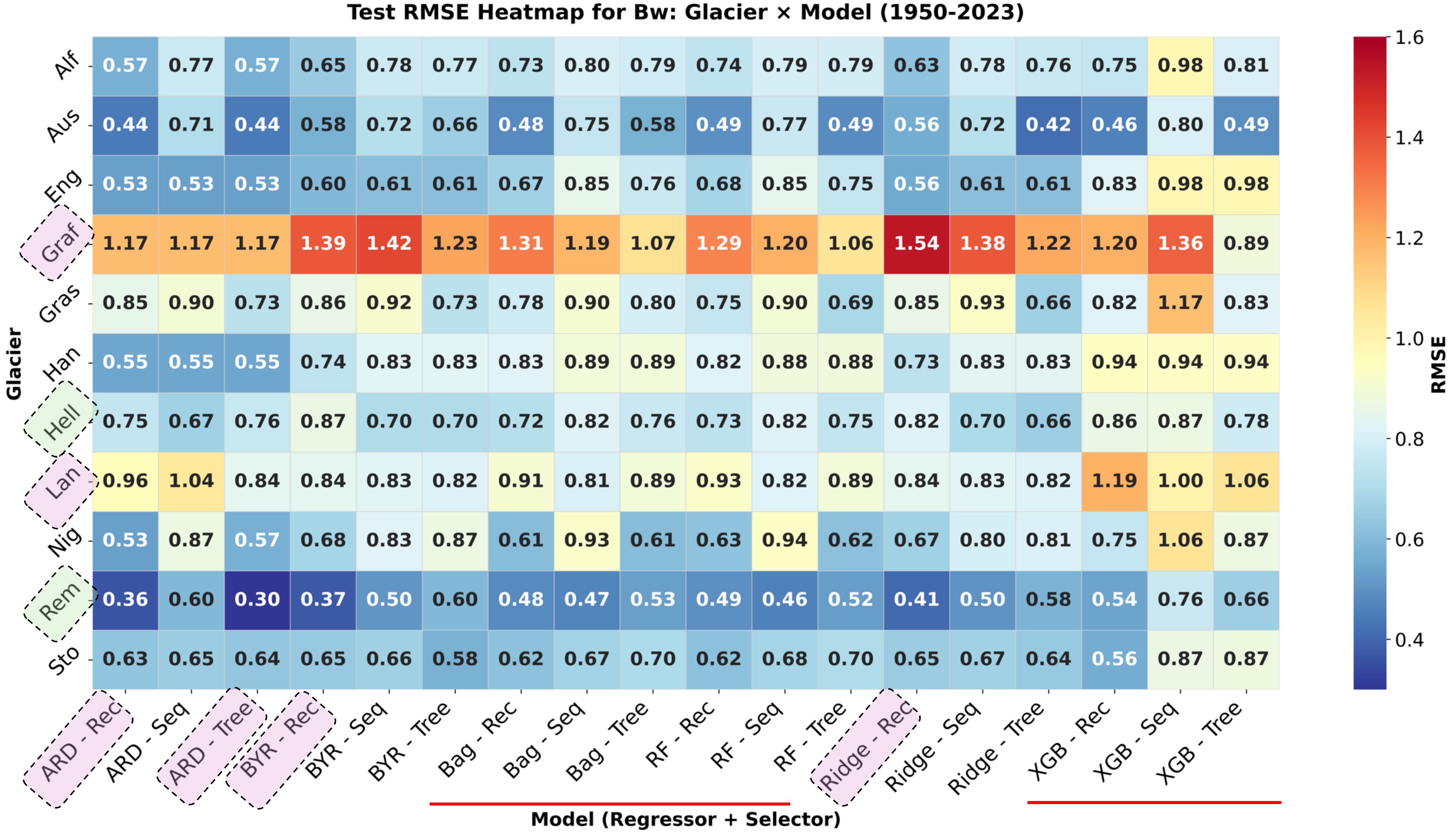
Test R^2


Test R2 Heatmap for Bs: Glacier × Model (1950-2023)
Glacier
Model (Regressor + Selector)
R2
ARD - Rec, ARD - Seq, ARD - Tree, BYR - Rec, BYR - Seq, BYR - Tree, Bag - Rec, Bag - Seq, Bag - Tree, RF - Rec, RF - Seq, RF - Tree, Ridge - Rec, Ridge - Seq, Ridge - Tree, XGB - Rec, XGB - Seq, XGB - Tree
Alf 0.15 0.05 0.15 0.20 -0.04 -0.02 0.09 0.06 -0.14 0.04 0.04 -0.14 0.37 -0.03 0.24 -0.25 -0.38 -0.56
Aus 0.07 0.27 0.27 0.12 0.07 -0.04 0.13 0.48 0.14 0.14 0.45 0.32 0.21 0.07 -0.07 0.02 -0.09 -1.47
Eng 0.19 0.17 0.17 -0.05 0.17 -0.05 0.35 0.02 0.18 0.38 -0.03 0.33 0.16 0.18 0.14 -0.16 -0.68 -0.39
Graf -0.54 -0.54 -0.53 -0.50 -0.47 -0.86 -1.32 -1.36 -1.39 -1.34 -1.31 -1.51 -1.05 -0.42 -0.93 -0.84 -0.83 -0.88
Gras 0.06 0.06 0.06 0.02 0.02 -0.01 0.07 0.25 0.27 0.09 0.25 0.30 0.11 0.02 0.02 0.03 -0.12 0.40
Han 0.11 0.25 -0.07 -0.04 0.23 -0.05 0.06 -0.02 0.04 0.13 -0.03 0.17 0.21 0.16 -0.14 0.07 -0.23 -0.07
Hell 0.14 0.14 0.14 0.03 0.17 0.03 0.33 0.35 0.34 0.34 0.36 -0.62 0.21 0.19 0.03 0.27 0.26 0.24
Lan 0.15 0.15 0.15 -0.03 0.15 0.12 0.15 -0.01 0.11 0.14 -0.01 0.08 0.13 0.17 0.19 0.07 -0.16 -0.06
Nig 0.40 0.31 0.40 0.33 0.11 0.13 0.18 -0.17 -0.29 0.14 -0.19 0.01 0.41 0.17 0.14 -0.18 -0.20 -0.28
Rem 0.23 0.26 0.26 0.32 0.22 0.29 0.04 -0.36 0.05 0.04 -0.35 0.04 0.37 0.25 0.31 -0.27 -1.39 -0.91
Sto 0.16 0.16 0.16 0.01 -0.07 0.01 0.13 0.42 0.36 0.13 0.41 0.19 0.17 -0.01 0.06 -0.37 0.29 -0.12
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00

Test RMSE

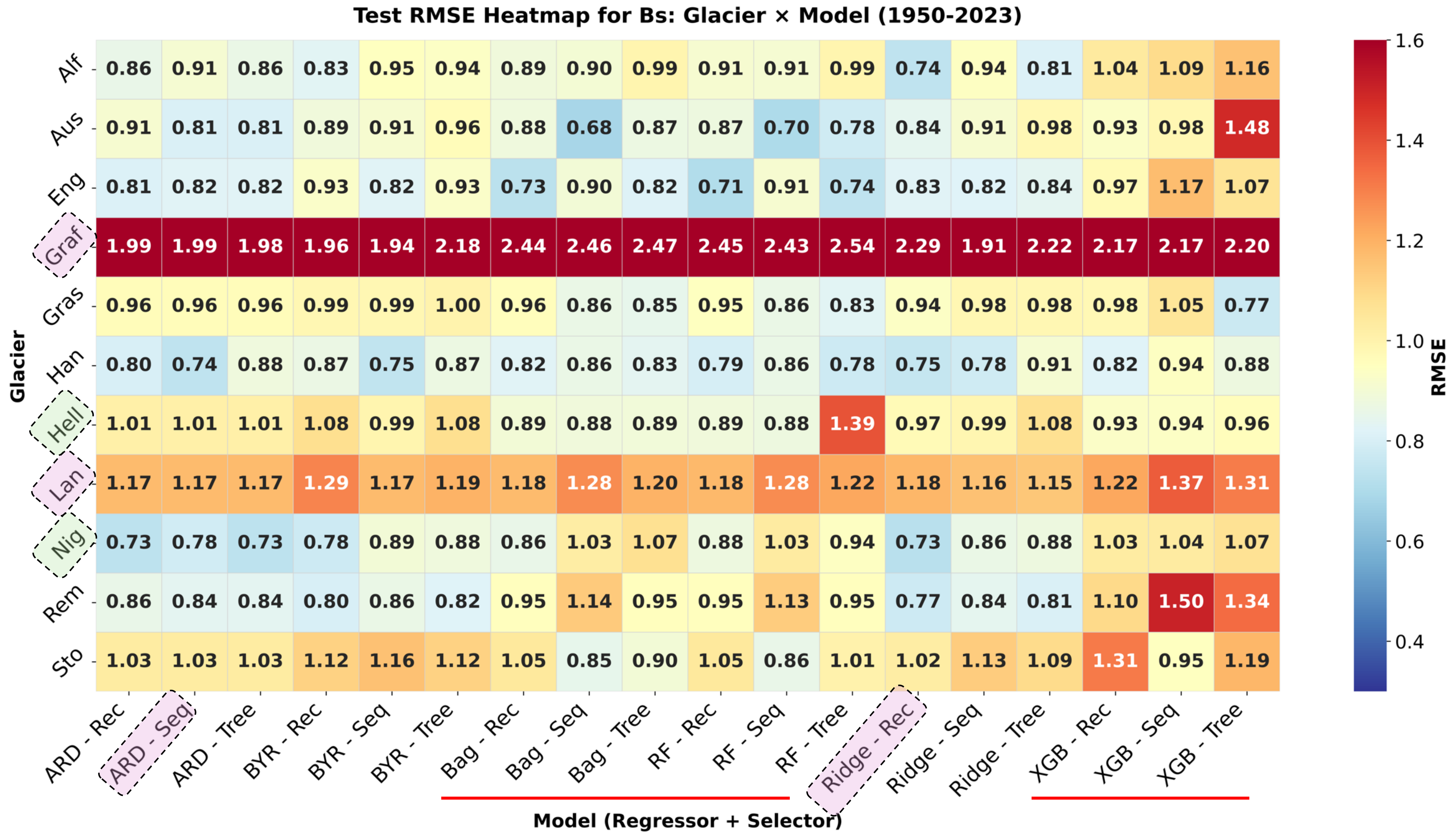

Test RMSE Heatmap for Ba: Glacier × Model (1950-2023)
Glacier
Alf 0.49 0.53 0.54 0.50 0.53 0.55 0.61 0.65 0.56 0.62 0.64 0.58 0.50 0.53 0.55 0.73 0.85 0.68
Aus 0.70 0.86 0.55 0.78 0.77 0.51 0.51 0.74 0.55 0.50 0.74 0.56 0.65 0.77 0.85 0.46 1.04 0.66
Eng 0.67 0.67 0.67 0.79 0.76 0.76 0.87 0.93 0.88 0.86 0.94 0.88 0.77 0.79 0.79 1.02 1.12 1.12
Graf 0.82 0.91 0.82 1.01 1.01 0.87 1.01 0.98 1.07 1.01 0.97 1.04 0.88 0.79 0.91 1.02 1.04 1.17
Gras 0.99 0.89 0.89 0.93 0.88 0.88 0.92 0.79 0.81 0.91 0.78 0.73 0.88 0.88 0.92 1.06 0.81 0.81
Han 0.46 0.58 0.54 0.74 0.60 0.57 0.50 0.62 0.55 0.51 0.63 0.53 0.55 0.59 0.60 0.69 0.76 0.73
Hell 0.92 0.88 0.92 1.04 0.92 0.91 0.79 1.10 0.80 0.80 1.06 0.96 0.88 0.90 0.98 0.82 1.15 0.87
Lan 1.17 1.06 1.17 1.11 1.05 1.18 1.16 1.19 1.10 1.16 1.18 1.22 1.09 1.05 1.13 1.37 1.52 1.40
Nig 0.54 0.59 0.54 0.76 0.57 0.62 0.66 0.76 0.71 0.65 0.77 0.60 0.63 0.60 0.86 0.74 0.91 0.56
Rem 0.59 0.39 0.58 0.55 0.39 0.43 0.70 0.65 0.69 0.71 0.65 0.72 0.56 0.51 0.49 0.83 0.90 0.78
Sto 0.77 0.78 0.77 0.72 0.84 0.91 0.74 0.80 0.77 0.75 0.80 0.73 0.77 0.88 0.98 0.87 0.97 0.86
ARD - Rec
ARD - Seq
ARD - Tree
BYR - Rec
BYR - Seq
BYR - Tree
Bag - Rec
Bag - Seq
Bag - Tree
RF - Rec
RF - Seq
RF - Tree
Ridge - Rec
Ridge - Seq
Ridge - Tree
XGB - Rec
XGB - Seq
XGB - Tree
Model (Regressor + Selector)
RMSE
1.6
1.4
1.2
1.0
0.8
0.6
0.4

Test RMSE


Test RMSE Heatmap for Bw: Glacier × Model (1950-2023)
Glacier
Model (Regressor + Selector)
RMSE
1.6
1.4
1.2
1.0
0.8
0.6
0.4

Glacier	ARD - Rec	ARD - Seq	ARD - Tree	BYR - Rec	BYR - Seq	BYR - Tree	Bag - Rec	Bag - Seq	Bag - Tree	RF - Rec	RF - Seq	RF - Tree	Ridge - Rec	Ridge - Seq	Ridge - Tree	XGB - Rec	XGB - Seq	XGB - Tree
Alf	0.57	0.77	0.57	0.65	0.78	0.77	0.73	0.80	0.79	0.74	0.79	0.79	0.63	0.78	0.76	0.75	0.98	0.81
Aus	0.44	0.71	0.44	0.58	0.72	0.66	0.48	0.75	0.58	0.49	0.77	0.49	0.56	0.72	0.42	0.46	0.80	0.49
Eng	0.53	0.53	0.53	0.60	0.61	0.61	0.67	0.85	0.76	0.68	0.85	0.75	0.56	0.61	0.61	0.83	0.98	0.98
Graf	1.17	1.17	1.17	1.39	1.42	1.23	1.31	1.19	1.07	1.29	1.20	1.06	1.54	1.38	1.22	1.20	1.36	0.89
Gras	0.85	0.90	0.73	0.86	0.92	0.73	0.78	0.90	0.80	0.75	0.90	0.69	0.85	0.93	0.66	0.82	1.17	0.83
Han	0.55	0.55	0.55	0.74	0.83	0.83	0.83	0.89	0.89	0.82	0.88	0.88	0.73	0.83	0.83	0.94	0.94	0.94
Hell	0.75	0.67	0.76	0.87	0.70	0.70	0.72	0.82	0.76	0.73	0.82	0.75	0.82	0.70	0.66	0.86	0.87	0.78
Lan	0.96	1.04	0.84	0.84	0.83	0.82	0.91	0.81	0.89	0.93	0.82	0.89	0.84	0.83	0.82	1.19	1.00	1.06
Nig	0.53	0.87	0.57	0.68	0.83	0.87	0.61	0.93	0.61	0.63	0.94	0.62	0.67	0.80	0.81	0.75	1.06	0.87
Rem	0.36	0.60	0.30	0.37	0.50	0.60	0.48	0.47	0.53	0.49	0.46	0.52	0.41	0.50	0.58	0.54	0.76	0.66
Sto	0.63	0.65	0.64	0.65	0.66	0.58	0.62	0.67	0.70	0.62	0.68	0.70	0.65	0.67	0.64	0.56	0.87	0.87

Test RMSE


Test RMSE Heatmap for Bs: Glacier × Model (1950-2023)
Glacier
Model (Regressor + Selector)
RMSE
1.6
1.4
1.2
1.0
0.8
0.6
0.4

Glacier	ARD - Rec	ARD - Seq	ARD - Tree	BYR - Rec	BYR - Seq	BYR - Tree	Bag - Rec	Bag - Seq	Bag - Tree	RF - Rec	RF - Seq	RF - Tree	Ridge - Rec	Ridge - Seq	Ridge - Tree	XGB - Rec	XGB - Seq	XGB - Tree
Alf	0.86	0.91	0.86	0.83	0.95	0.94	0.89	0.90	0.99	0.91	0.91	0.99	0.74	0.94	0.81	1.04	1.09	1.16
Aus	0.91	0.81	0.81	0.89	0.91	0.96	0.88	0.68	0.87	0.87	0.70	0.78	0.84	0.91	0.98	0.93	0.98	1.48
Eng	0.81	0.82	0.82	0.93	0.82	0.93	0.73	0.90	0.82	0.71	0.91	0.74	0.83	0.82	0.84	0.97	1.17	1.07
Graf	1.99	1.99	1.98	1.96	1.94	2.18	2.44	2.46	2.47	2.45	2.43	2.54	2.29	1.91	2.22	2.17	2.17	2.20
Gras	0.96	0.96	0.96	0.99	0.99	1.00	0.96	0.86	0.85	0.95	0.86	0.83	0.94	0.98	0.98	0.98	1.05	0.77
Han	0.80	0.74	0.88	0.87	0.75	0.87	0.82	0.86	0.83	0.79	0.86	0.78	0.75	0.78	0.91	0.82	0.94	0.88
Hell	1.01	1.01	1.01	1.08	0.99	1.08	0.89	0.88	0.89	0.89	0.88	1.39	0.97	0.99	1.08	0.93	0.94	0.96
Lan	1.17	1.17	1.17	1.29	1.17	1.19	1.18	1.28	1.20	1.18	1.28	1.22	1.18	1.16	1.15	1.22	1.37	1.31
Nig	0.73	0.78	0.73	0.78	0.89	0.88	0.86	1.03	1.07	0.88	1.03	0.94	0.73	0.86	0.88	1.03	1.04	1.07
Rem	0.86	0.84	0.84	0.80	0.86	0.82	0.95	1.14	0.95	0.95	1.13	0.95	0.77	0.84	0.81	1.10	1.50	1.34
Sto	1.03	1.03	1.03	1.12	1.16	1.12	1.05	0.85	0.90	1.05	0.86	1.01	1.02	1.13	1.09	1.31	0.95	1.19