Hydrological impact of climate change in mountain regions: Will we have enough water in the future?

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Introduction

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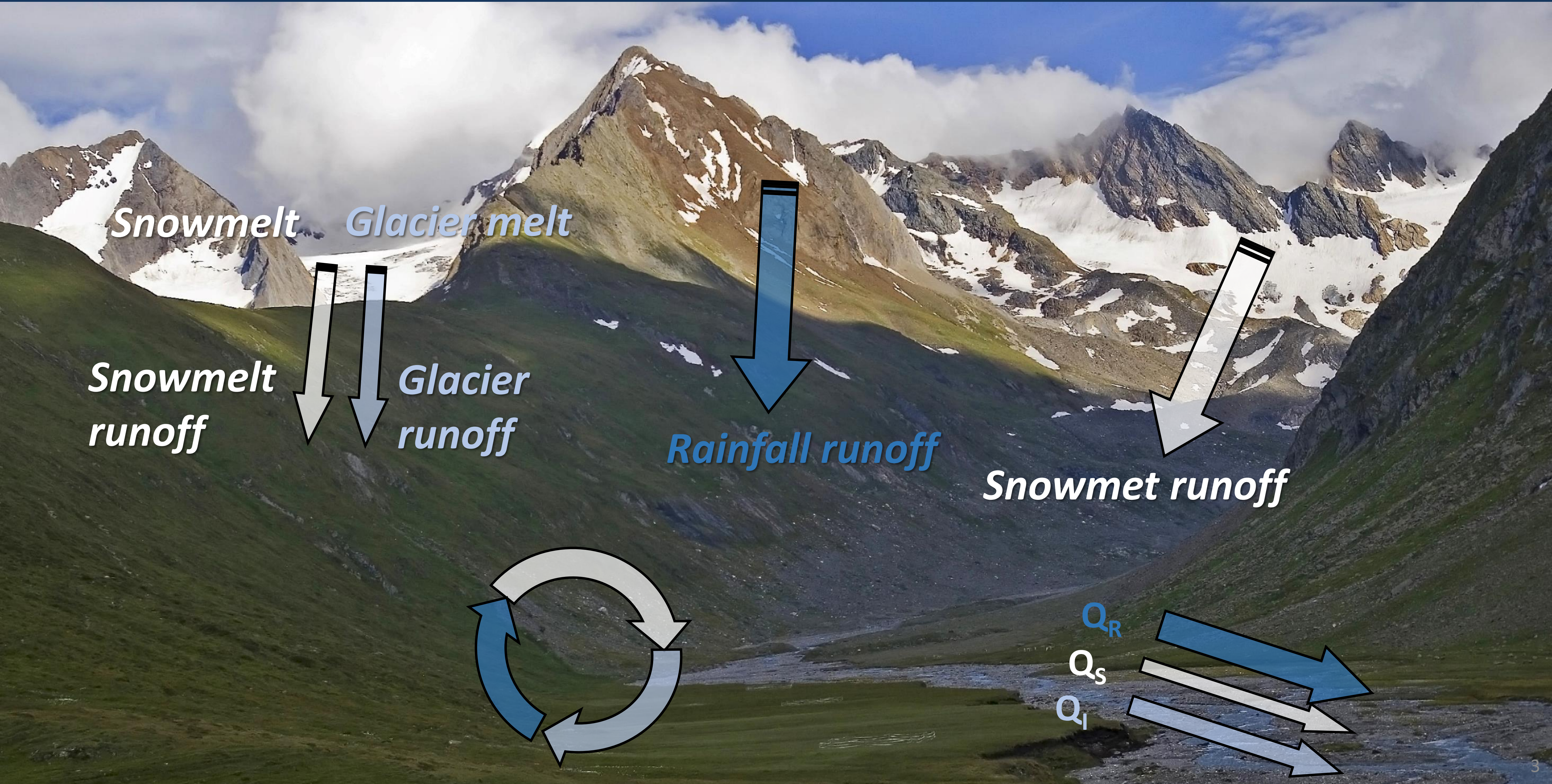


Introduction

January 18, 2013
SWE: normal conditions

January 18, 2014
SWE: 10-30% of normal

Source: NASA Earth Observatory (http://earthobservatory.nasa.gov/NaturalHazards/)

Role of snow in water balance – a global scale (Berghuijs et al., 2014)

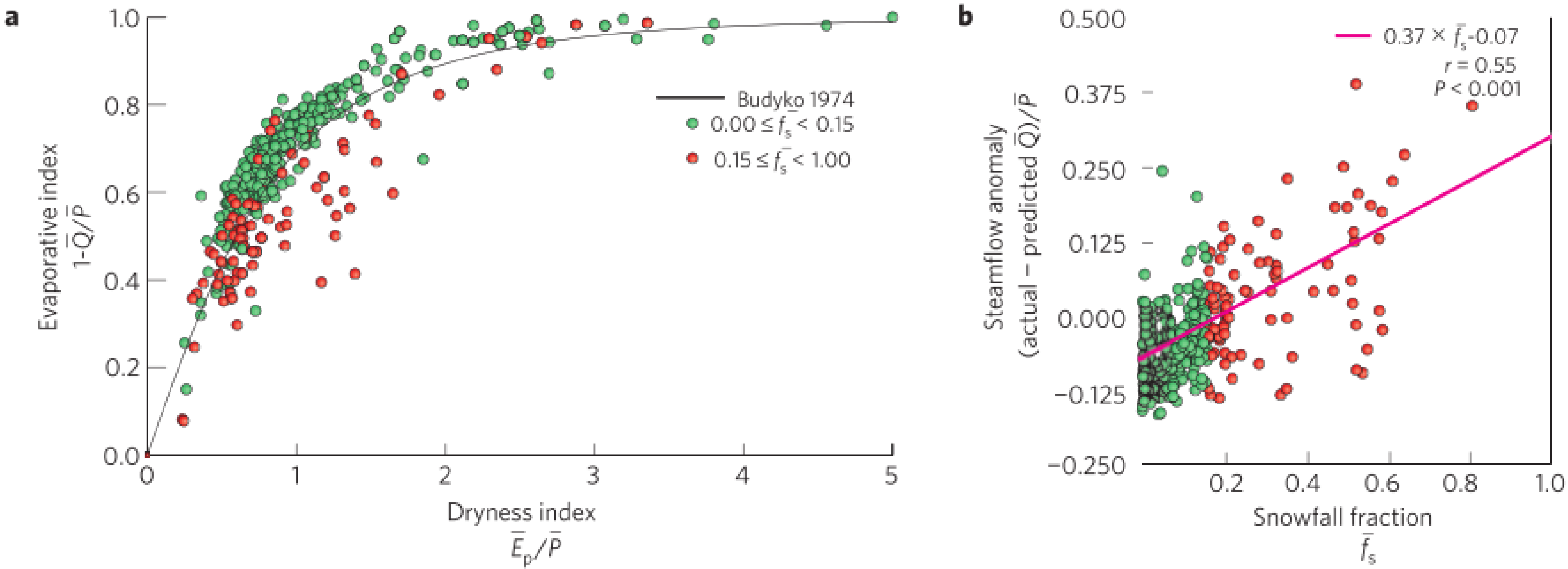
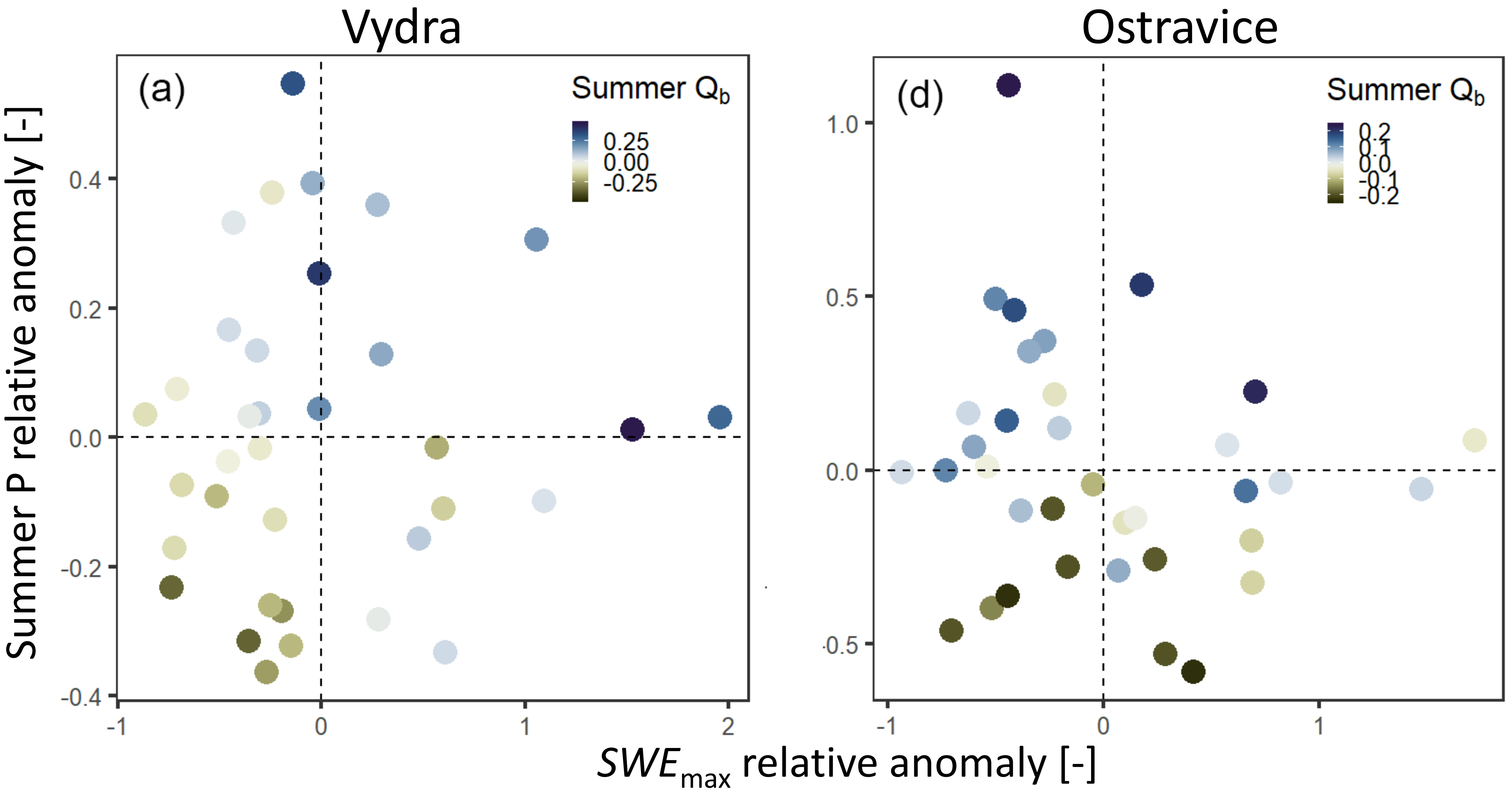
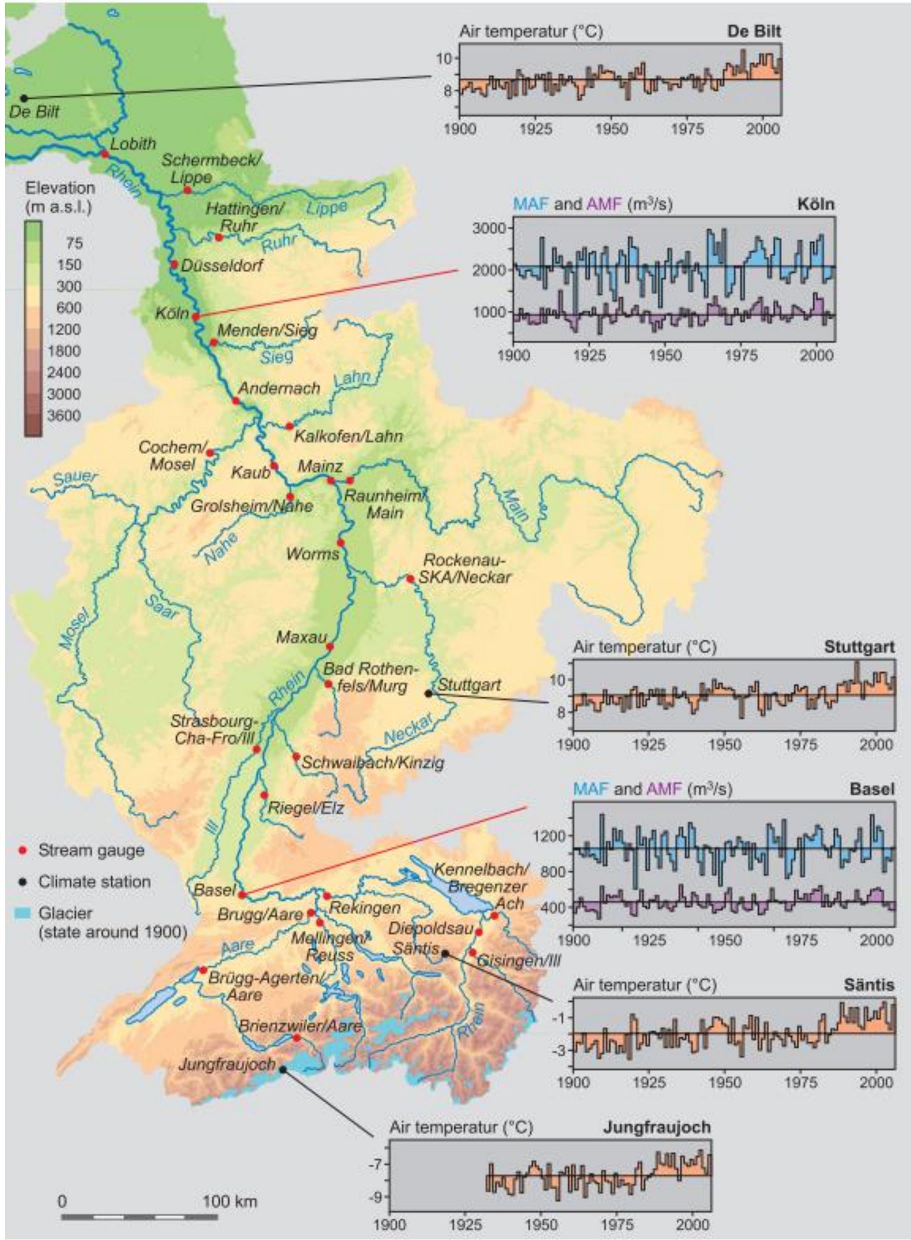


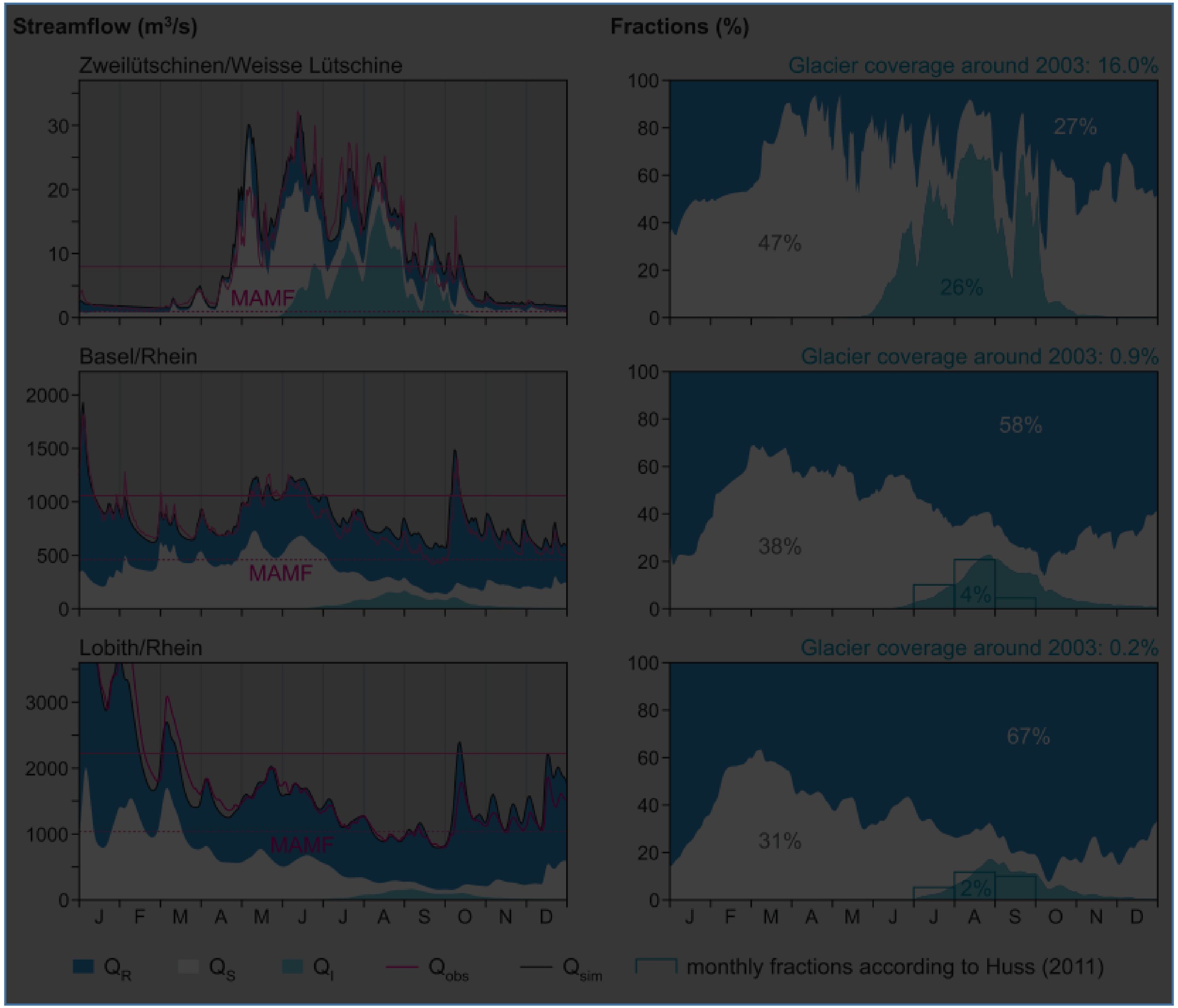
Figure 1 | Mean annual streamflow and streamflow anomaly in the context of the Budyko hypothesis, stratified by snow fraction. The observed long-term streamflow and precipitation measurements are placed in the context of the Budyko hypothesis. The Budyko hypothesis states the mean streamflow is primarily a function of the catchment's annual precipitation and potential evaporation as shown by the black line in **a**. Departures below the Budyko curve for catchments with a significant fraction of the precipitation falling as snow indicate that an increased fraction of precipitation as snowfall is associated with higher streamflow, as clarified by the linear regression in **b**.

Snow effect on baseflow (Jenicek and Ledvinka, 2020)



Impact of glaciers on summer runoff (Stahl et al., 2016)





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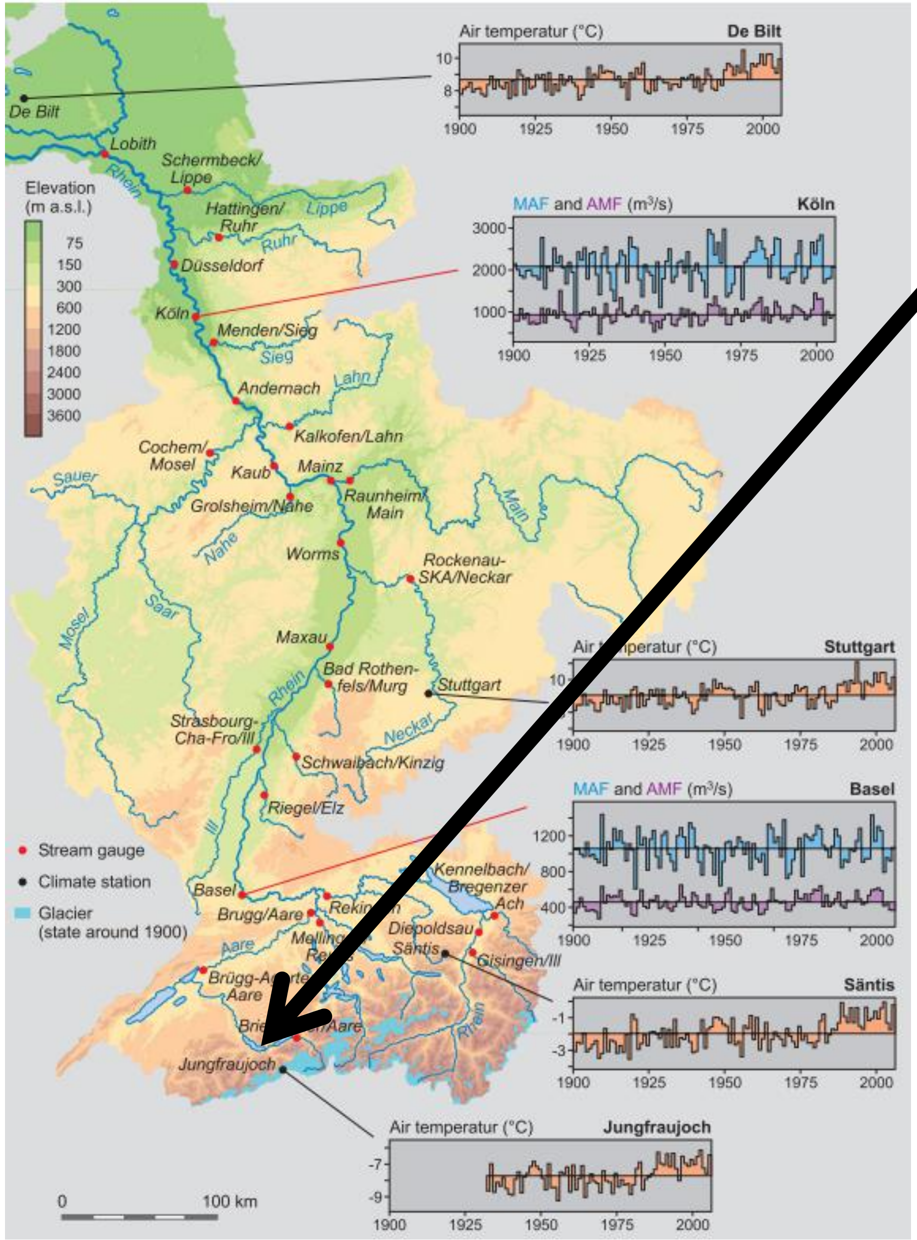

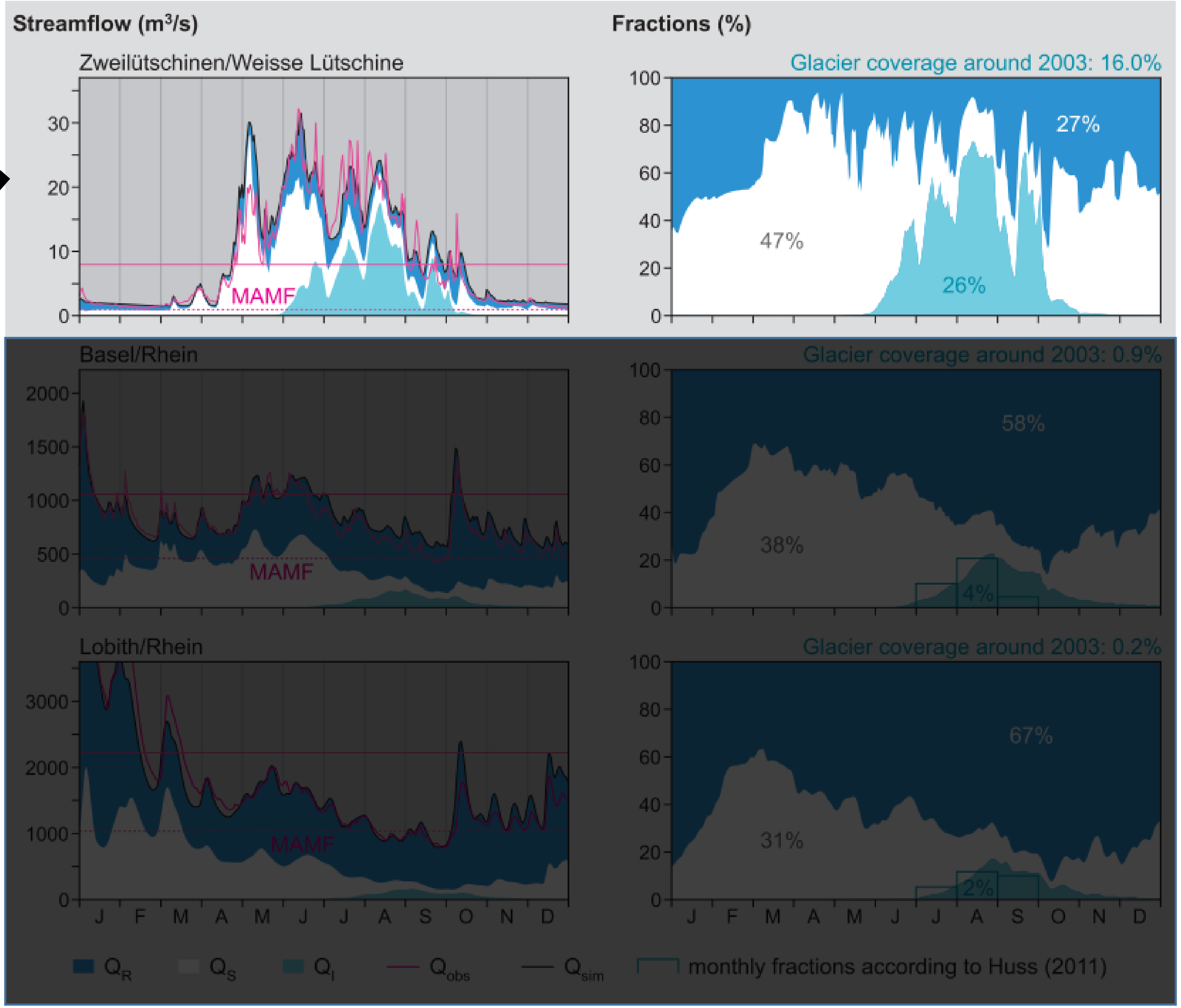

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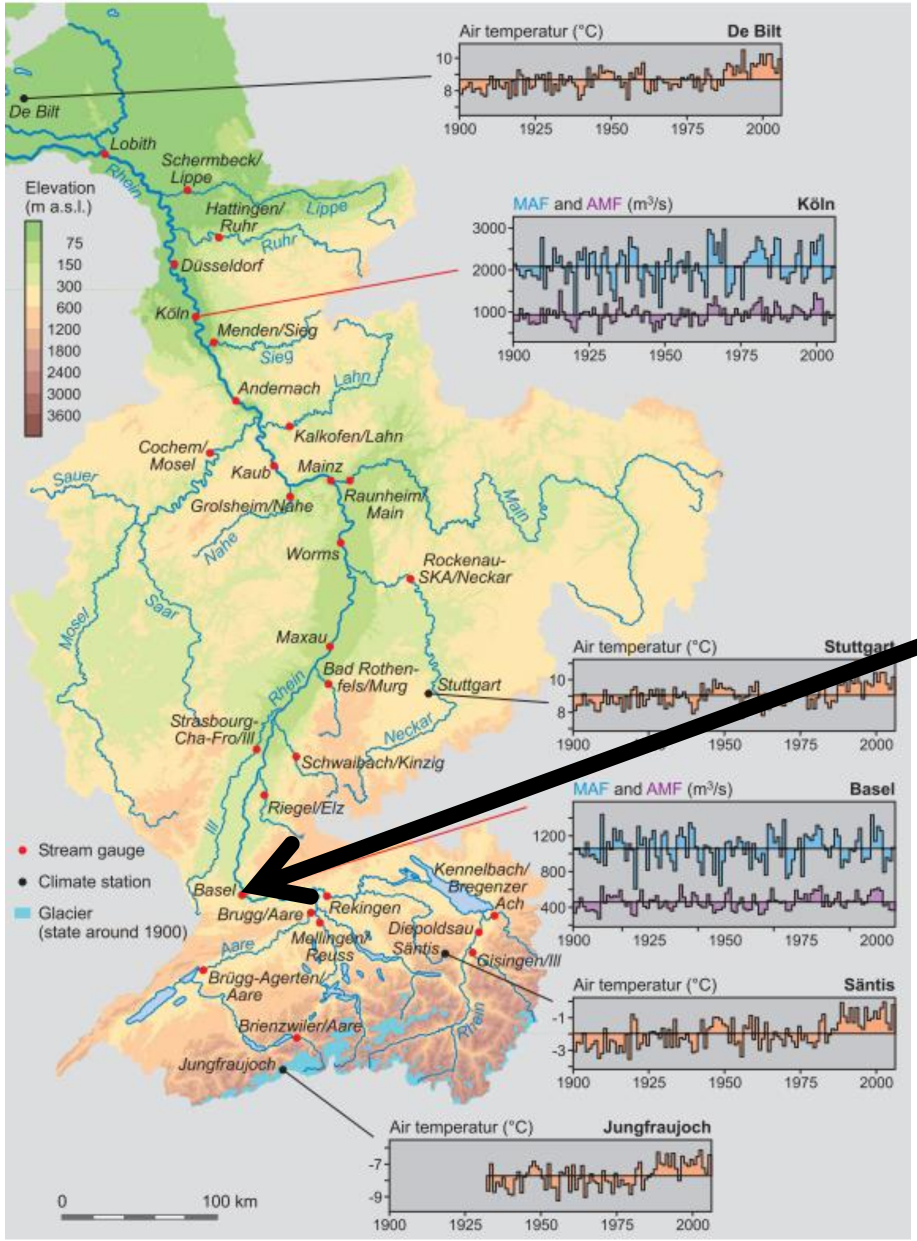

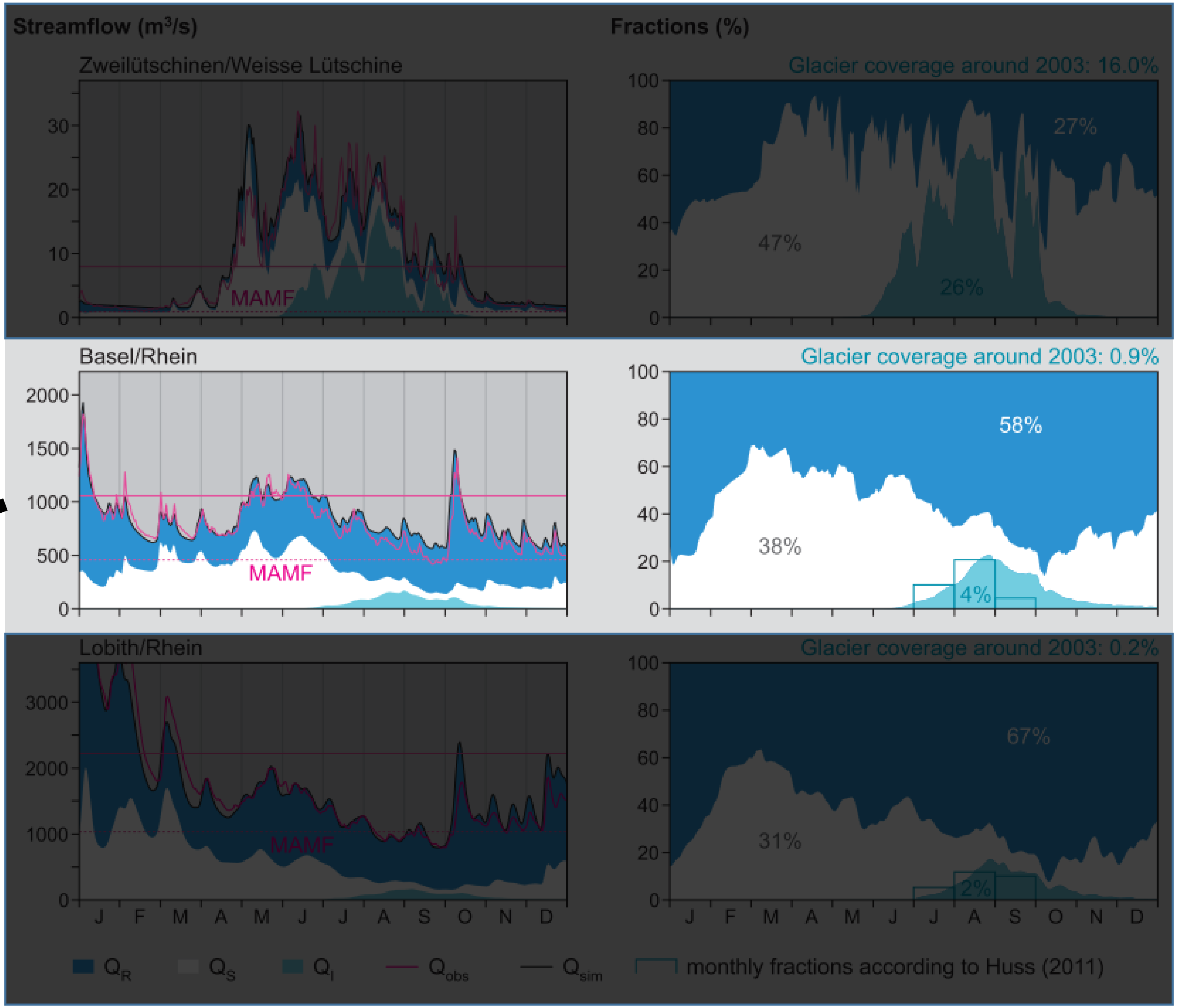

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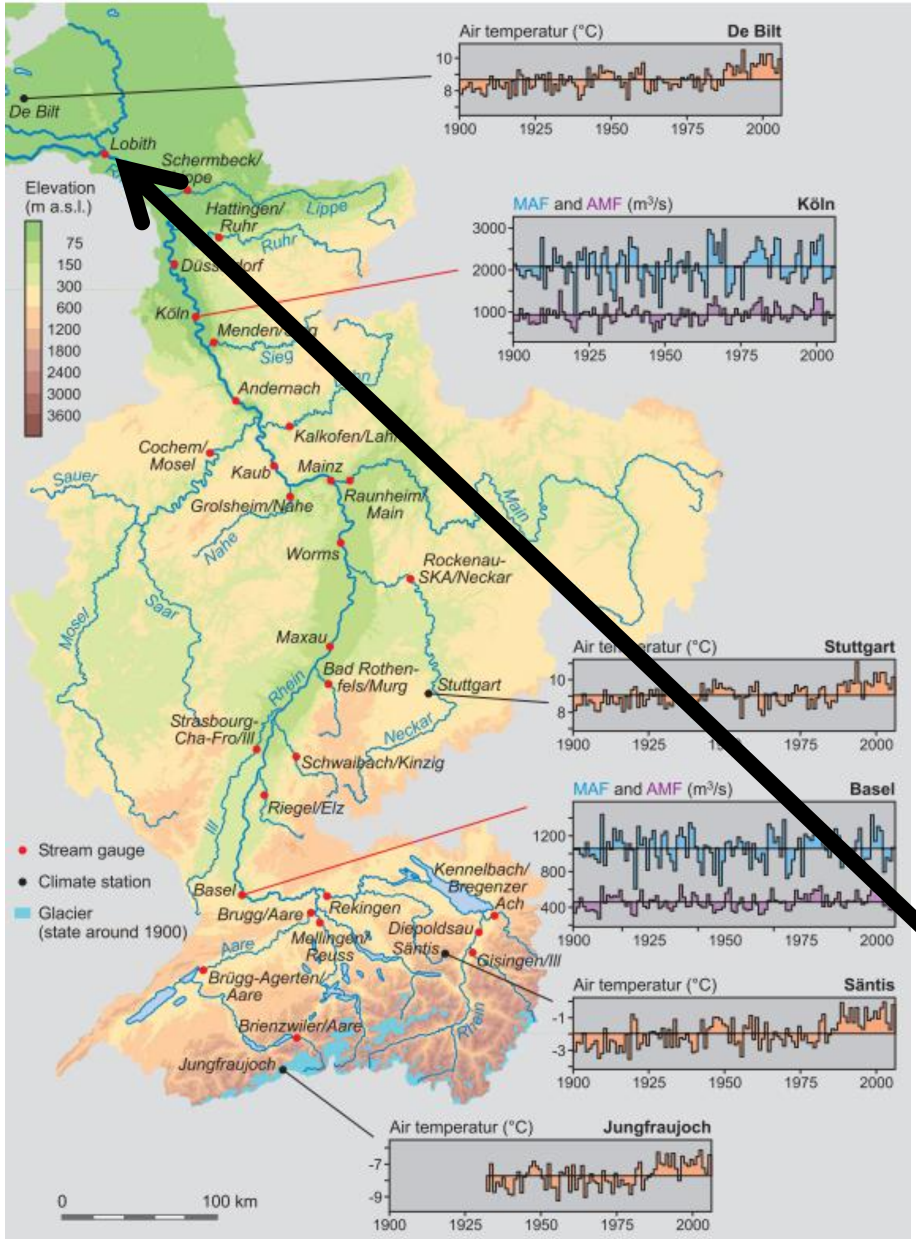

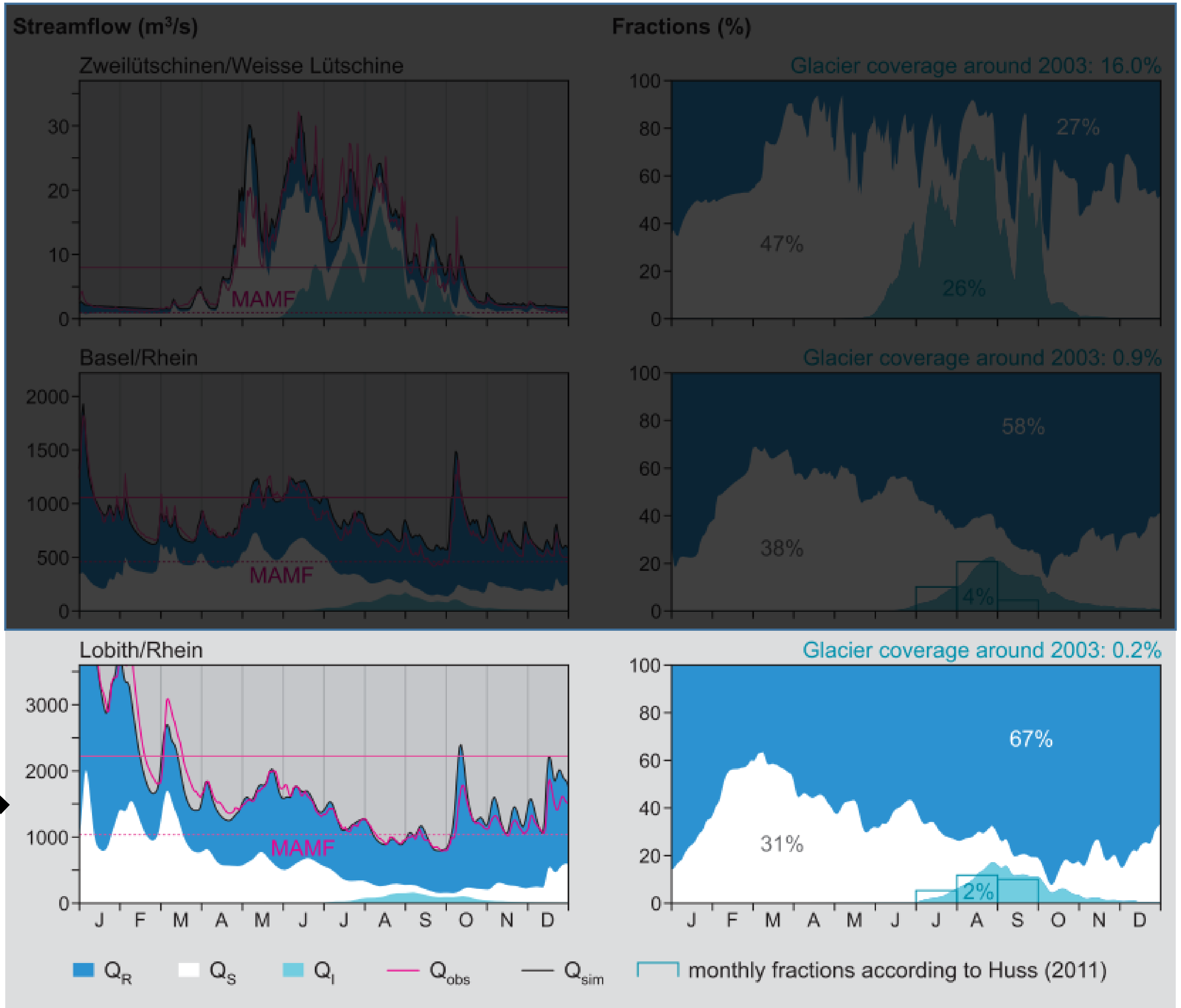

And glaciers are melting ...

Austria, Ötztal, Gurgler Ferner

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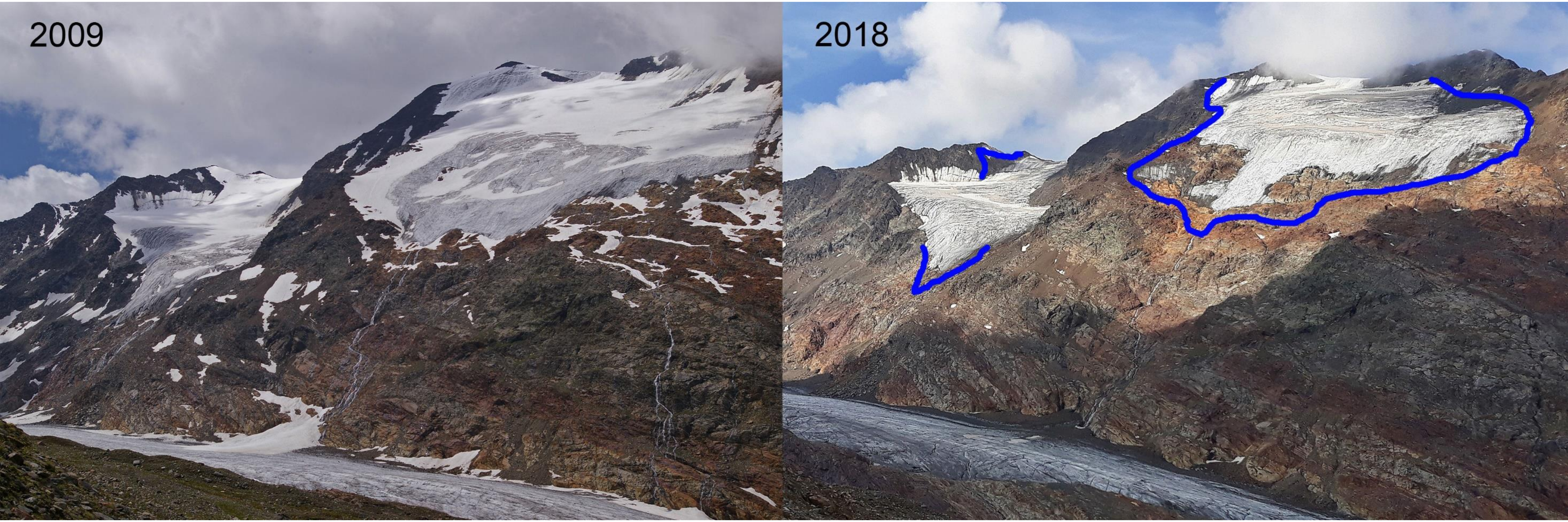
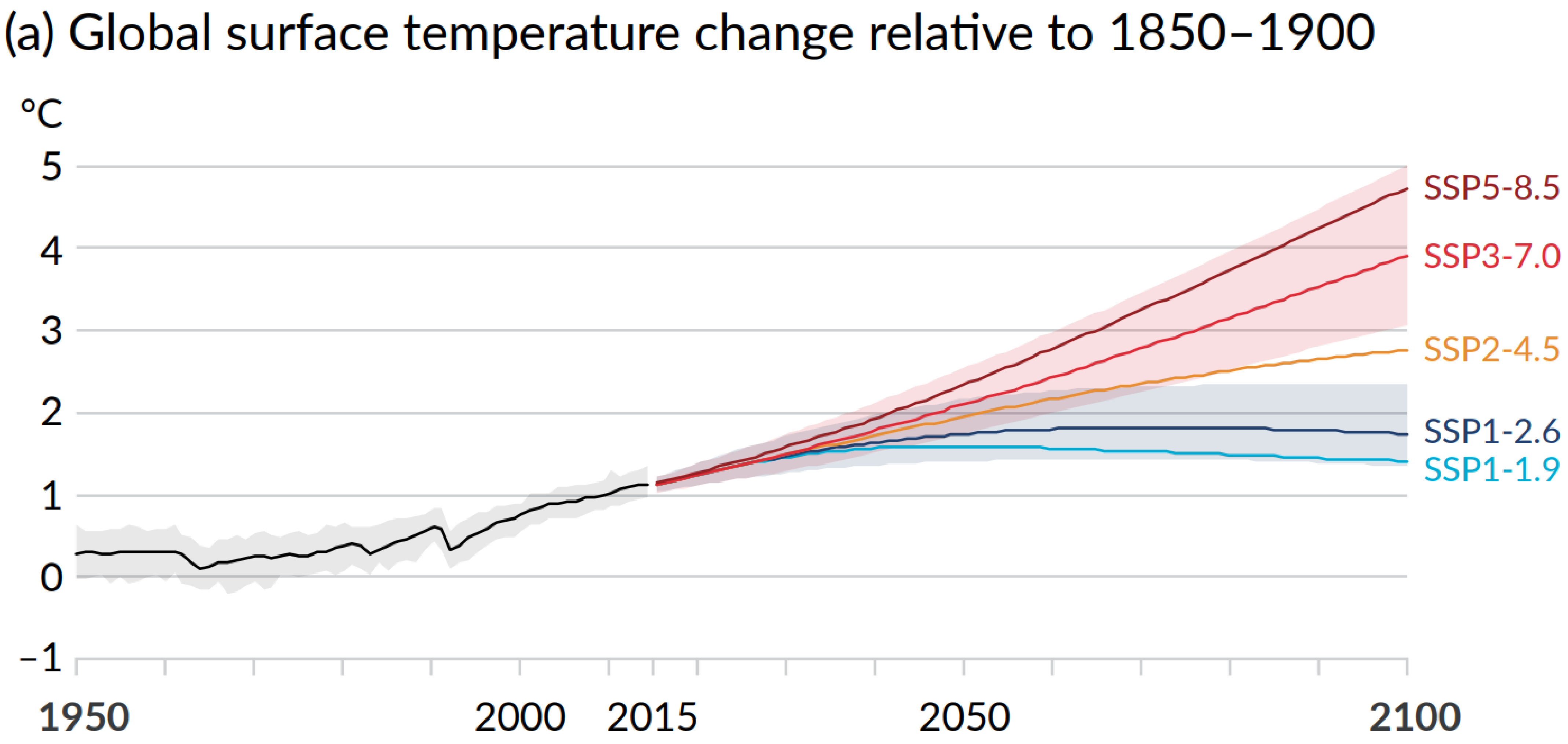


Austria, Ötztal, Gurgler Ferner

What can we expect?



Source: AR6 Climate Change 2021: The Physical Science Basis, Summary for Policymakers

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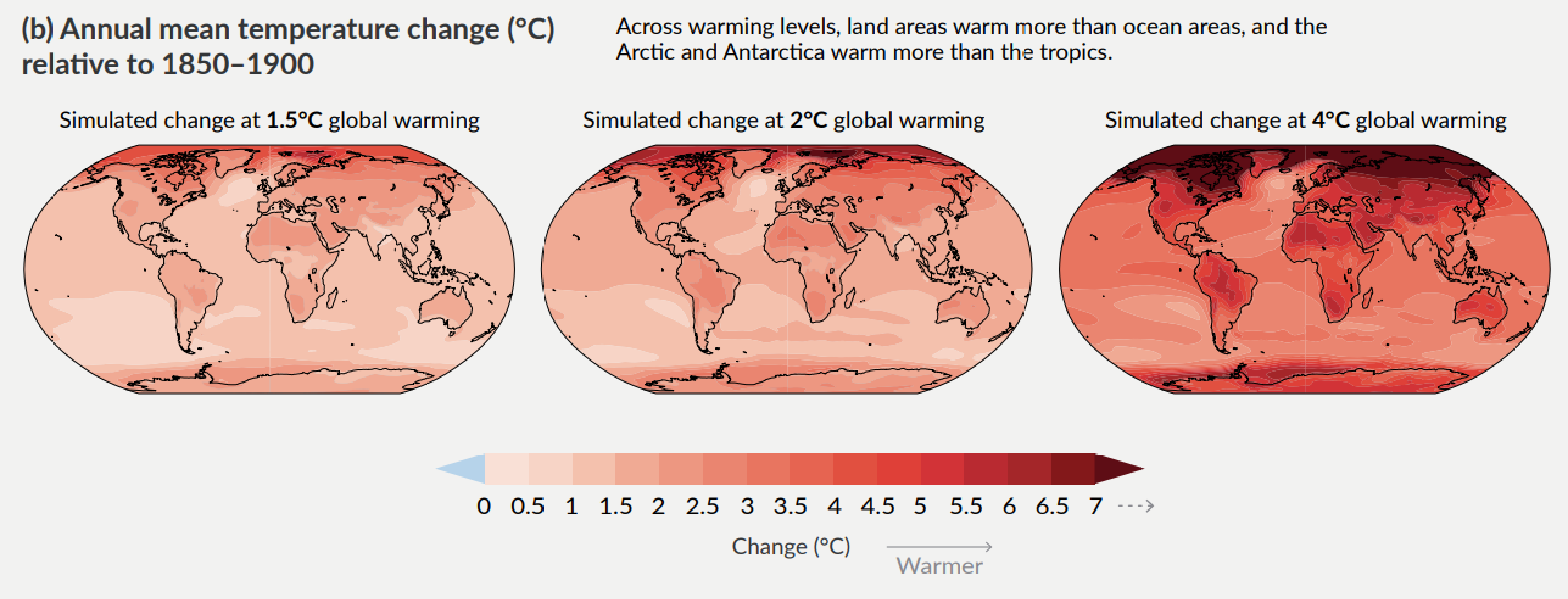

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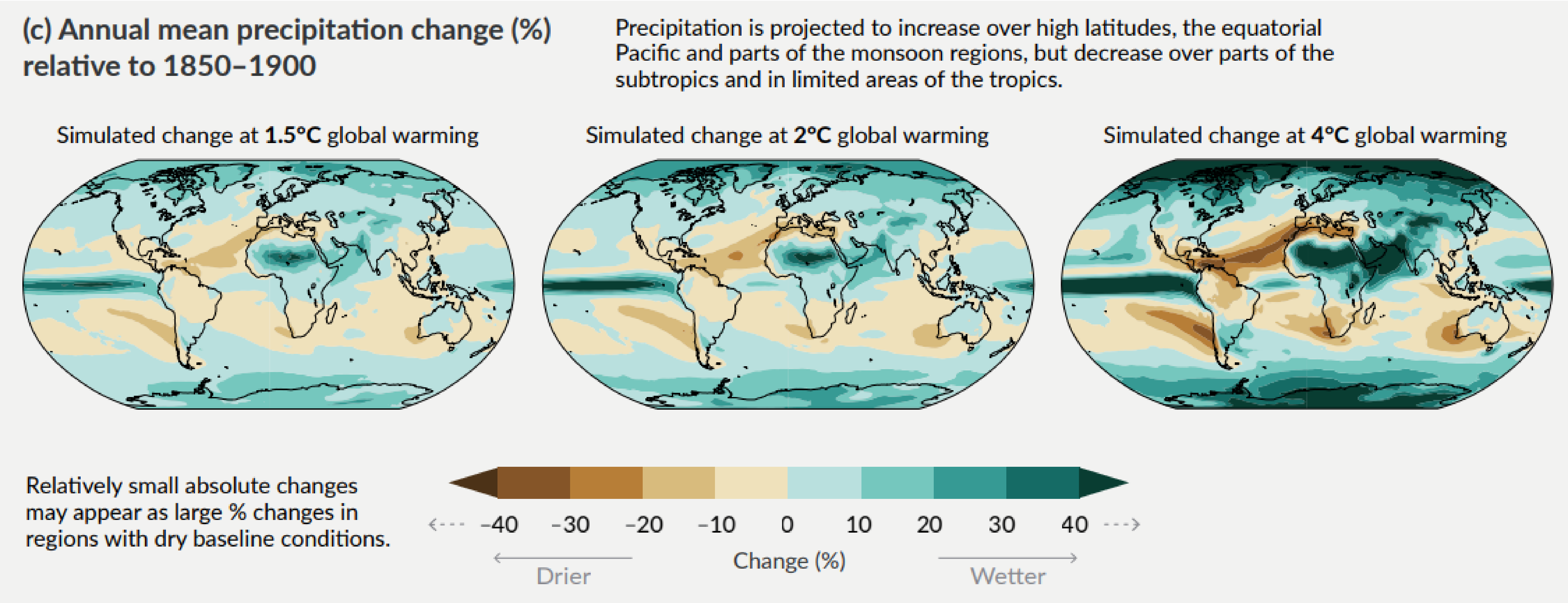

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How do we assess impact of climate changes on runoff?

Extrapolation of observed runoff trends into the future

Analysing runoff quantiles (e.g. Q_{95} i.e. the flow that is exceeded 95% of the time) using e.g. Mann-Kendall approach (analyse of trends in a time series)

Extrapolation of changing stochastic rainfall characteristics into the future combined with rainfall-runoff modelling

A stochastic model may be used to investigate what would happen if the trend of observed precipitation and air temperature characteristics in the historical period would persist into the future

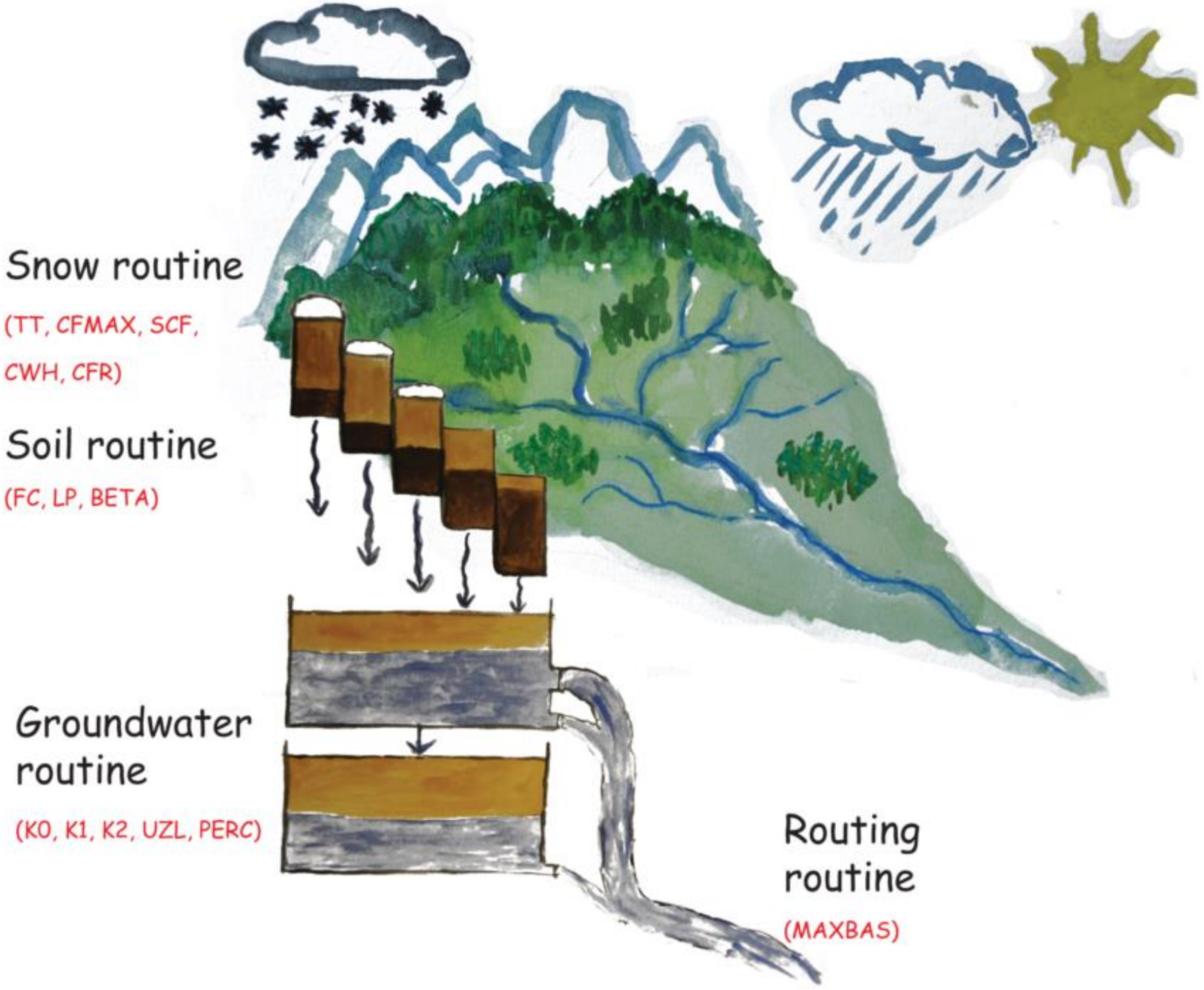
Rainfall–runoff projections based on climate scenarios

Modelling the catchment runoff based on climate scenarios (typically ensemble approach based on RCMs)

(based on Laaha et al. 2016, HESS)

How do we assess impact of climate changes on runoff?

1. HBV-light model (Seibert and Vis, 2012)
2. Observed data: precipitation, air temperature, discharge, SWE
3. Model calibration agains streamflow and SWE.
4. Results analysis



How do we assess impact of climate changes on runoff?

Model set-up and calibration

- Model set-up and calibration based on historical observations

Scenario preparation

- Daily corrections of temperature and precipitation applied to the ref. period
- Considers e.g. CO_2 evolution

Scenario simulation

- Application of different climate scenarios in a hydrological model
- Simulation of ensemble of future hydrological projections

Results analysis

- Changes in snow storages
- Changes in runoff seasonality
- Changes in runoff extremity
- etc.

Changes in hydrological regime in Czechia (Hanel et al, 2012)

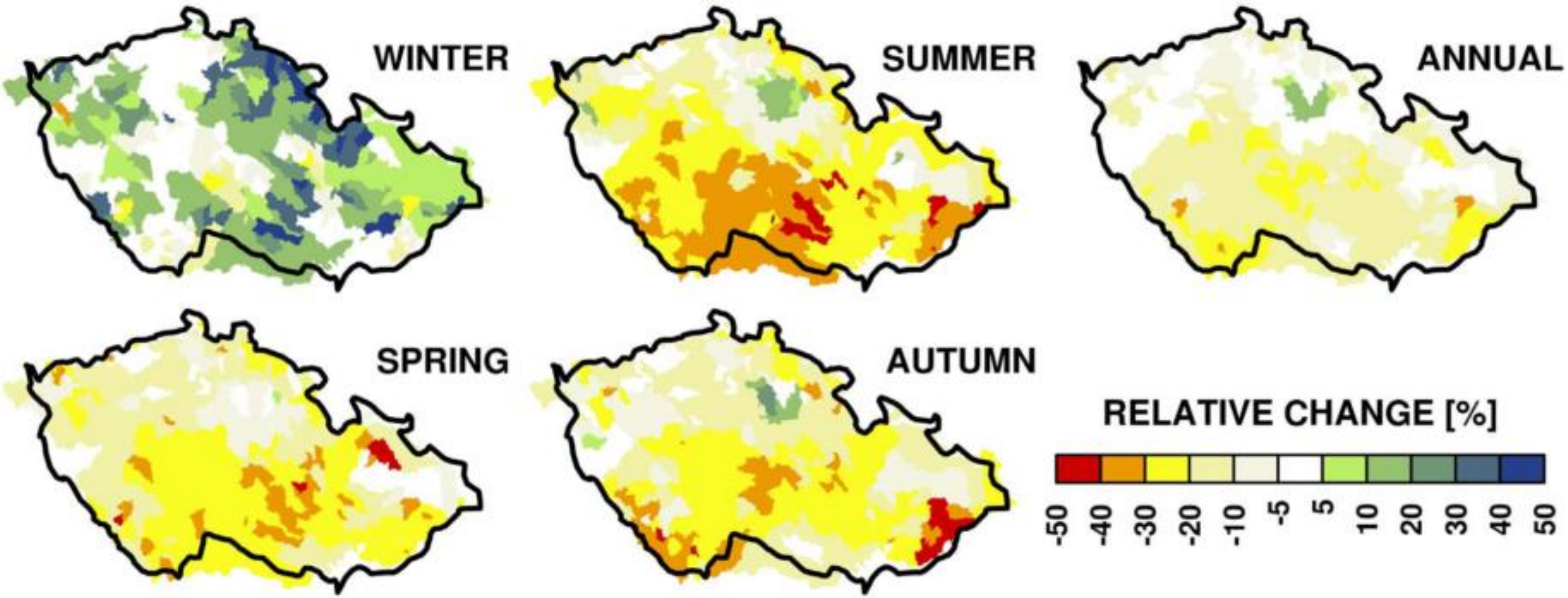
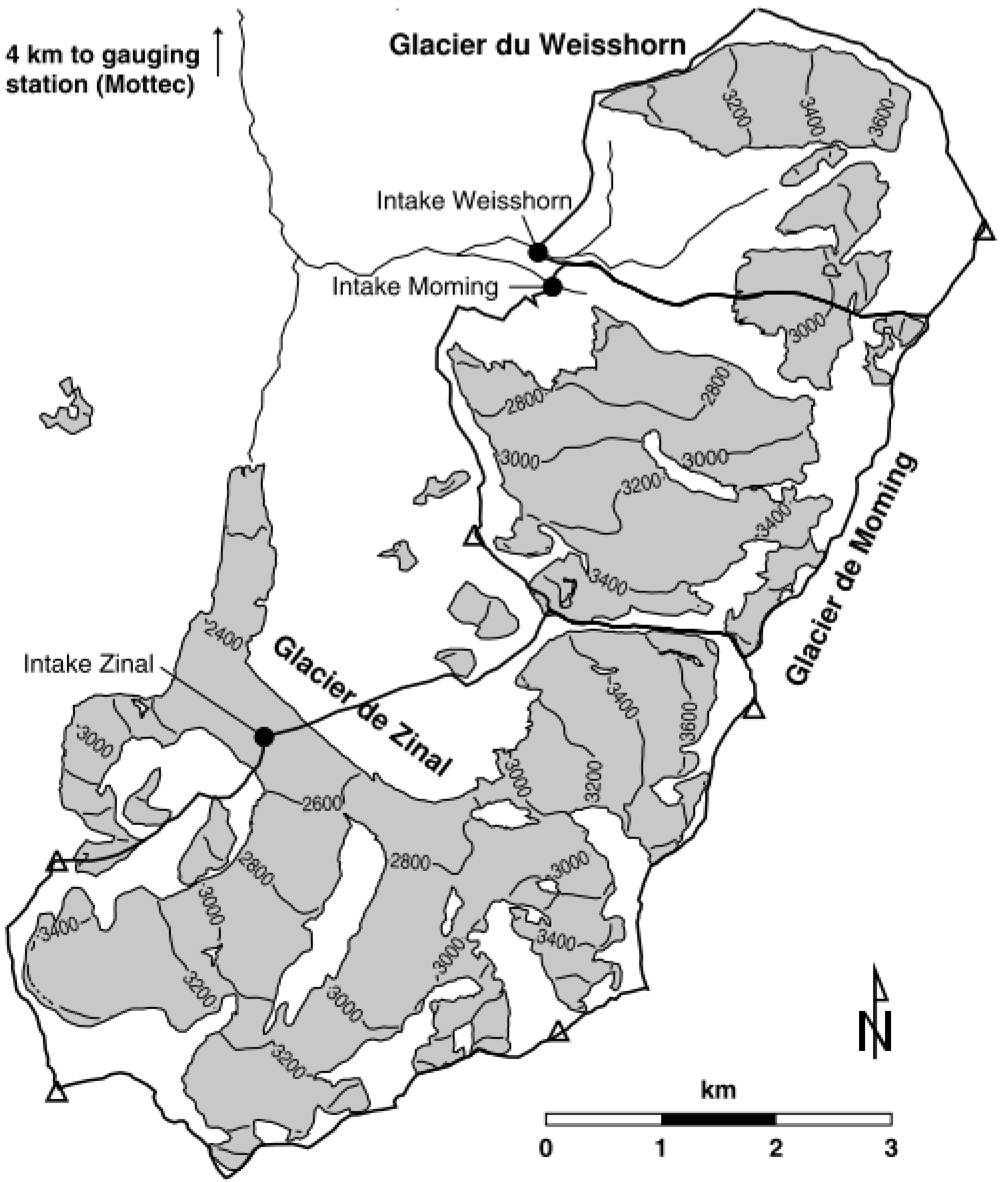
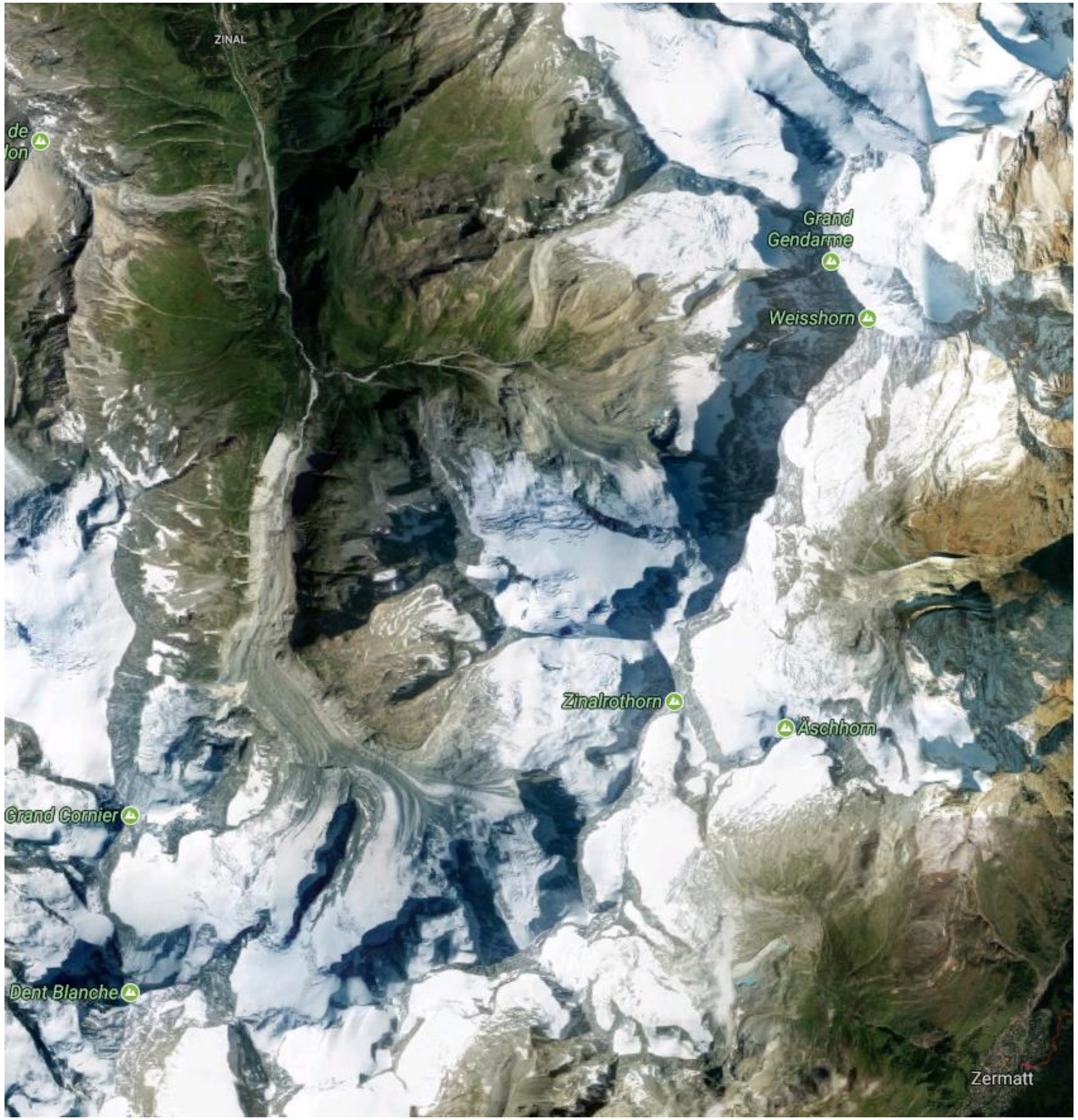


Fig. 4. Seasonal and annual relative changes in runoff [%] between the control and scenario period. Note that the changes are mostly positive in winter and negative in the other seasons.

Glaciers influence on summer runoff (Huss et al. 2008)

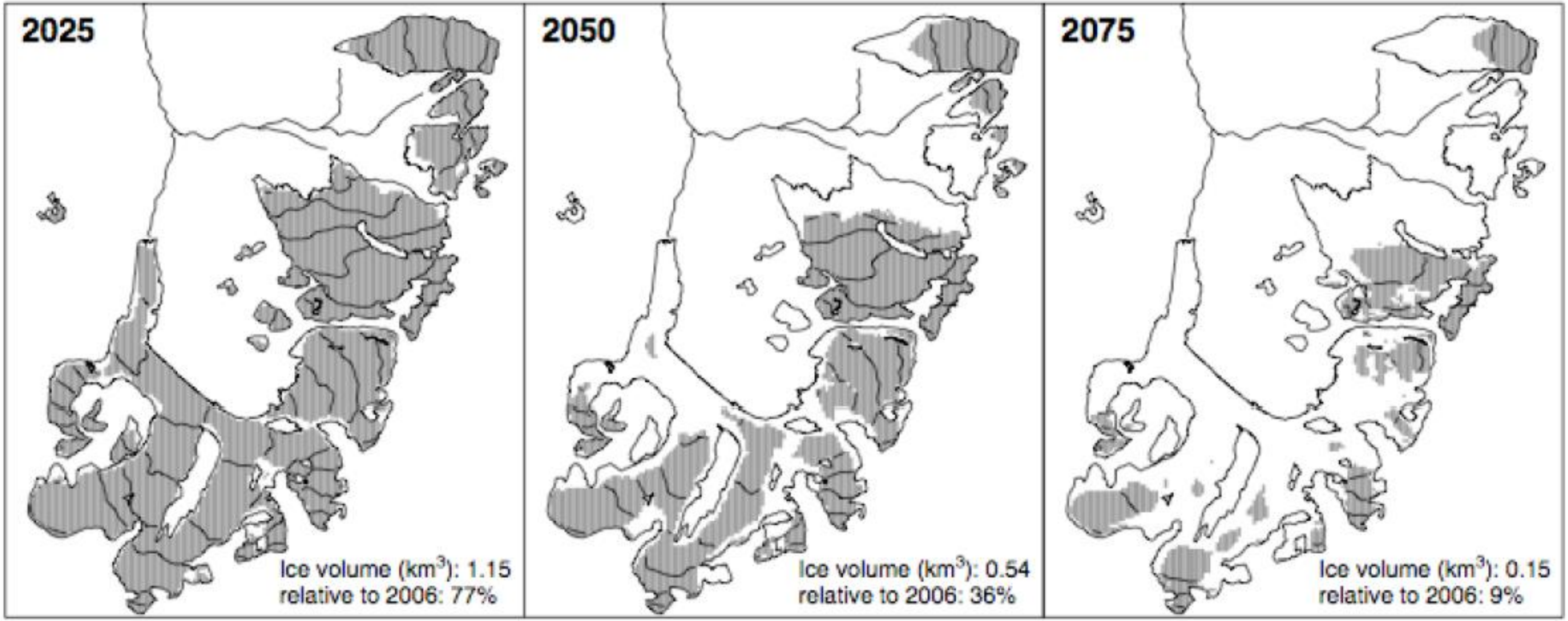




Glaciers influence on summer runoff (Huss et al. 2008)

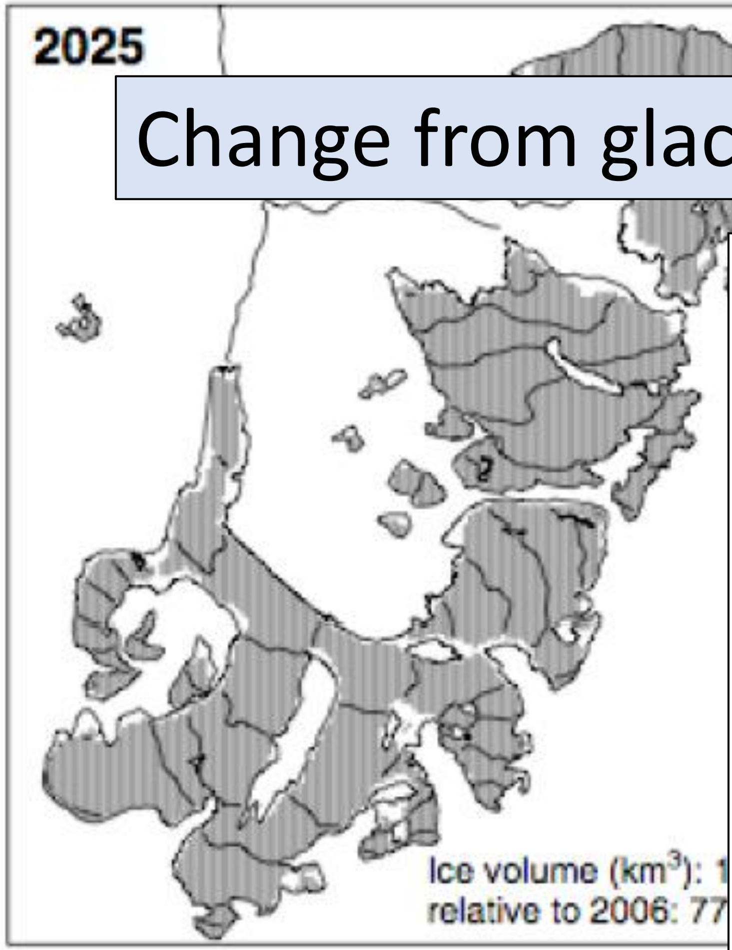
Zinal valley, Switzerland: from Weisshorn (4506 m a.s.l.) to Dent Blanche (4357 m a.s.l). Photo by Michal Jenicek

Glaciers influence on summer runoff (Huss et al. 2008)

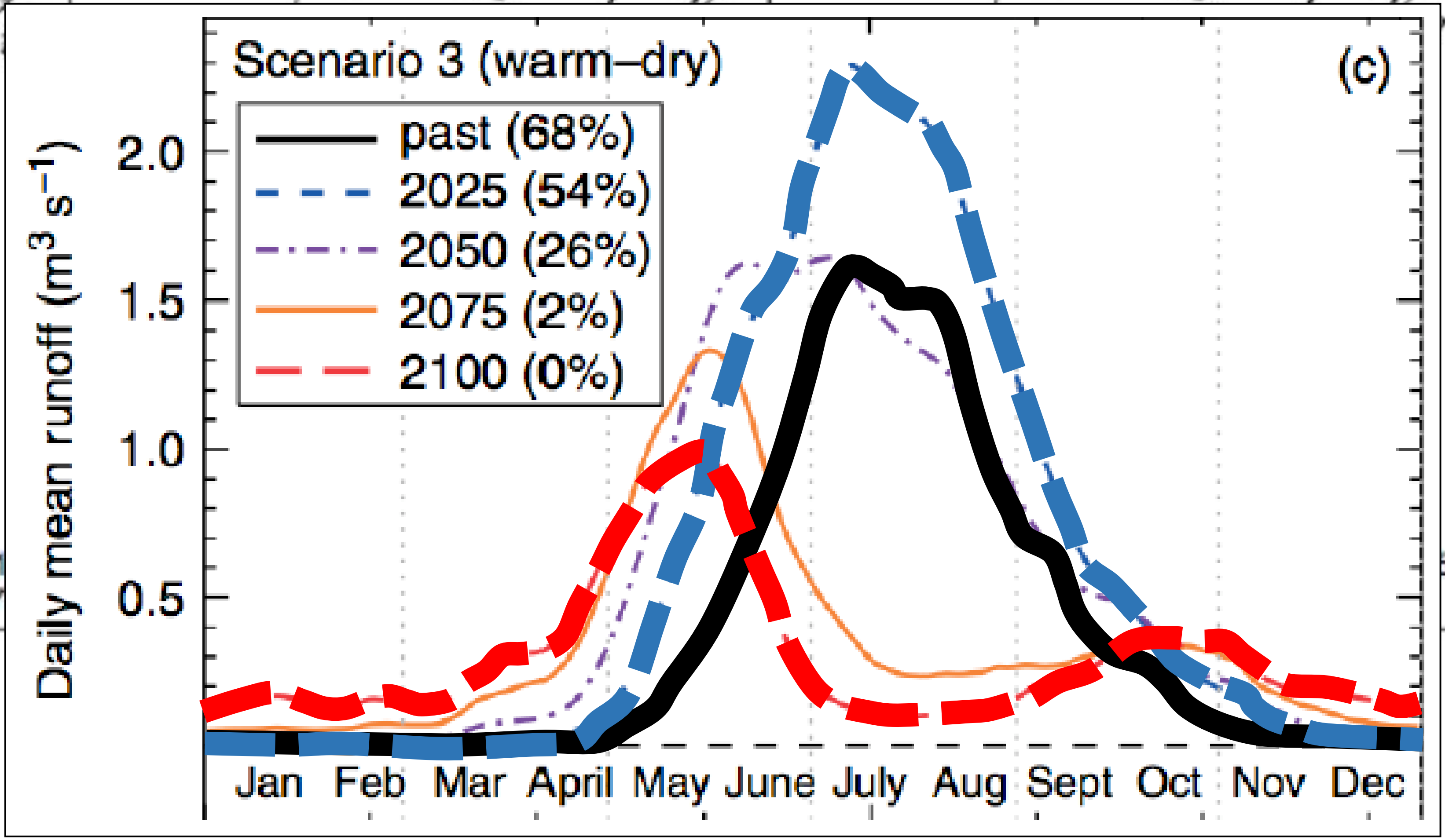


Switzerland, Wallis, Glacier de Zinal, Glacier de Moming and Glacier du Weisshorn

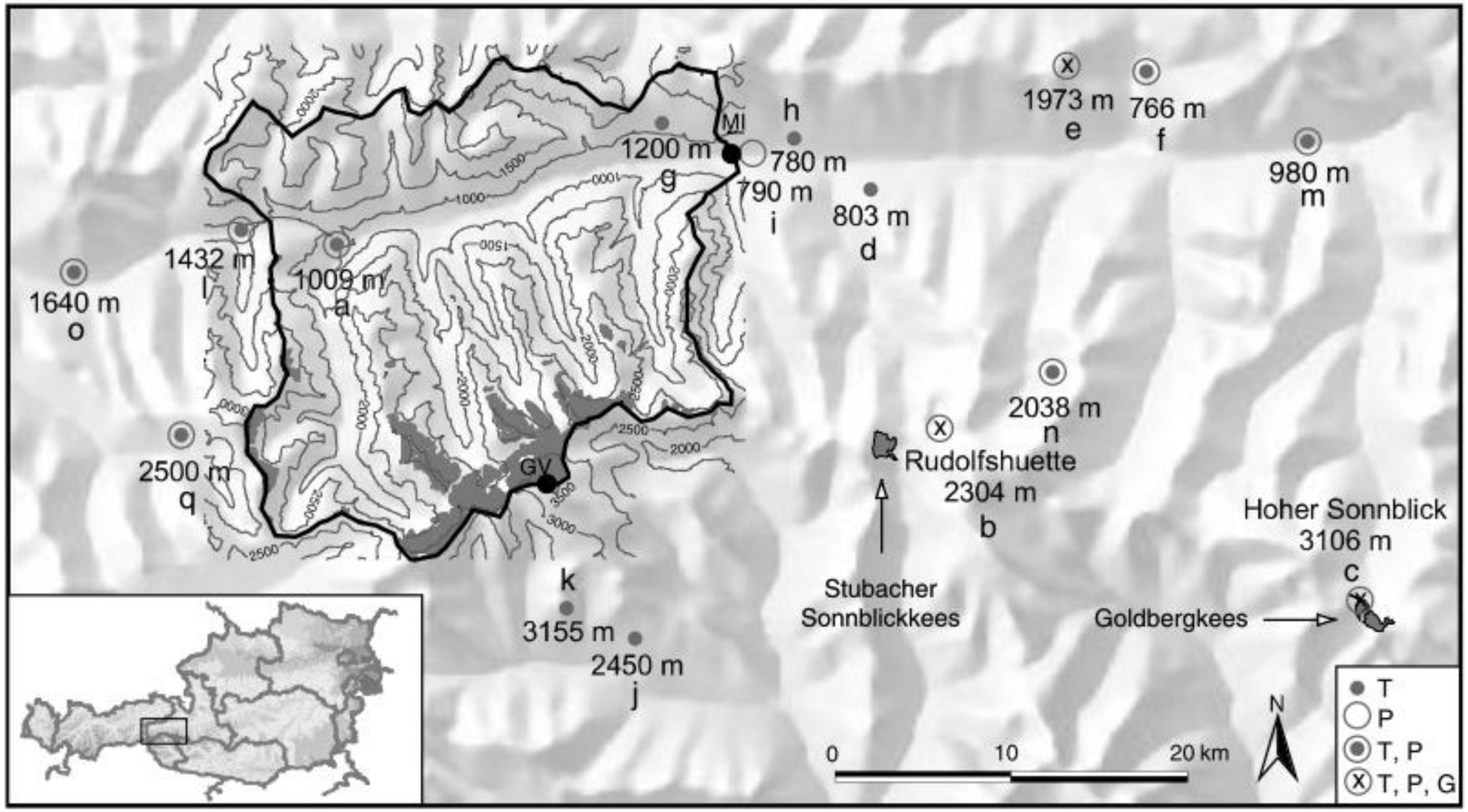
Glaciers influence on summer runoff (Huss et al. 2008)



Change from glacier to snow-rain (nival-pluvial) runoff regime

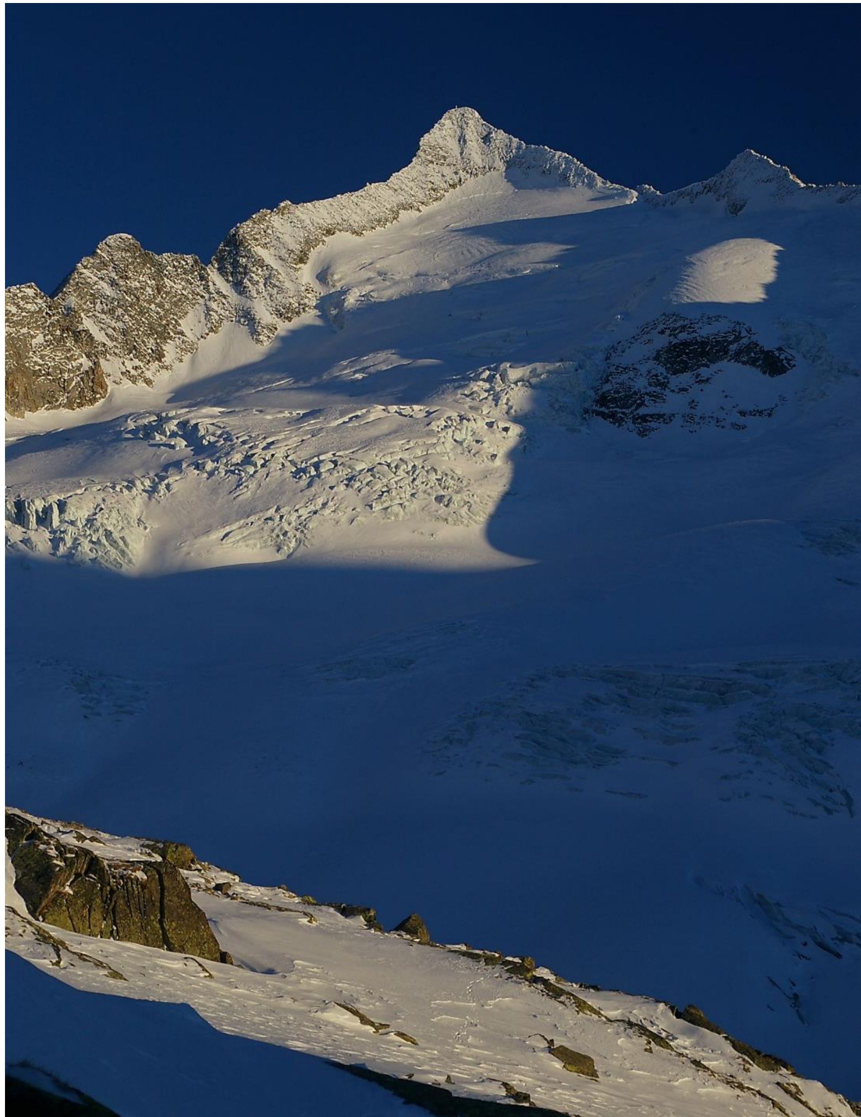


Glaciers influence on summer runoff (Koboltschnig et al. 2008)



Location of the Upper Salzach watershed. Dark grey areas indicate glaciers.

Grossvenediger (3667 m a.s.l.): the highest point of the area (Photo: Michal Jenicek)



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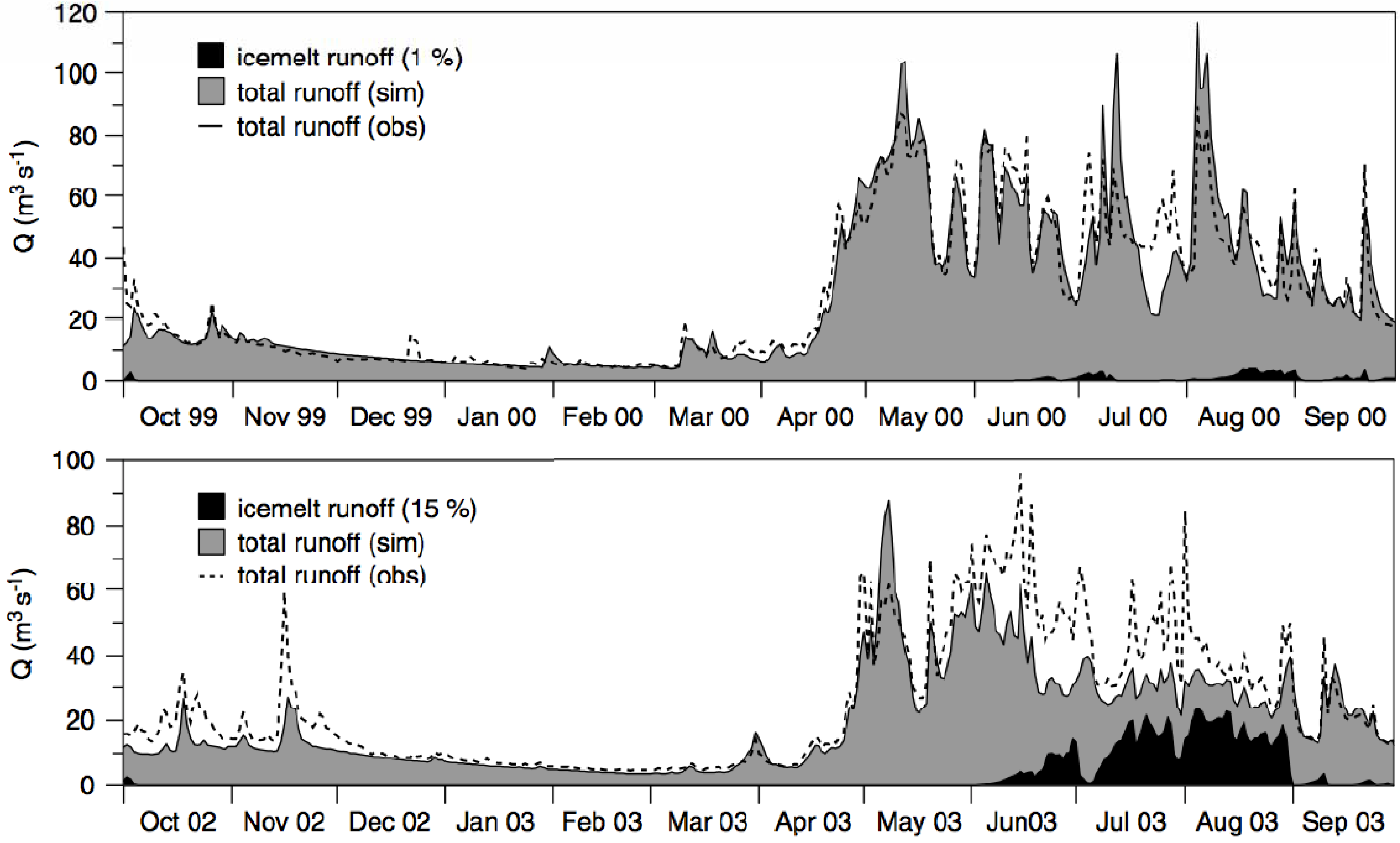

Austria, Obere Pinzgau (590 km^2)
Glaciation 5%

Glacier runoff 58% in August 2003

Simulated daily hydrograph at the gauging station Mittersill (grey) with contributing glacier melt (firn/ice melt, black) and observed daily runoff (dashed line) for the years 1999/2000 and 2002/2003

Changes in hydrological regime in Swiss catchments (Addor et al., 2014)

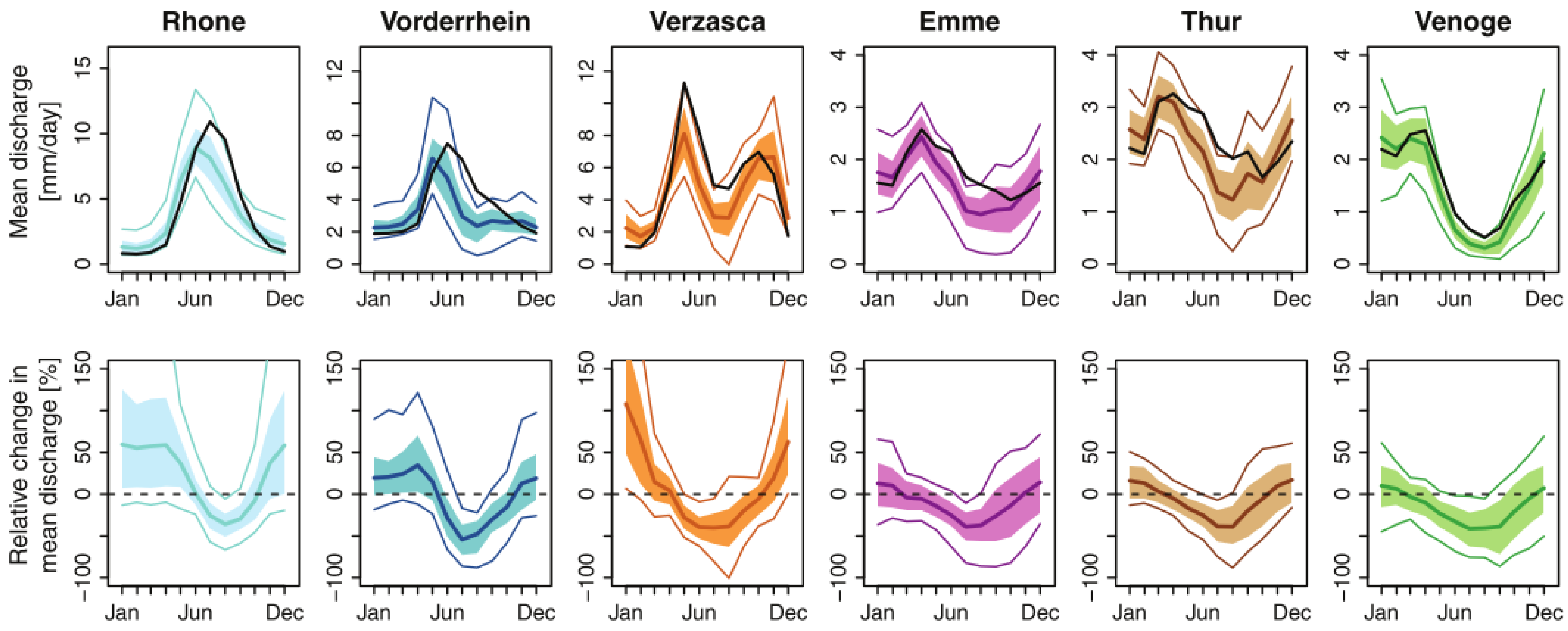

Figure 6. Projected regime changes for 2070–2099. The mean of the projections is represented by the thick colored line, the likely range (colored area) encompasses two thirds of all 54 model chains, and the minimum and maximum are shown by thin colored lines. The reference discharge (1980–2009) is depicted by a black line in the top row. The bottom row shows the relative difference between the reference and the projections. In Figures 6, 9, and 11, the catchments are ordered according to their mean elevation, from (left) the highest to (right) the lowest.

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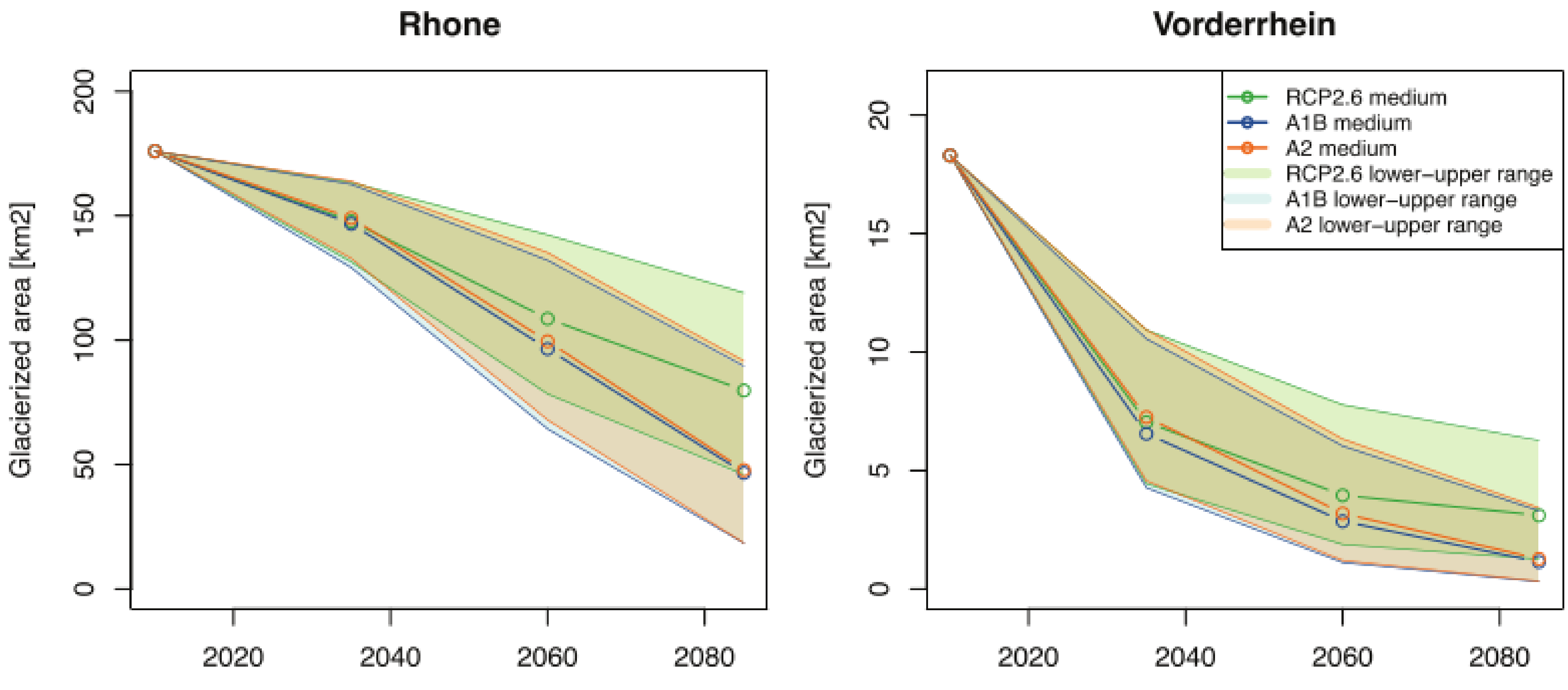
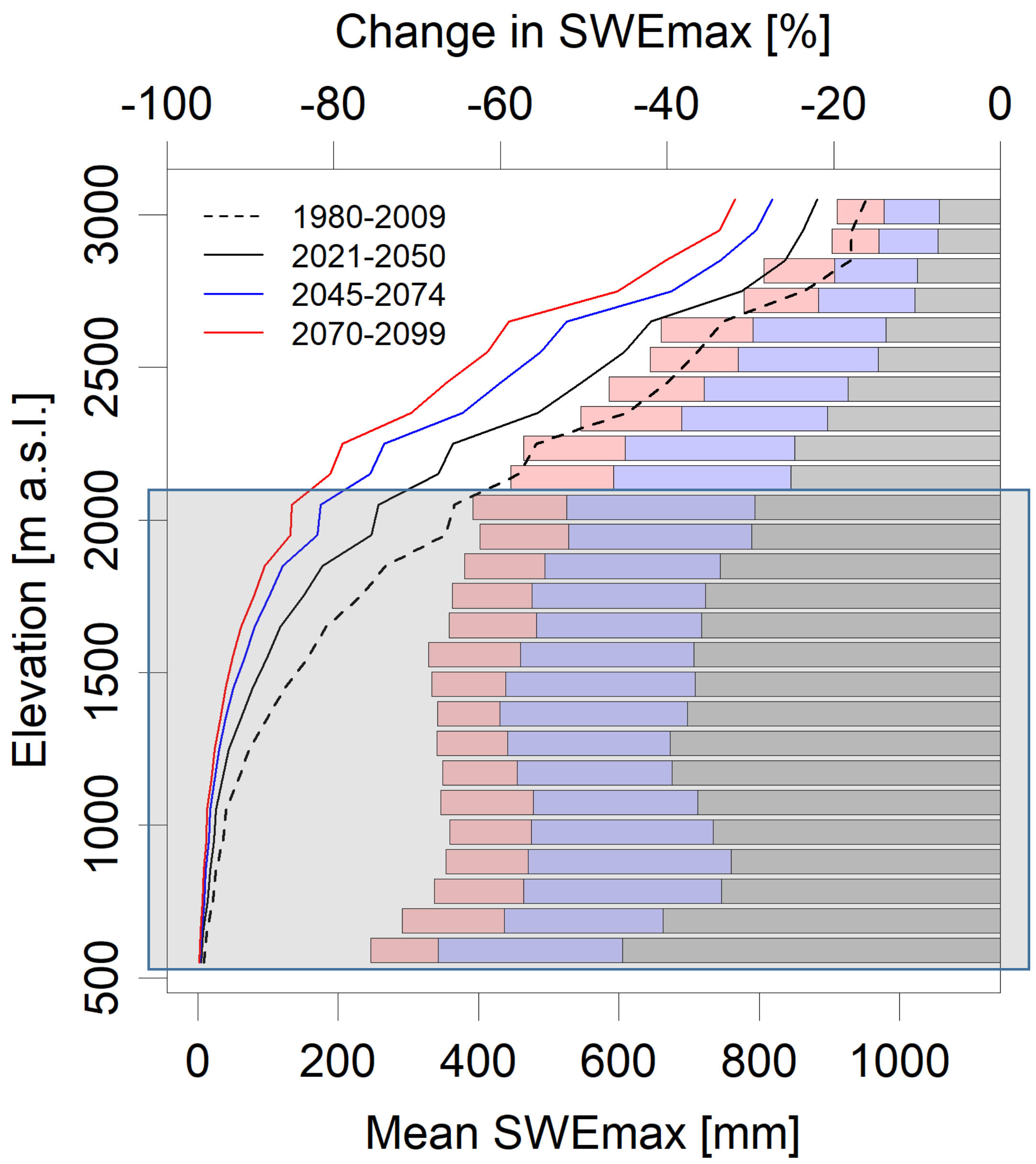


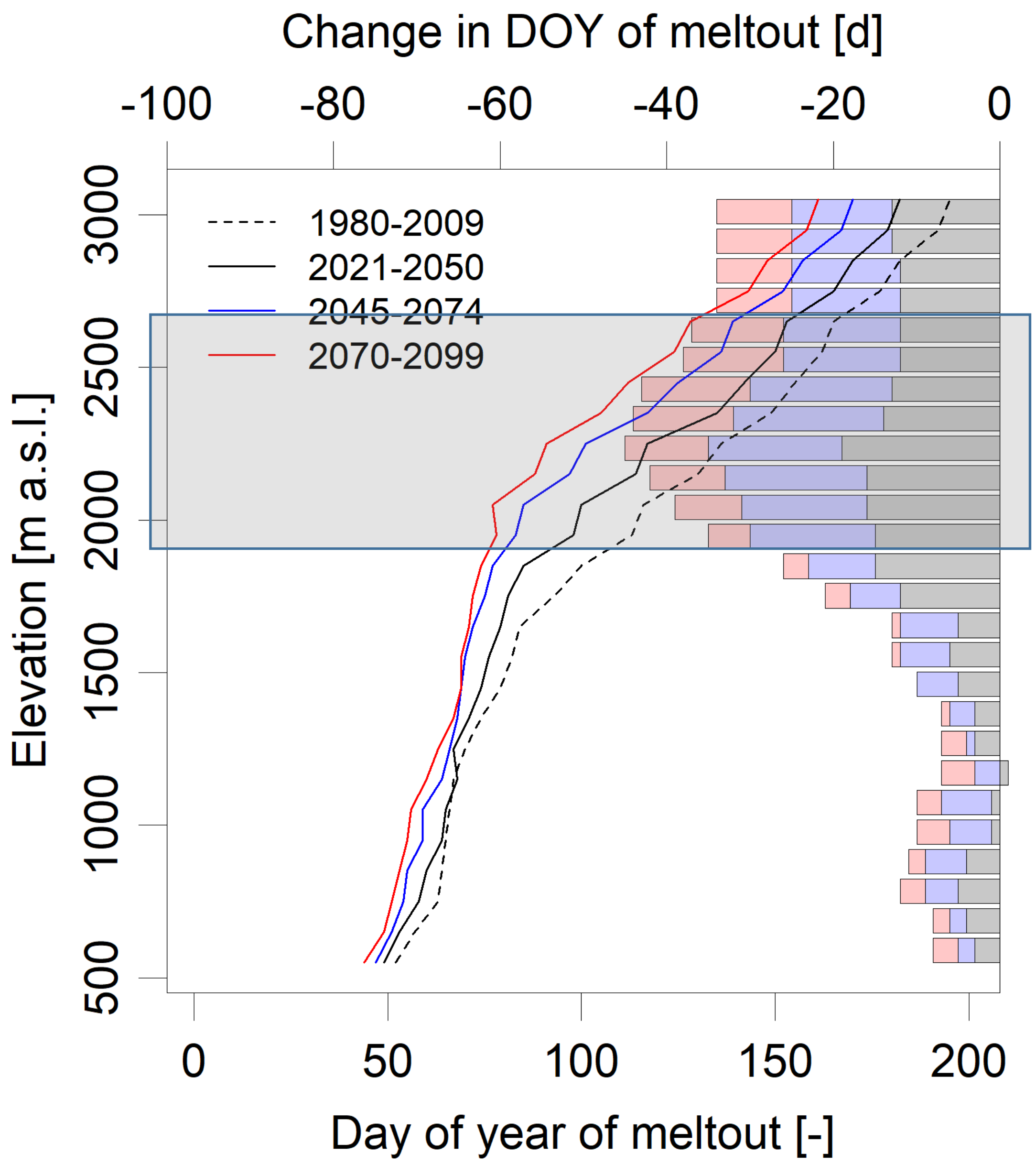
Figure 7. Projected evolution of glacierized area, for the lower, medium, and high estimates of the probabilistic climate projections under the RCP2.6, A1B, and A2 emission scenarios. Note the different scales of the *y* axes.

Changes in snow signatures (Jenicek et al., 2018)



- The largest absolute decrease in SWE_{max} from 2200 to 2700 m a.s.l
- Relative decrease in SWE_{max} up to 80 % below 1500 m a.s.l.
- The decrease in SWE_{max} caused by decrease in snowfall fraction

Changes in snow signatures (Jenicek et al., 2018)



- Earlier onset of snowmelt and earlier melt-out (largest changes between 1800-2500 m a.s.l.
- Shortening of the snowmelt period

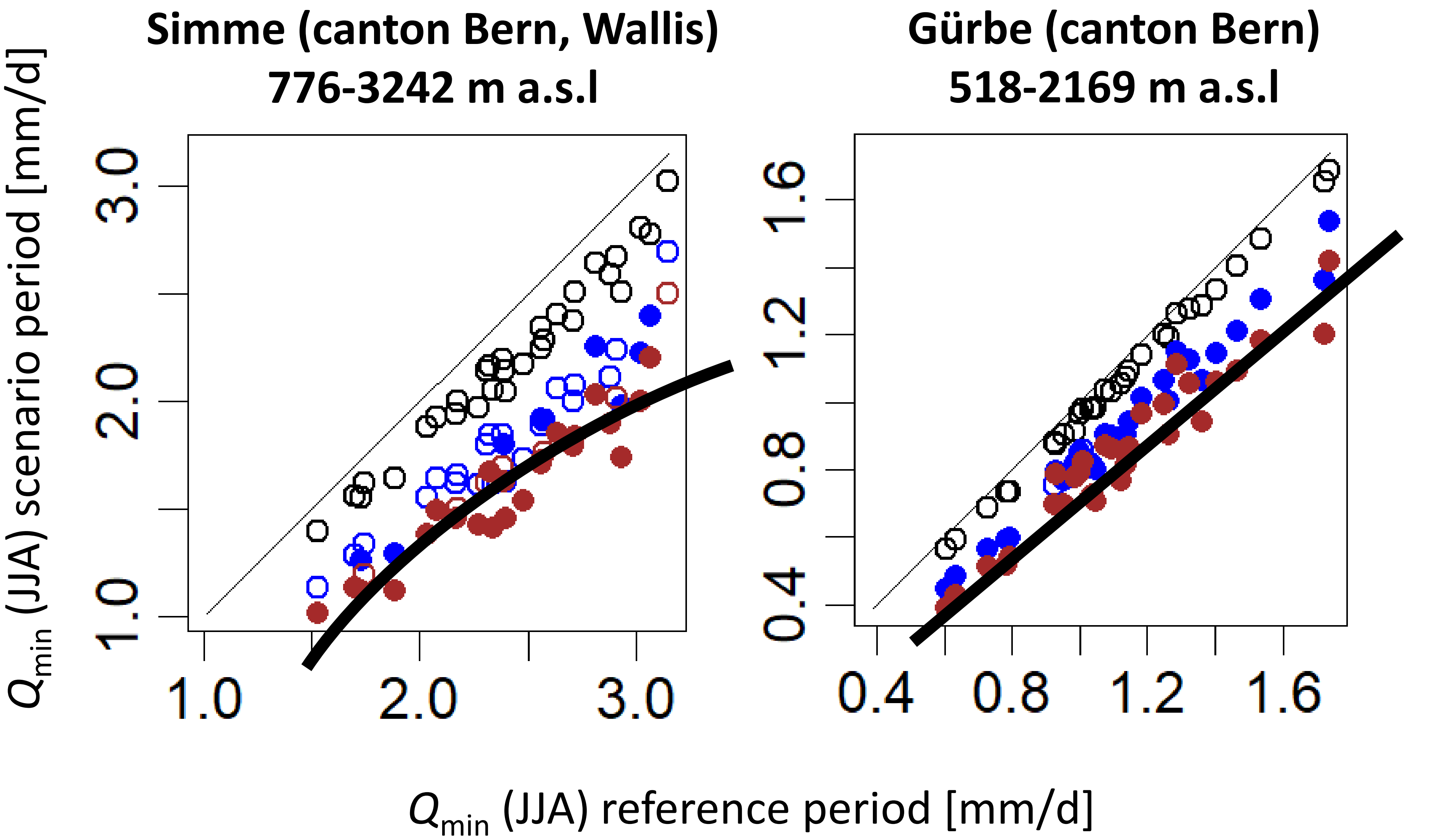
And what about skiing? (Marty et al., 2017)

Zone	Reference	A2 2035	A2 2060	A2 2085
600 – 800 m	🔴	🔴	🔴	🔴
800 – 1000 m	🔴	🔴	🔴	🔴
1000 – 1200 m	🟡	🔴	🔴	🔴
1200 – 1400 m	🟡	🟡	🔴	🔴
1400 – 1600 m	🟡	🟡	🟡	🔴
1600 – 1800 m	🟢	🟡	🟡	🔴
1800 – 2000 m	🟢	🟡	🟡	🔴
2000 – 2200 m	🟢	🟢	🟡	🟡
2200 – 2400 m	🟢	🟢	🟢	🟡
2400 – 2600 m	🟢	🟢	🟢	🟡
2600 – 2800 m	🟢	🟢	🟢	🟢
2800 – 3000 m	🟢	🟢	🟢	🟢
3000 – 3200 m	🟢	🟢	🟢	🟢

Aare river, Switzerland (southern slopes)

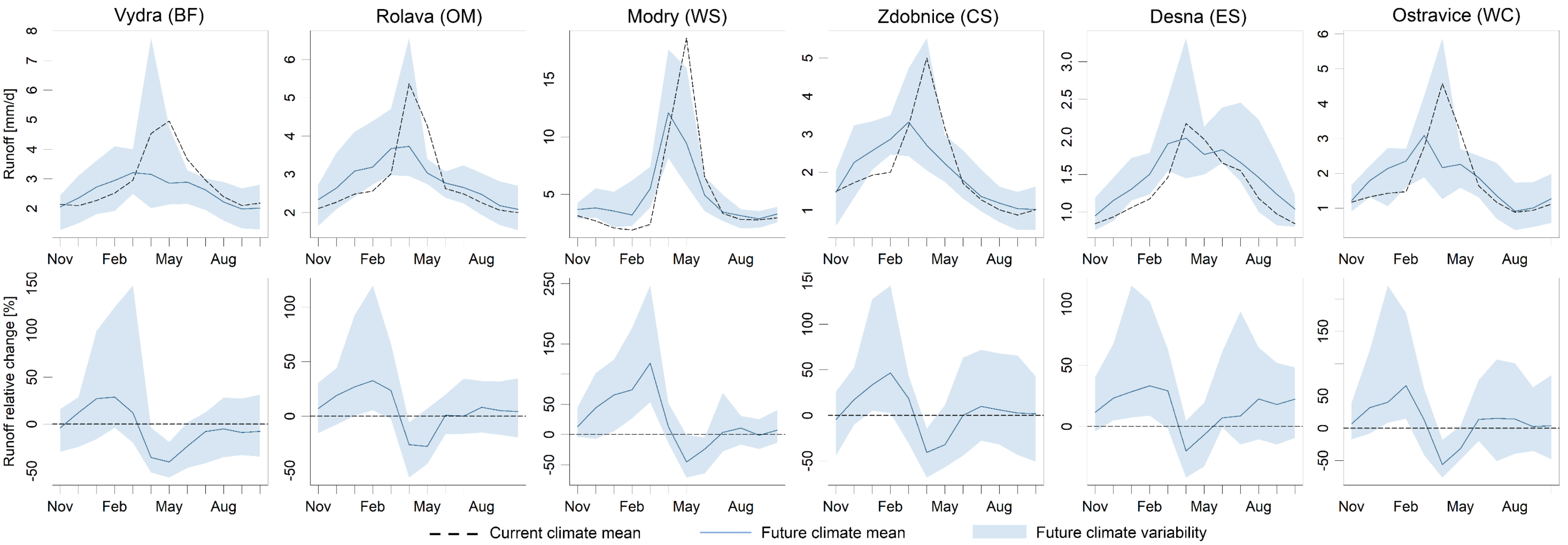
- Red: snow unlikely (30 cm snow depth exceeded for less than 40 days in a year)
- Green: snow likely (30 cm of snow exceeded for 100 days and more in a year)
- Yellow: something in between

Influence of snow storage on low flows: decrease in Q_{min} (Jenicek et al., 2018)



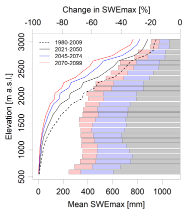
- Q_{min} from June to August for scenarios compared to the ref. period.
- Full-colored marks indicate years when SWE_{max} decreased to less than 50% of respective SWE_{max} in the ref. period
- Black: 2020-2049
  Blue: 2045-2074
  Red: 2070-2099

Changes in future runoff (Jenicek et al., 2021)

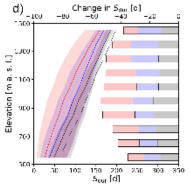


- Monthly runoff for the reference period and for the period 2070-2099
- Relative changes in monthly runoff for the period 2070-2099 compared to the reference period
- Black dashed line indicates reference period, blue line represents future period 2070-2099, light blue area indicates the range of different future climate projections.

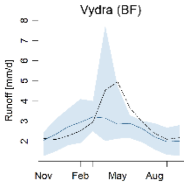
Conclusions



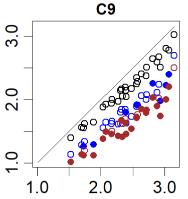
- Decrease in snow-related variables for all study catchments in central Europe at all elevations (e.g., SWE_{max} will decrease by 30%-70%).



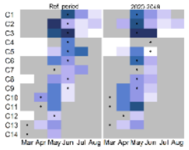
- Shorter snow-covered season by 40-60 days in the future. The shortening will be caused more by earlier melt-out rather than by later snow onset.



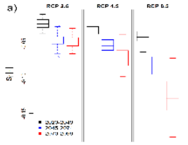
- The period of highest streamflow will occur a month earlier and the seasonal runoff volume will be lower. Increase in winter runoff was predicted.



- Summer low flows will significantly decrease in the future in snow dominated areas.



- Higher elevations are more sensitive to the decrease in snow storage → decrease of water availability in summer



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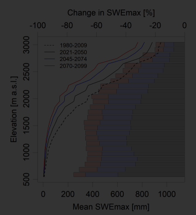
Conclusions



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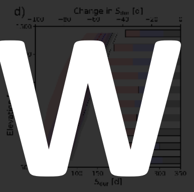

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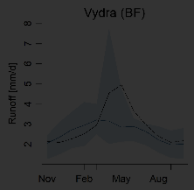

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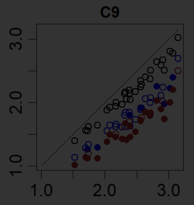
Will we have enough water in the future?



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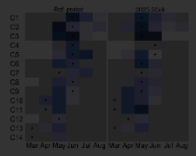

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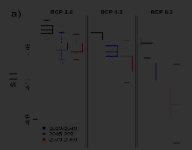
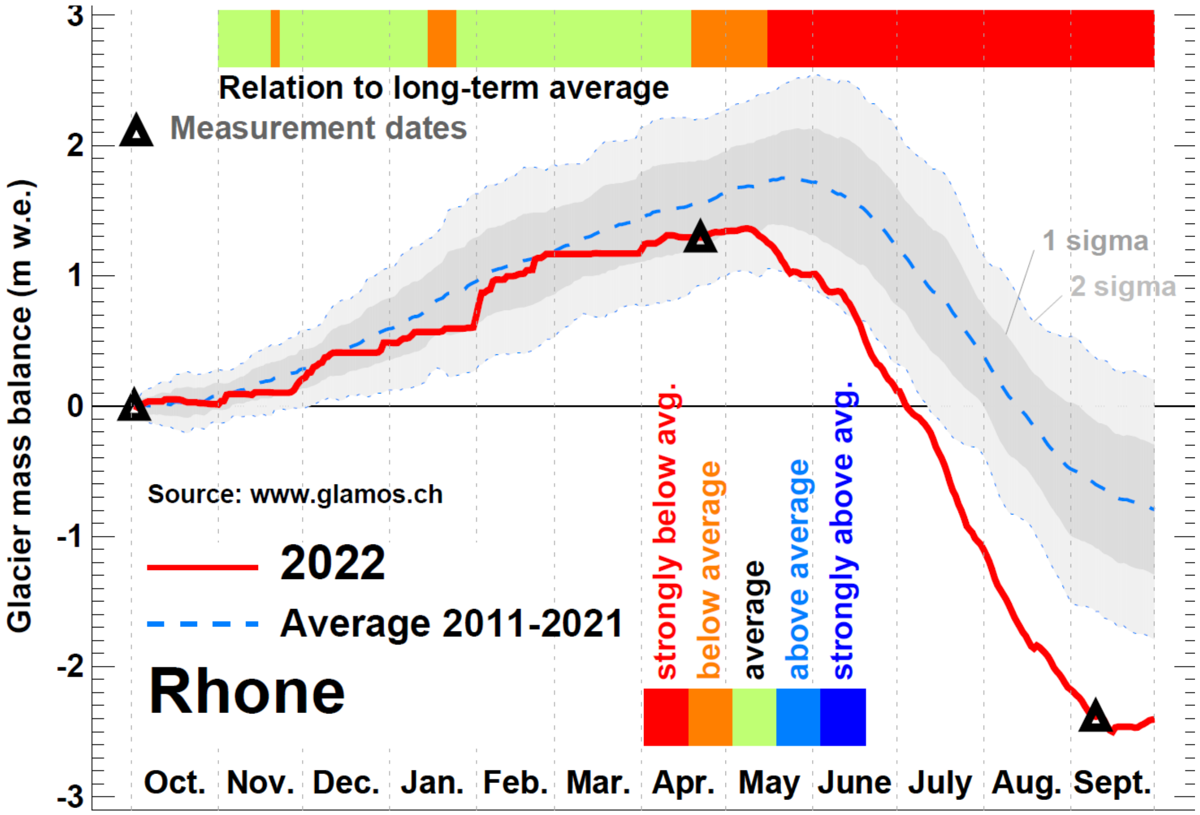


- The RCP 2.6 showed significantly smaller changes compared to the RCP 4.5 and 8.5

Year 2022 in the Alps

Konkordiaplatz, Grosser Aletschgletscher
(Credit: Matthias Huss)



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References

- Addor N, Rössler O, Köplin N, Huss M, Weingartner R, Seibert J. (2014): Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. *Water Resources Research* 50 (10): 7541–7562 DOI: 10.1002/2014WR015549
- Berghuijs WR, Woods RA, Hrachowitz M. (2014): A precipitation shift from snow towards rain leads to a decrease in streamflow. *Nature Climate Change* 4: 583–586 DOI: 10.1038/NCLIMATE2246
- Hanel M, Vizina A, Máca P, Pavlásek J. (2012): A Multi-Model Assessment of Climate Change Impact on Hydrological Regime in the Czech Republic. *Journal of Hydrology and Hydromechanics* 60 (3): 152–161 DOI: 10.2478/v10098-012-0013-4
- Huss, M., D. Farinotti, A. Bauder, and M. Funk (2008): Modelling runoff from highly glacierized alpine drainage basins in a changing climate, *Hydrol. Process.*, *22*(19), 3888–3902, doi:10.1002/hyp.7055.
- Jenicek, M., Hnilica, J., Nedelcev, O., Sipek, V. (2021). Future changes in snowpack will impact seasonal runoff and low flows in Czechia. J. Hydrol. Reg. Stud. 37, 100899. doi: 10.1016/j.ejrh.2021.100899.
- Jenicek, M., Ledvinka, O. (2020). Importance of snowmelt contribution to seasonal runoff and summer low flows in Czechia. Hydrology and Earth System Sciences, 24 (7), 3475–3491. doi: 10.5194/hess-24-3475-2020.
- Jenicek, M., Seibert, J., Staudinger, M. (2018): Modeling of future changes in seasonal snowpack and impacts on summer low flows in Alpine catchments, Water Resources Research, 54(1), 538-556. doi: 10.1002/2017WR021648.
- Koboltschnig, G. R., W. Schöner, M. Zappa, C. Kroisleitner, and H. Holzmann (2008): Runoff modelling of the glacierized Alpine Upper Salzach basin (Austria): multi-criteria result validation, *Hydrol. Process.*, *22*(19), 3950–3964, doi:10.1002/hyp.7112.
- Marty, C., S. Schlögl, M. Bavay, and M. Lehning (2017), How much can we save? Impact of different emission scenarios on future snow cover in the Alps, Cryosph., 11(1), 517–529.
- Stahl, K., M. Weiler, I. Kohn, D. Freudiger, J. Seibert, M. Vis, K. Gerlinger, and M. Böhm (2016), The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change.