Snow accumulation over the world's glaciers (1981-2021) inferred from climate reanalyses and machine learning

EGU General Assembly 2022

Matteo Guidicelli[1], Matthias Huss[1,2,3], Marco Gabella[4], Nadine Salzmann[5,6]

[1]Department of Geosciences, University of Fribourg, Fribourg, Switzerland
[2]Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland
[3]Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland
[4]Federal Office of Meteorology and Climatology MeteoSwiss, Locarno-Monti, Switzerland
[5]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[6]Climate Change, Extremes and Natural Hazards in Alpine Regions Research Center CERC, Davos, Switzerland

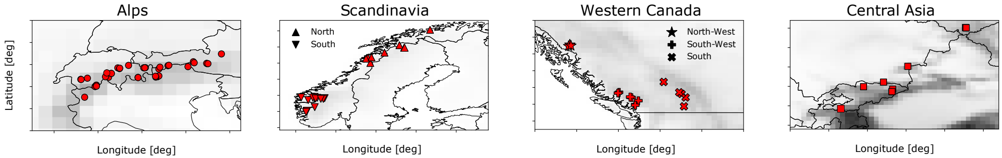
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

Snow and precipitation in remote high-mountain regions

Snow and precipitation in remote high-mountain regions

- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

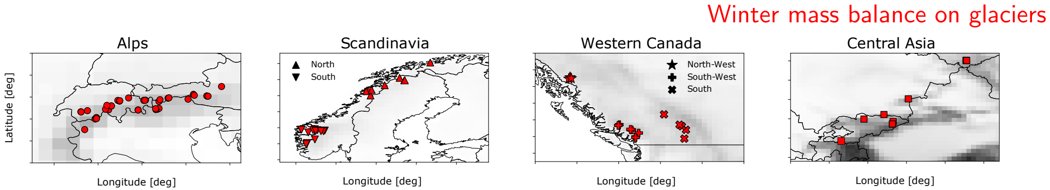
Winter mass balance on glaciers



Snow and precipitation in remote high-mountain regions

- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

UNI FR UNIVERSITÉ DE FRIBOURG UNIVERSITÄT FREIBURG

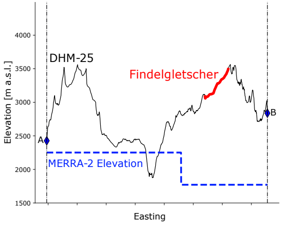


Snow and precipitation in remote high-mountain regions

- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

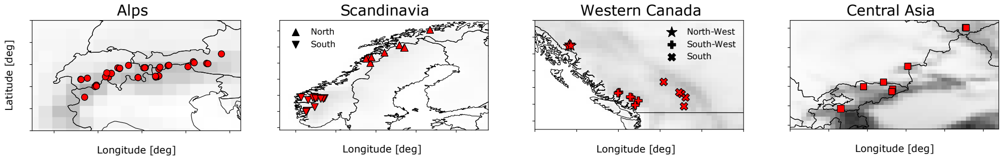
Reanalyses (ERA-5, MERRA-2)

∼Global coverage but unsuited for complex topography



UNI FR UNIVERSITÉ DE FRIBOURG UNIVERSITÄT FREIBURG

Winter mass balance on glaciers

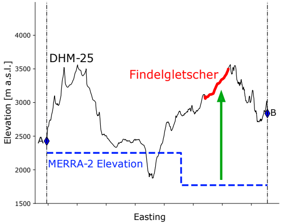


Snow and precipitation in remote high-mountain regions

- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

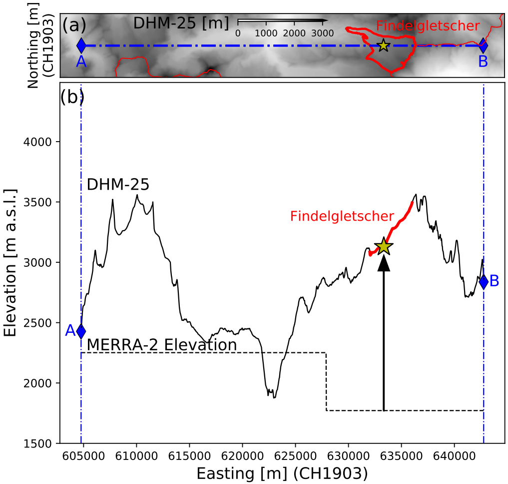
Reanalyses (ERA-5, MERRA-2)

∼Global coverage but unsuited for complex topography

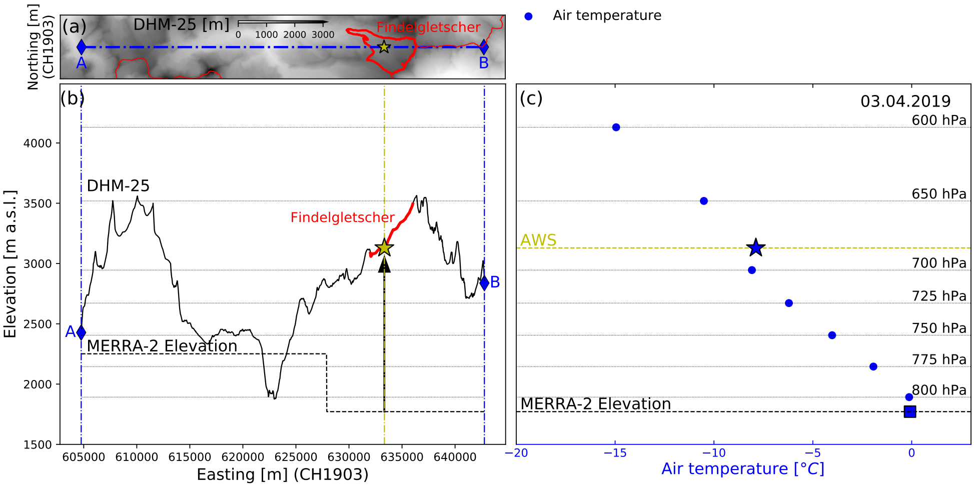


UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

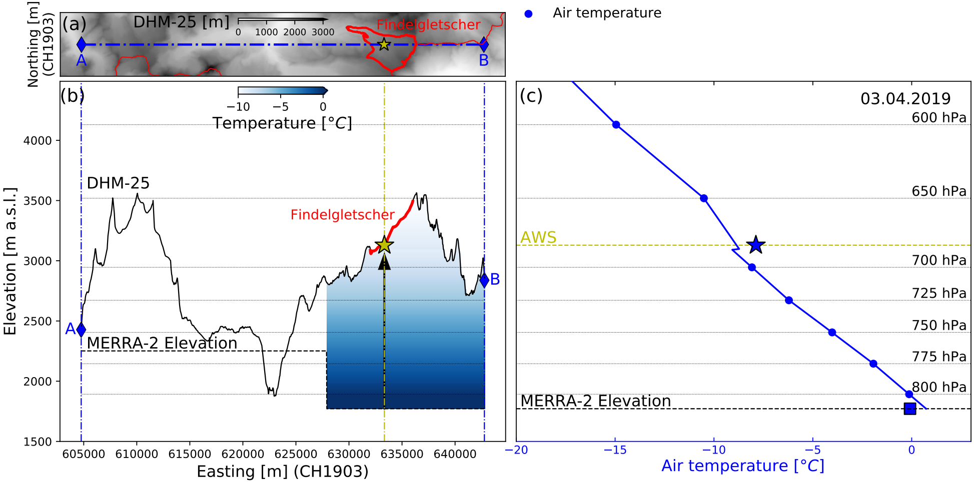
Downscaling reanalysis estimates in high-mountain regions



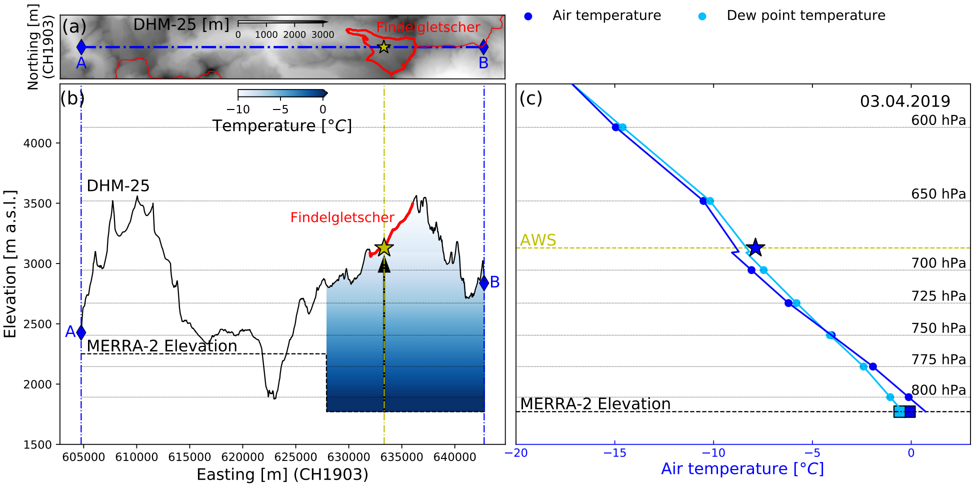
Downscaling reanalysis estimates in high-mountain regions



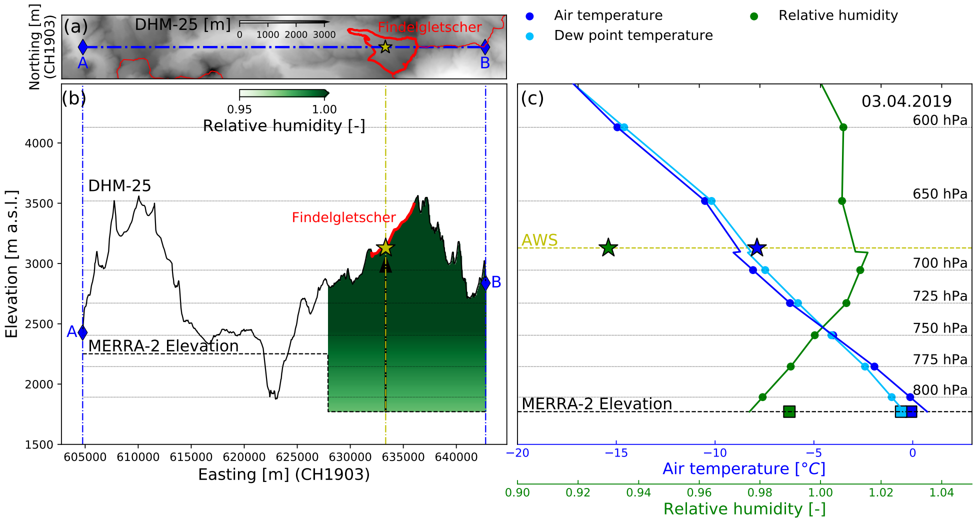
Downscaling reanalysis estimates in high-mountain regions



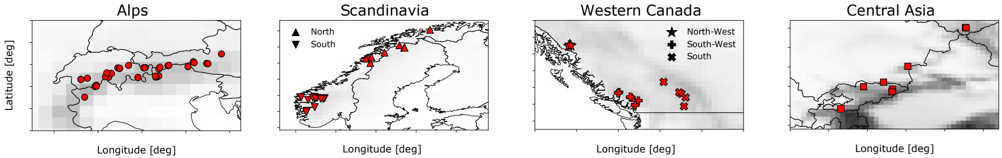
Downscaling reanalysis estimates in high-mountain regions



Downscaling reanalysis estimates in high-mountain regions



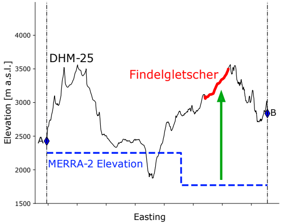
Winter mass balance on glaciers



Snow and precipitation in remote high-mountain regions

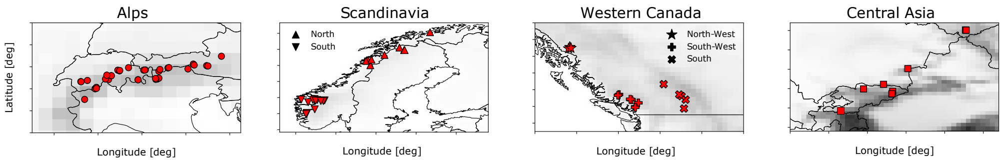
- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

Reanalyses (ERA-5, MERRA-2)
∼Global coverage but unsuited for complex topography



UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

Winter mass balance on glaciers

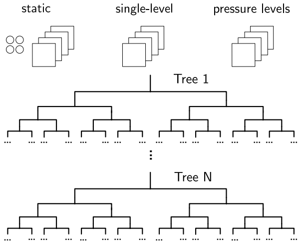


Snow and precipitation in remote high-mountain regions

- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

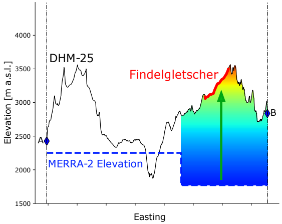
Gradient boosting regressor

From reanalysis' precipitation to SWE

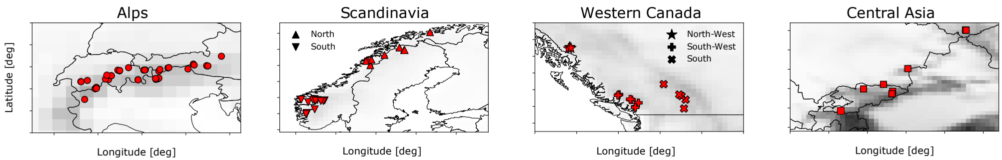


Reanalyses (ERA-5, MERRA-2)

∼Global coverage but unsuited for complex topography



Winter mass balance on glaciers



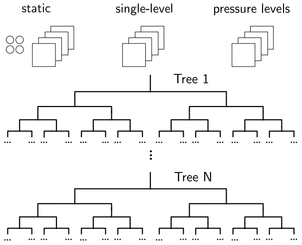
Snow and precipitation in remote high-mountain regions

- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

Cross-validation on independent glaciers/years

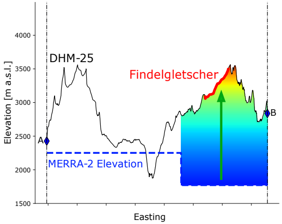
Gradient boosting regressor

From reanalysis' precipitation to SWE



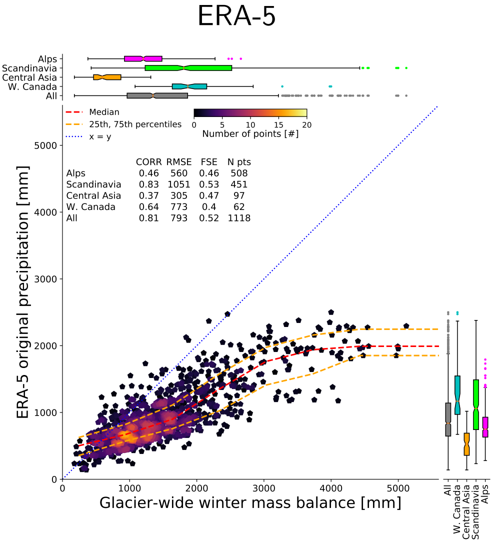
Reanalyses (ERA-5, MERRA-2)

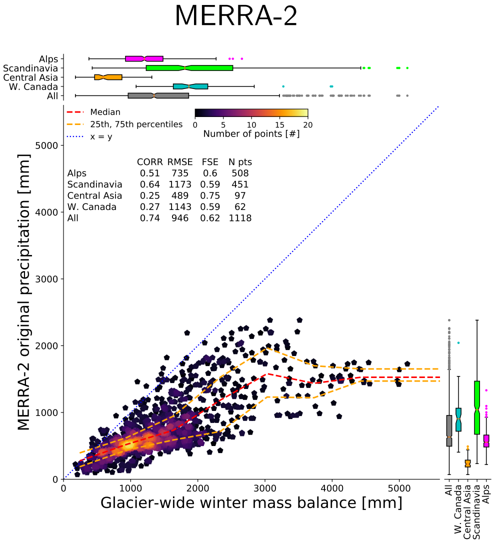
~Global coverage but unsuited for complex topography



UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

Models evaluation: original reanalyses

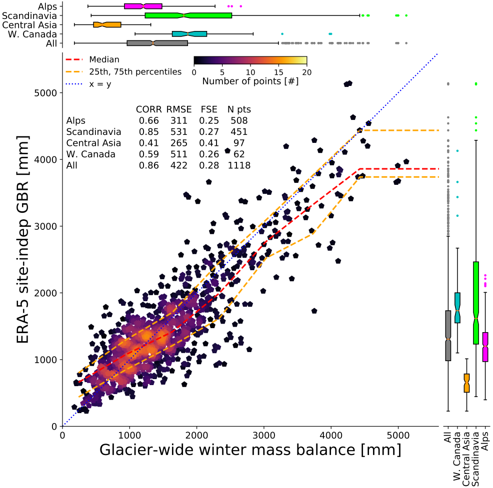




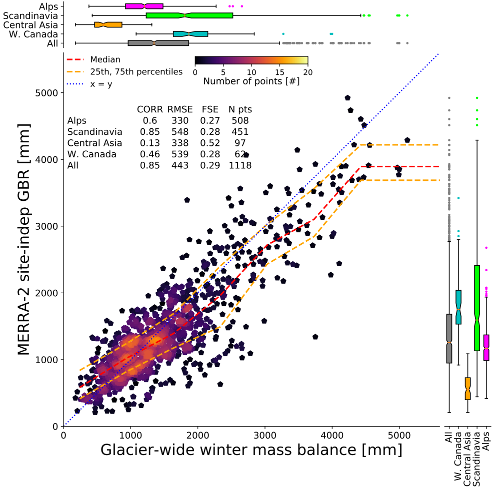
UNI FR UNIVERSITÉ DE FRIBOURG UNIVERSITÄT FREIBURG

Models evaluation: site-independent GBRs

ERA-5



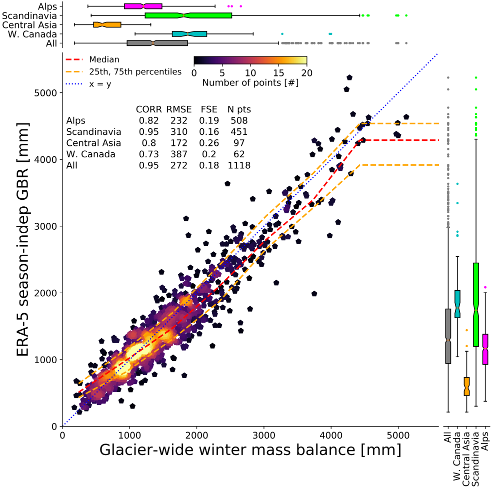
MERRA-2



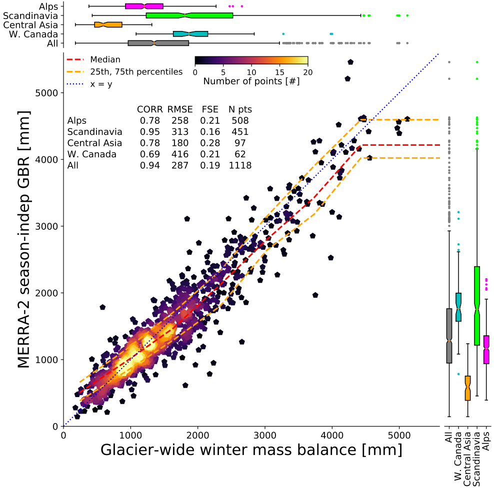
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

Models evaluation: season-independent GBRs

ERA-5

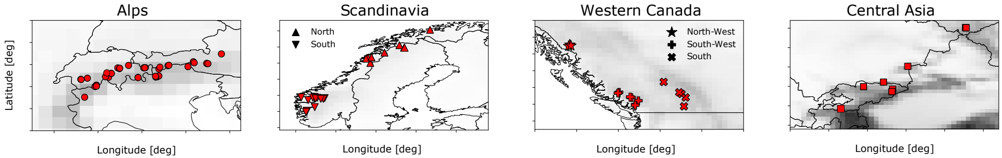


MERRA-2



UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

Winter mass balance on glaciers



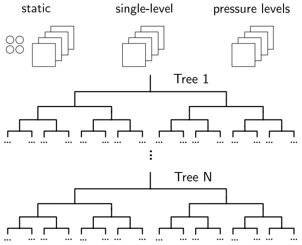
Snow and precipitation in remote high-mountain regions

- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

Cross-validation on independent glaciers/years

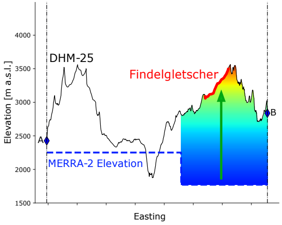
Gradient boosting regressor

From reanalysis' precipitation to SWE

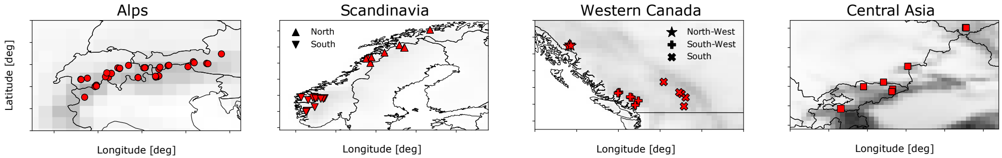


Reanalyses (ERA-5, MERRA-2)

∼Global coverage but unsuited for complex topography



Winter mass balance on glaciers



Snow and precipitation in remote high-mountain regions

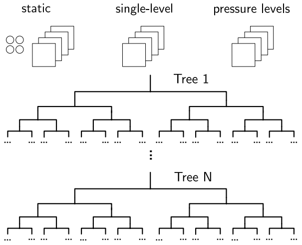
- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

Cross-validation on independent glaciers/years

- Spatial performance

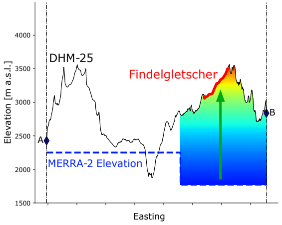
Gradient boosting regressor

From reanalysis' precipitation to SWE



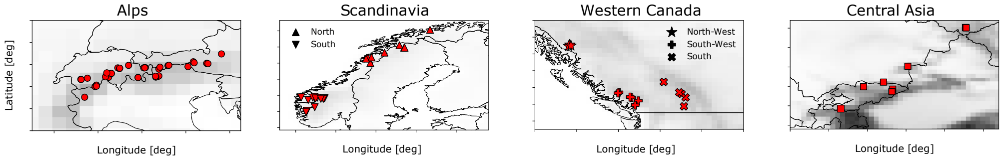
Reanalyses (ERA-5, MERRA-2)

∼Global coverage but unsuited for complex topography



UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

Winter mass balance on glaciers



Snow and precipitation in remote high-mountain regions

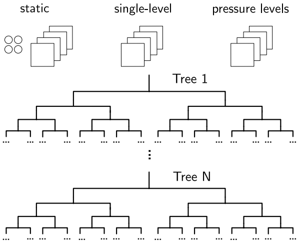
- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

Cross-validation on independent glaciers/years

- Spatial performance
- Temporal performance

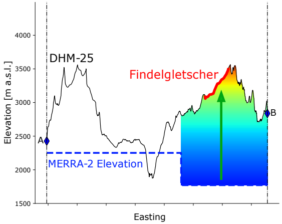
Gradient boosting regressor

From reanalysis' precipitation to SWE

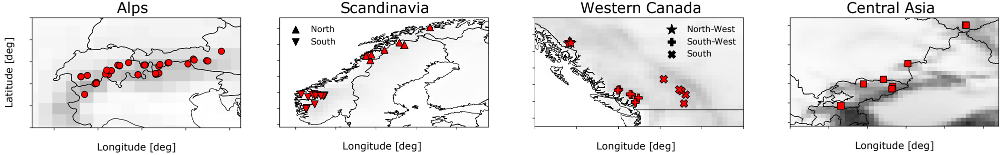


Reanalyses (ERA-5, MERRA-2)

∼Global coverage but unsuited for complex topography



Winter mass balance on glaciers



Snow and precipitation in remote high-mountain regions

- Essential for water availability, natural hazards, climate impact studies,...
- Scarcity of ground observations
- How precipitation and snow are changing?

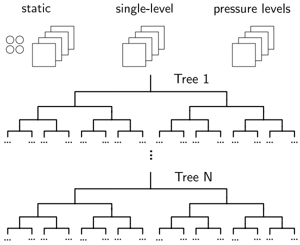
Cross-validation on independent glaciers/years

- Spatial performance
- Temporal performance

➡ **Climatological trends of snow accumulation (1981-2021)**

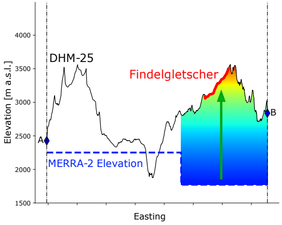
Gradient boosting regressor

From reanalysis' precipitation to SWE



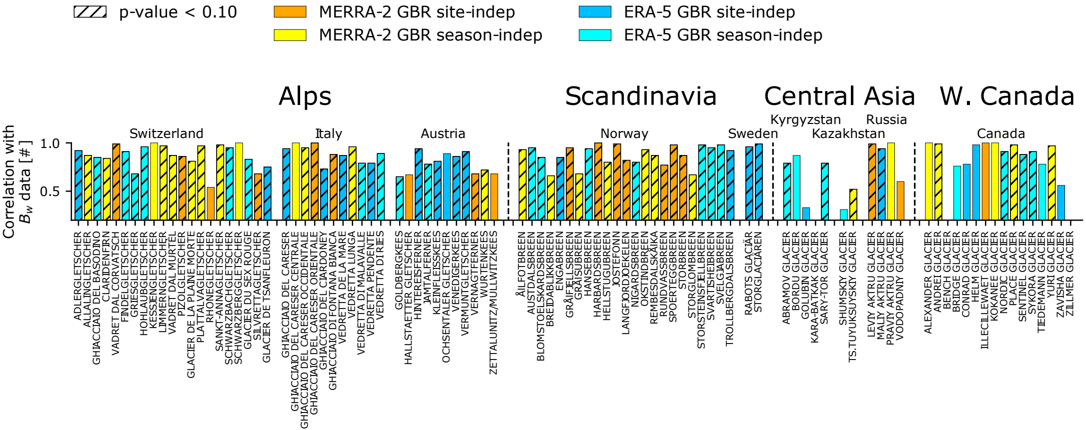
Reanalyses (ERA-5, MERRA-2)

∼Global coverage but unsuited for complex topography

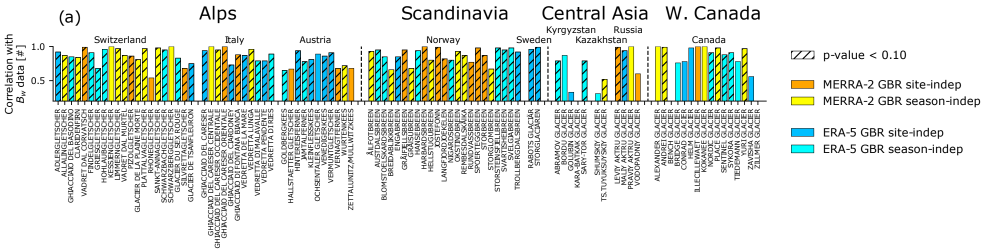


UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

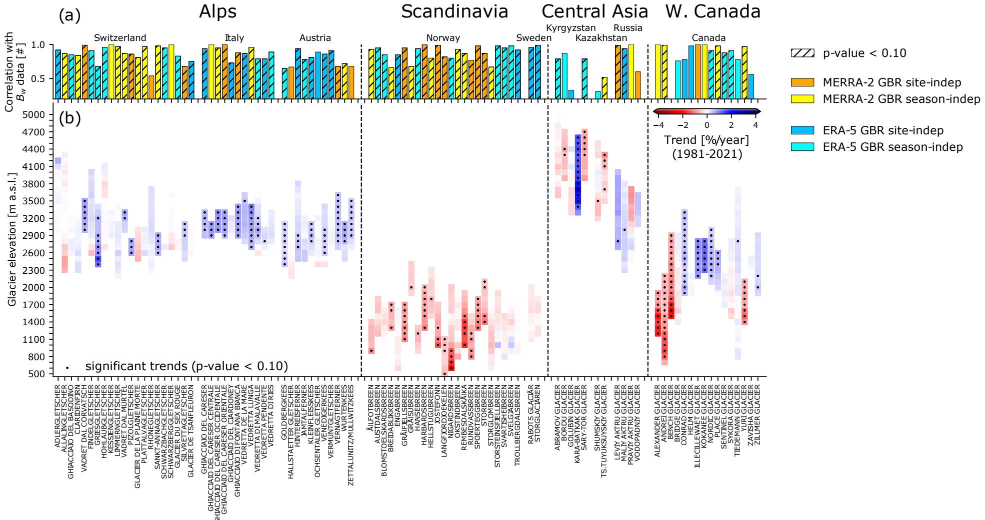
GBR-derived SWE trends (1981-2021)



GBR-derived SWE trends (1981-2021)



GBR-derived SWE trends (1981-2021)



UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

For further information, please see:

Guidicelli, M., Huss, M., Gabella, M., and Salzmann, N. Snow accumulation over the world's glaciers (1981–2021) inferred from climate reanalyses and machine learning, *The Cryosphere Discuss.* [preprint], https://doi.org/10.5194/tc-2022-69, in review, 2022.

References

Zemp, M. and Nussbaumer, S.U. and Gärtner-Roer, I. and Bannwart, J. and Paul, F. and Hoelzle, M. (eds.)
WGMS: Global Glacier Change Bulletin No. 4 (2018-2019)
ISC(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 278 pp.

Gugerli R., Salzmann N., Huss M., and Desilets D. (2019)
Evaluating continuous and autonomous snow water equivalent measurements by a cosmic ray sensor on a Swiss glacier
The Cryosphere 13, 3413–3434.

Gugerli R., Gabella M., Salzmann N., and Huss M. (2020)
Can weather radars be used to estimate snow accumulation on alpine glaciers? an evaluation based on glaciological surveys.
Journal of Hydrometeorology

Guidicelli, M., Gugerli, R., Gabella, M., Marty, C., and Salzmann, N. (2021)
Continuous spatio-temporal high-resolution estimates of SWE across the Swiss Alps - a statistical two-step approach for high-mountain topography.
Front. Earth Sci. - Cryospheric Sciences

Guidicelli M., Huss M., Gabella, M. and Salzmann N. (in review, 2022)
Snow accumulation over the world's glaciers (1981–2021) inferred from climate reanalyses and machine learning.
The Cryosphere Discuss. [preprint].

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., and Hsu, K.-L. (2018)
A review of global precipitation data sets: Data sources, estimation, and inter-comparison.
Reviews of Geophysics 56, 79-107.

Liston, G. E., and Elder, K. (2006)
A Meteorological Distribution System for High-Resolution Terrestrial Modeling (MicroMet).
Journal of Hydrometeorology 7, 217-234.

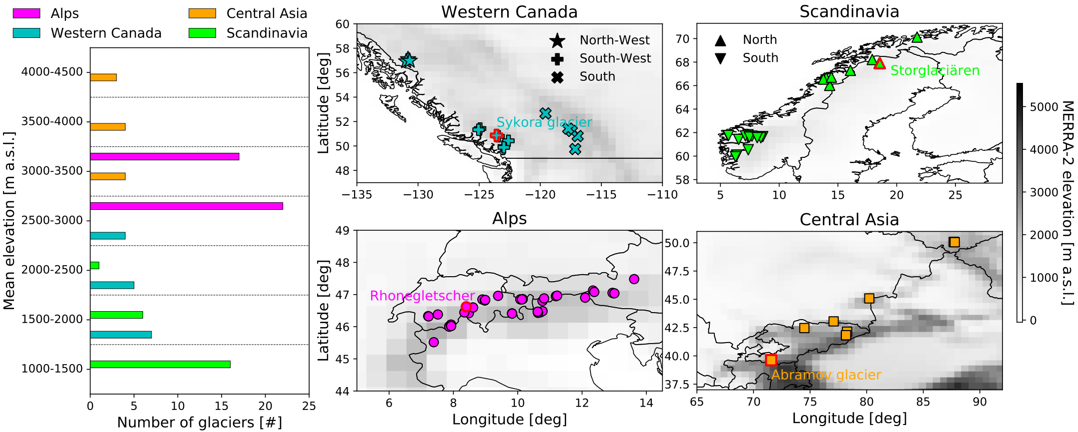
Fiddes, J. and Gruber, S. (2014)
TopoSCALE v.1.0: downscaling gridded climate data in complex terrain.
Geoscientific Model Development 7, 387-405.

Gupta, A. S. and Tarboton, D. G. (2016)
A tool for downscaling weather data from large-grid reanalysis products to finer spatial scales for distributed hydrological applications.
Environmental Modelling & Software 84, 50-69.

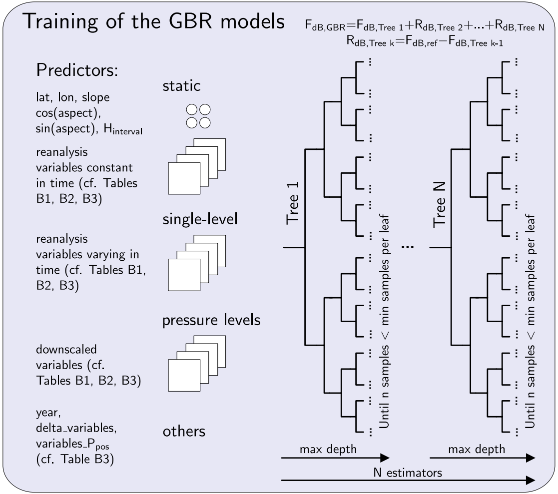
Thank you for your attention!

Questions?

Winter mass balance data from WGMS

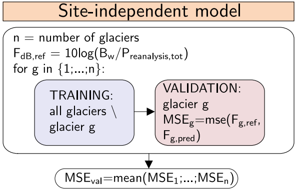


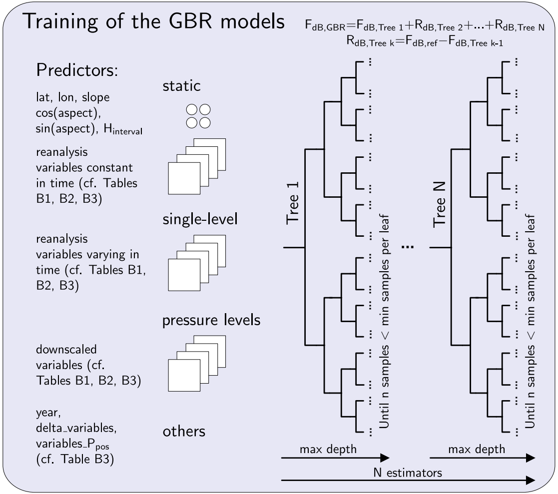
Gradient boosting regressor and cross-validation schemes



Gradient boosting regressor and cross-validation schemes

Cross-validation schemes:





Gradient boosting regressor and cross-validation schemes

Cross-validation schemes:

Site-independent model

n = number of glaciers
$F_{dB,ref} = 10\log(B_w/P_{reanalysis,tot})$
for g in {1;...;n}:

TRAINING: all glaciers \ glacier g → VALIDATION: glacier g $MSE_g = mse(F_{g,ref}, F_{g,pred})$

$MSE_{val} = mean(MSE_1;...;MSE_n)$

Season-independent model

n = number of glaciers
$F_{dB,ref} = 10\log(B_w/P_{reanalysis,tot})$
for g in {1;...;n}:

m = number of seasons for glacier g
for s in {1;...;m}:

TRAINING: all glaciers & all seasons \ season s of glacier g → VALIDATION: season s of glacier g $MSE_{g,s} = mse(F_{g,s,ref}, F_{g,s,pred})$

$MSE_{val} = mean(MSE_{1,1(1)};...;MSE_{1,m(1)};...;MSE_{n,1(n)};...;MSE_{n,m(n)})$

Training of the GBR models

$F_{dB,GBR} = F_{dB,Tree\ 1} + R_{dB,Tree\ 2} + ... + R_{dB,Tree\ N}$
$R_{dB,Tree\ k} = F_{dB,ref} - F_{dB,Tree\ k\text{-}1}$

Predictors:

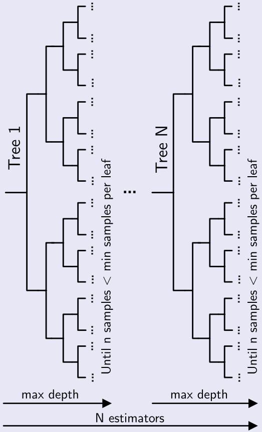
static: lat, lon, slope cos(aspect), sin(aspect), $H_{interval}$

single-level: reanalysis variables constant in time (cf. Tables B1, B2, B3)

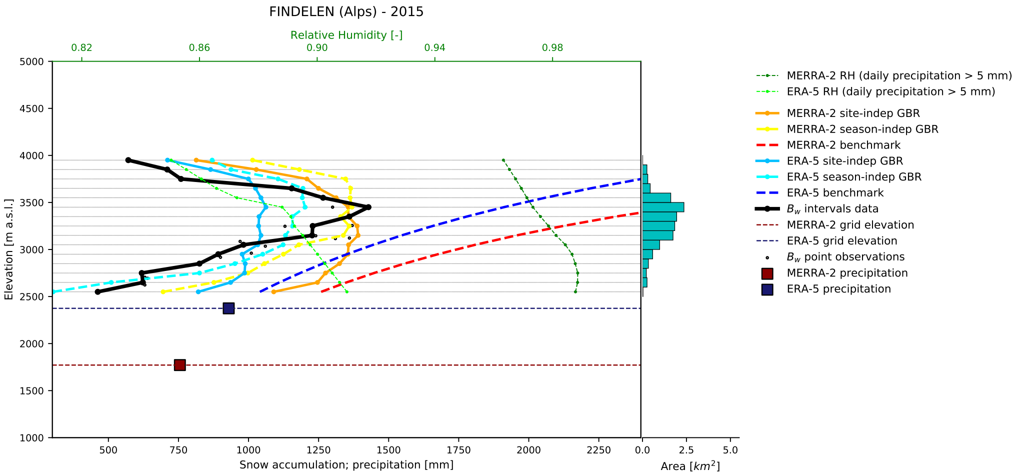
reanalysis variables varying in time (cf. Tables B1, B2, B3)

pressure levels: downscaled variables (cf. Tables B1, B2, B3)

others: year, delta_variables, variables_P_{pos} (cf. Table B3)

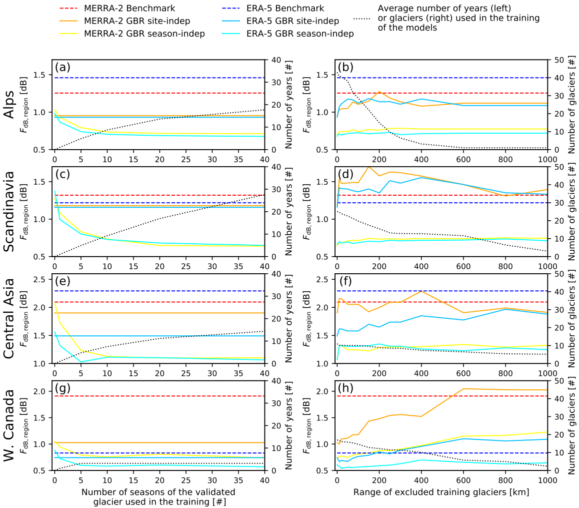


Spatial evaluation



UNI FR
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG

Further spatio-temporal validation



UNI FR UNIVERSITÉ DE FRIBOURG UNIVERSITÄT FREIBURG