EGU 2024 - CR1.1

Irreversible glacier change and "trough water" over centuries after overshooting the Paris Agreement temperature goal

Lilian Schuster[1], Fabien Maussion[1,2], Patrick Schmitt[1], David Rounce[3], Lizz Ultee[4], Fabrice Lacroix[5,6], Thomas Frölicher[5,6]

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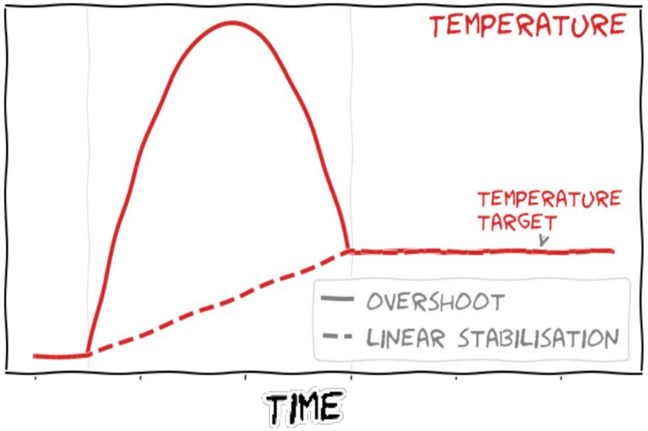
OGGM Open Global Glacier Model https://oggm.org
ÖAW

[1]Department of Atmospheric and Cryospheric Sciences (ACINN), Universität Innsbruck, Innsbruck, Austria (lilian.schuster@uibk.ac.at); [2]School of Geographical Sciences, University of Bristol, UK; [3]Civil and Environmental Engineering Department, Carnegie Mellon University, Pittsburgh, PA, USA; [4]Department of Earth and Climate Sciences, Middlebury College, Middlebury, VT, USA; [5]Climate and Environmental Physics, University of Bern, Bern, Switzerland; [6]Oeschger Centre for Climate Change Research, Bern, Switzerland

Sharing is encouraged

↑ abstract + slides



1 Motivation

- Under current emissions trajectories, overshooting the 1.5°C target is very likely
- Stringent mitigation and carbon removal policies may limit global warming over that target and return to it afterward (overshoot)

→ Goal: analyse overshoot impacts on glacier volume and runoff changes using OGGM Open Global Glacier Model

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Reversing climate overshoot

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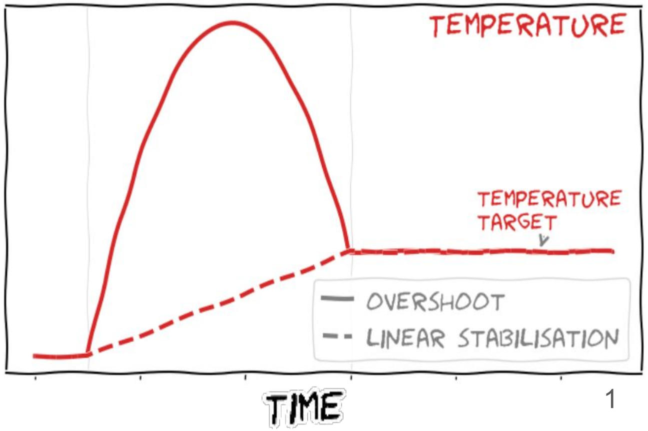
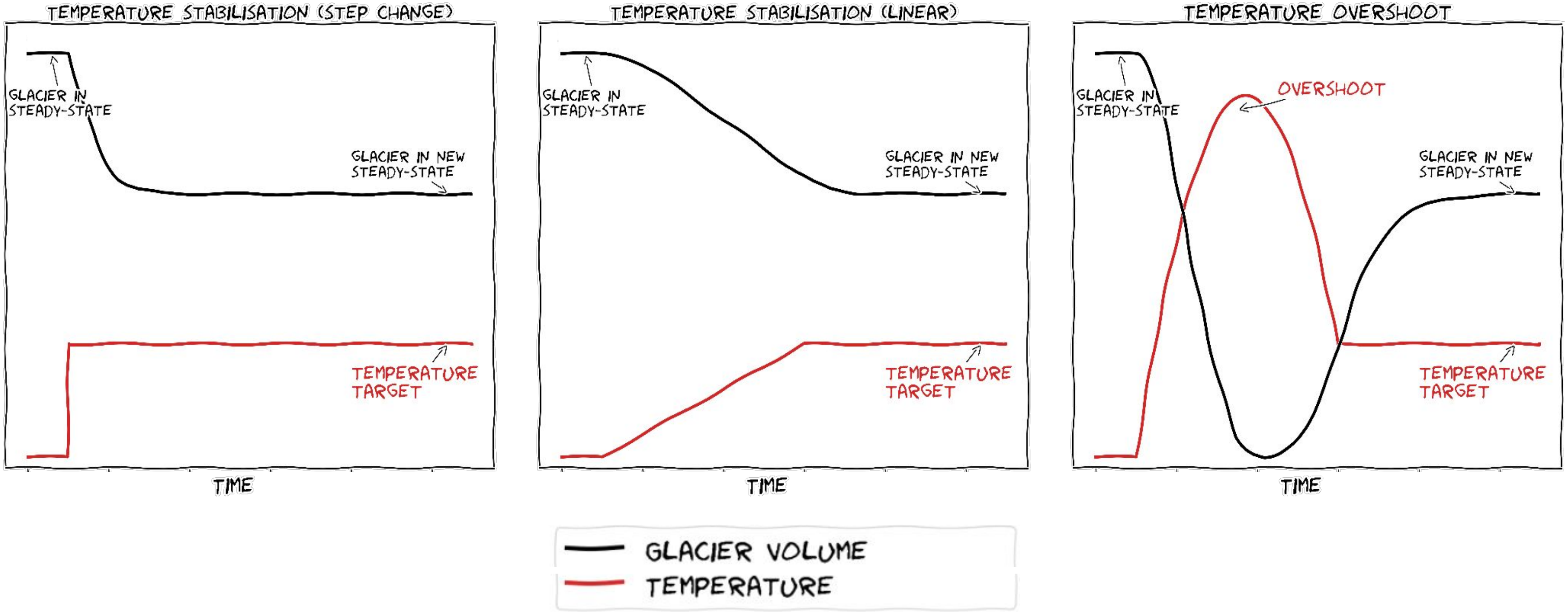
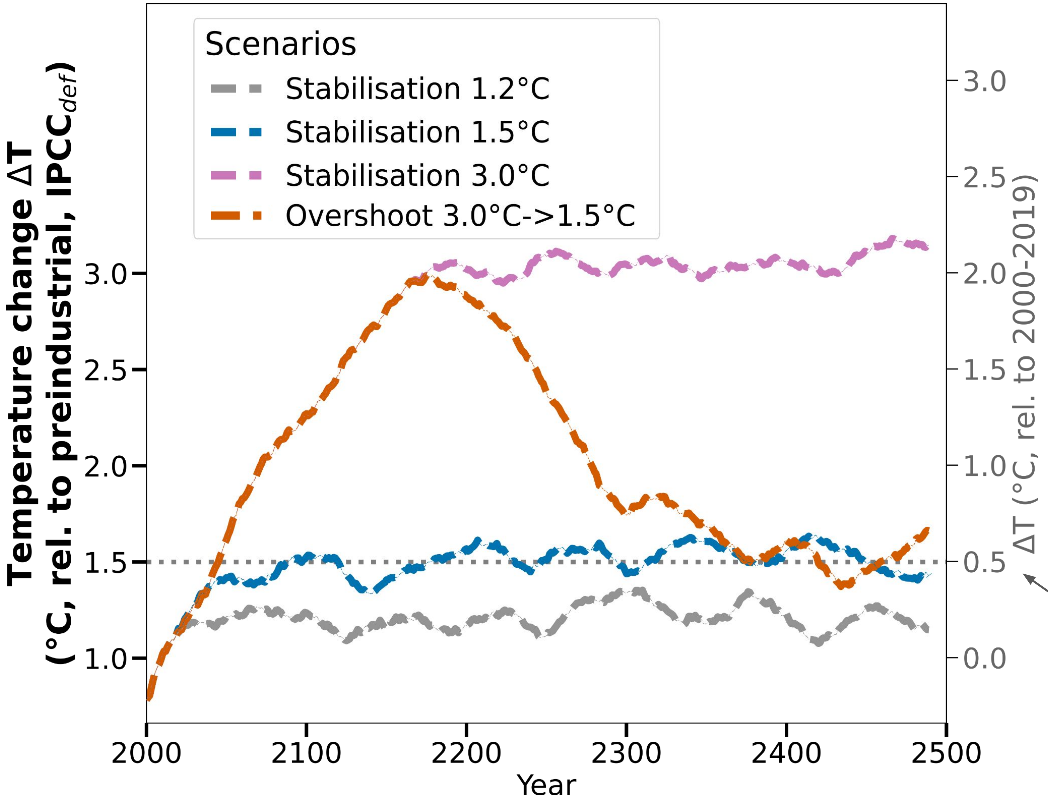
Temporarily overshooting climate targets is a distinct possibility given our current emissions trajectory. It is crucial that we understand which of the associated impacts are reversible, and to what extent.



1b Idealised glacier volume experiments



using Aletsch glacier
on the background…

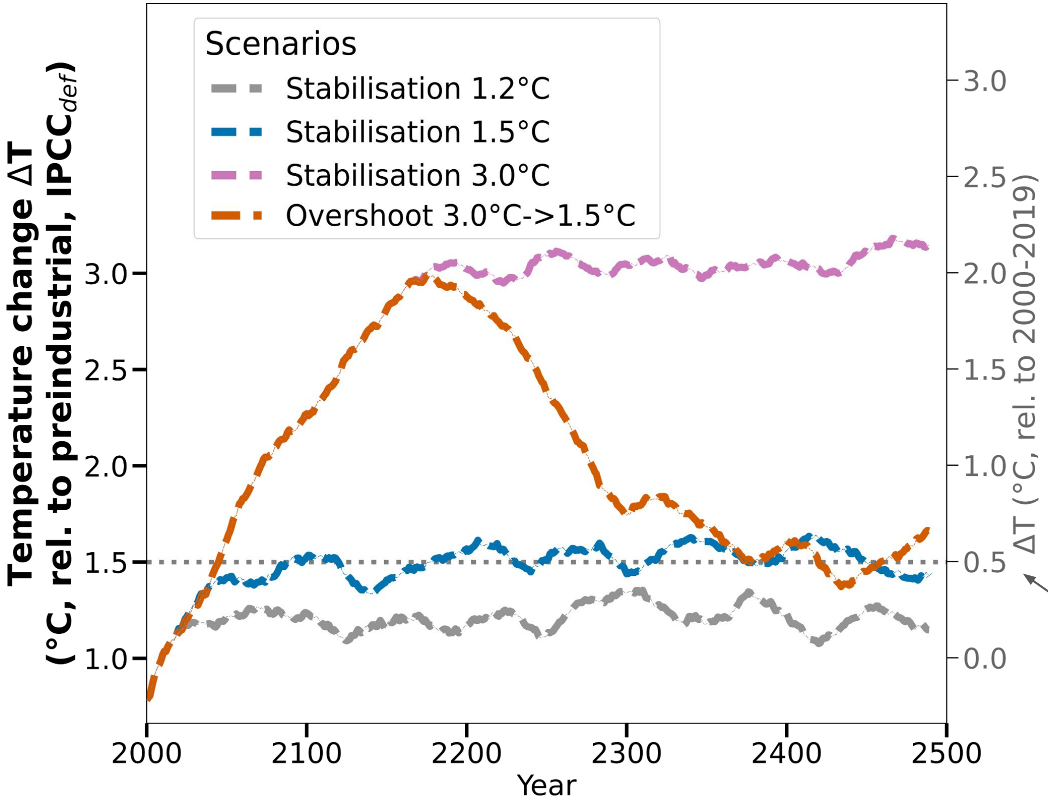


2a Used ESM with overshoot & stabilisation scenarios for this talk:

- **GFDL ESM2M** Earth System Model[1] (ESM, 2.5° resolution)

Overshoot 3.0°C->1.5°C stabilises around +1.5°C at year ~2374

[1] Lacroix, F., Burger, F., Silvy, Y., Rodrigues, R., Schleussner, C. F., and Frölicher, T. L.: Long-Term Negative Emissions and Irreversibilities following Temporary Overshoots: An Earth System Model Perspective, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-12063, https://doi.org/10.5194/egusphere-egu24-12063, 2024.



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only one ESM available→results show only one potential outcome out of many

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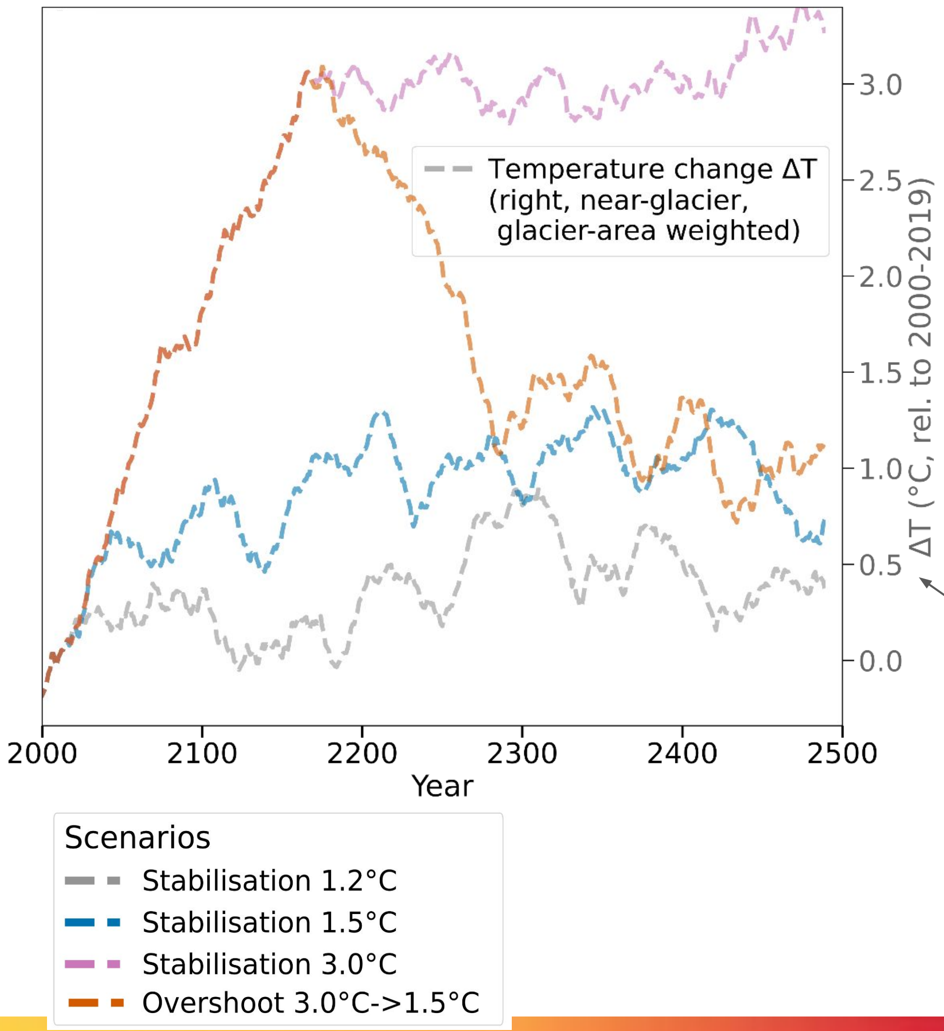
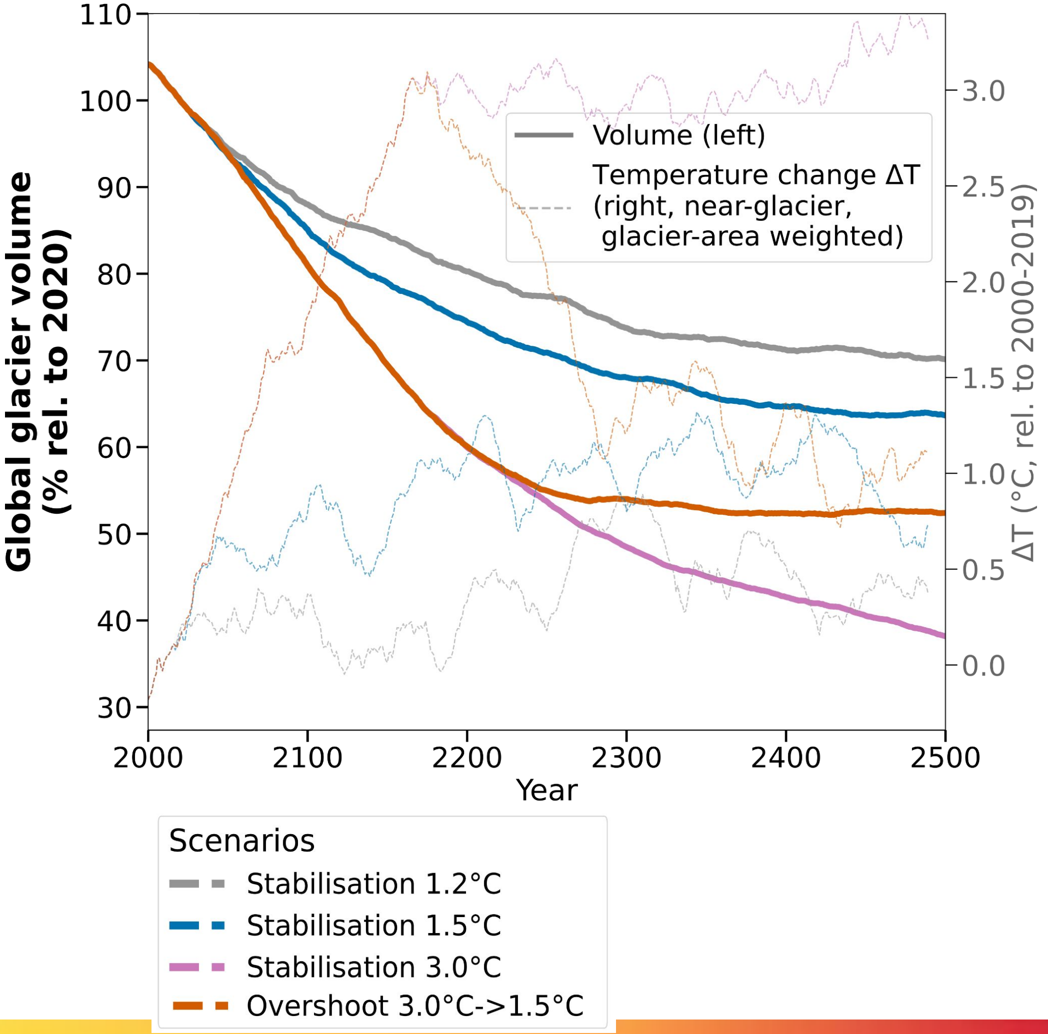
2b Global near-glacier temperature changes until 2500 of that ESM



temperature change for near-glacier gridpoints around +1°C larger than on global average!

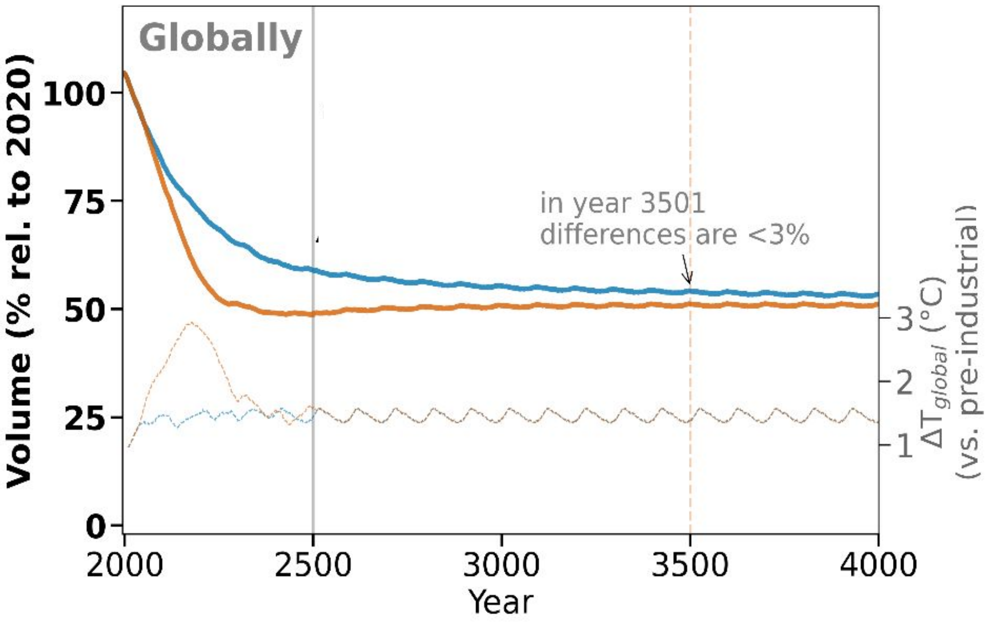
3a Global glacier **volume** evolution until 2500

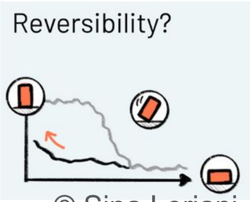


- 30% of 2020 global glacier volume lost under 1.2°C
  → Glaciers are in disequilibrium with current warming!

- in 2500, Overshoot 3.0°C→1.5°C results in 11% more loss than in Stabilisation 1.5°C
  → Globally, recovery is slow and needs longer than simulation period

3b What happens after 2500?





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Used scenarios until 2500:

- Stabilisation 1.5°C
- Overshoot 3.0°->1.5°C

→ Identical climate forced after 2500

(last 100 years from Stabilisation 1.5°C)

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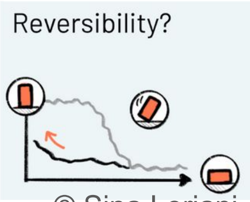

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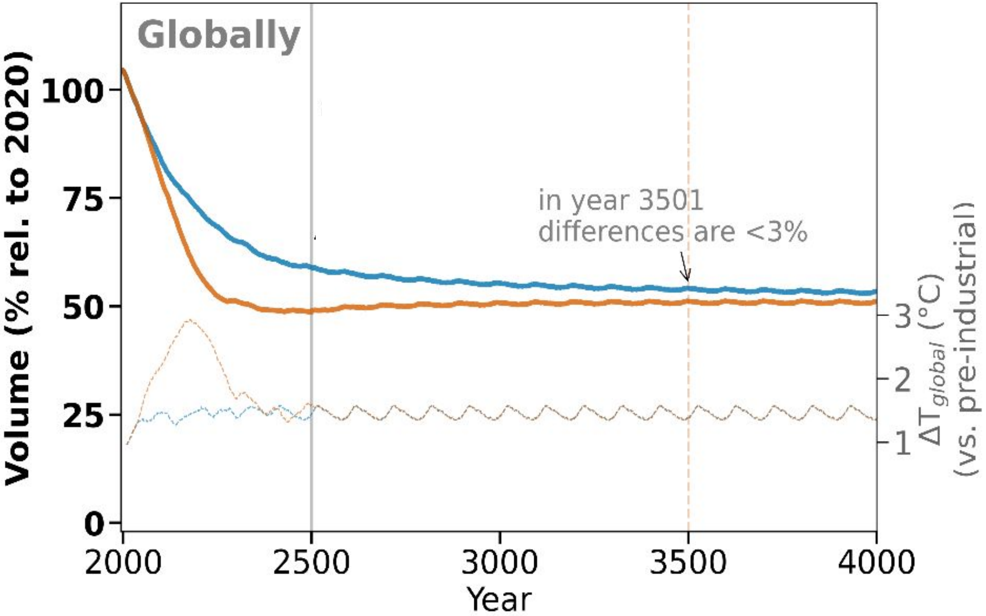


Used scenarios until 2500:

- Stabilisation 1.5°C
- Overshoot 3.0°->1.5°C

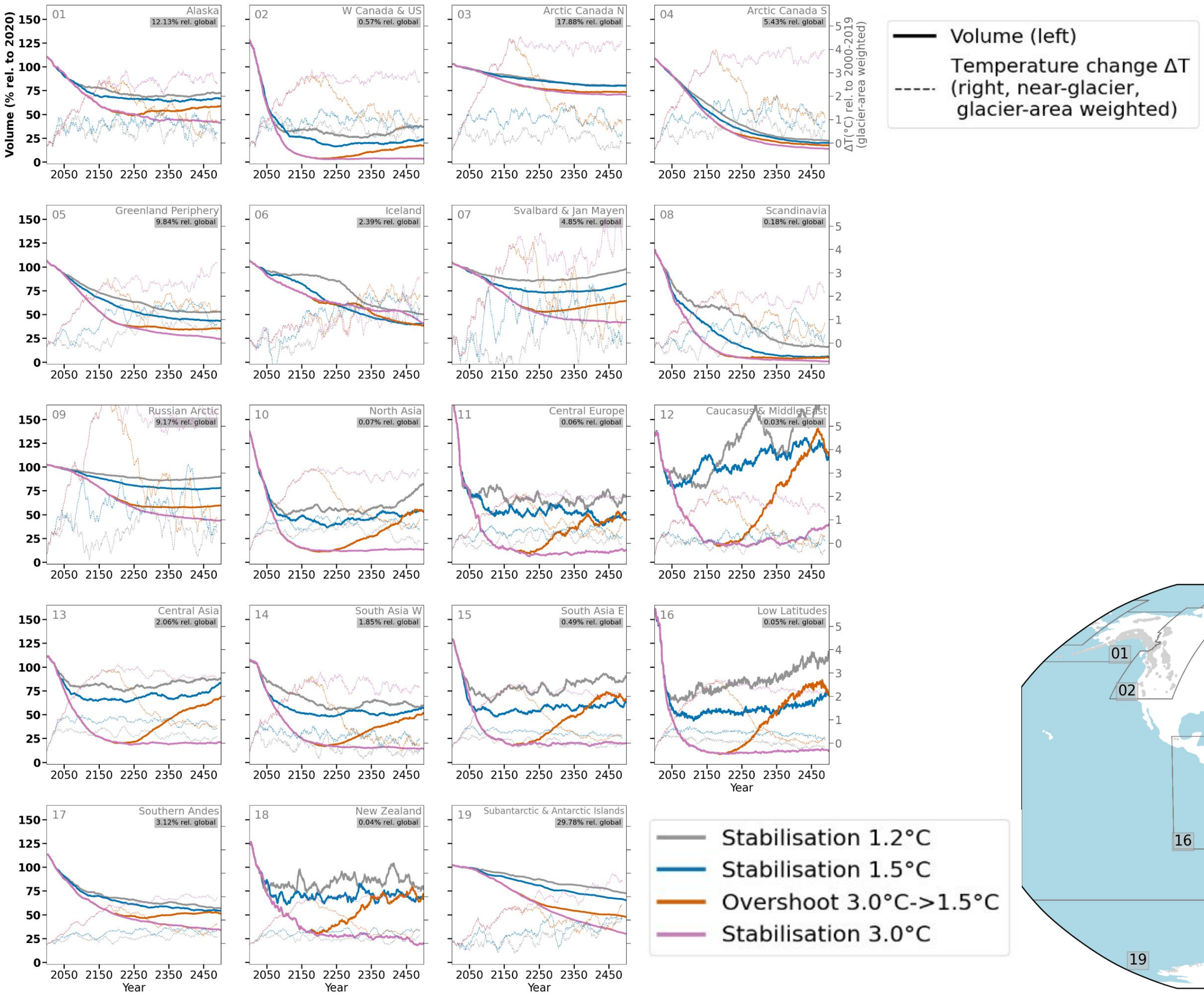
→ Identical climate forced after 2500

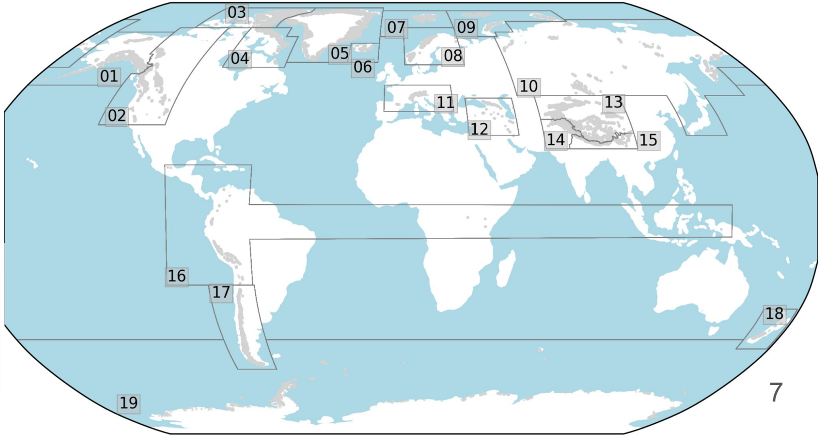
(last 100 years from Stabilisation 1.5°C)

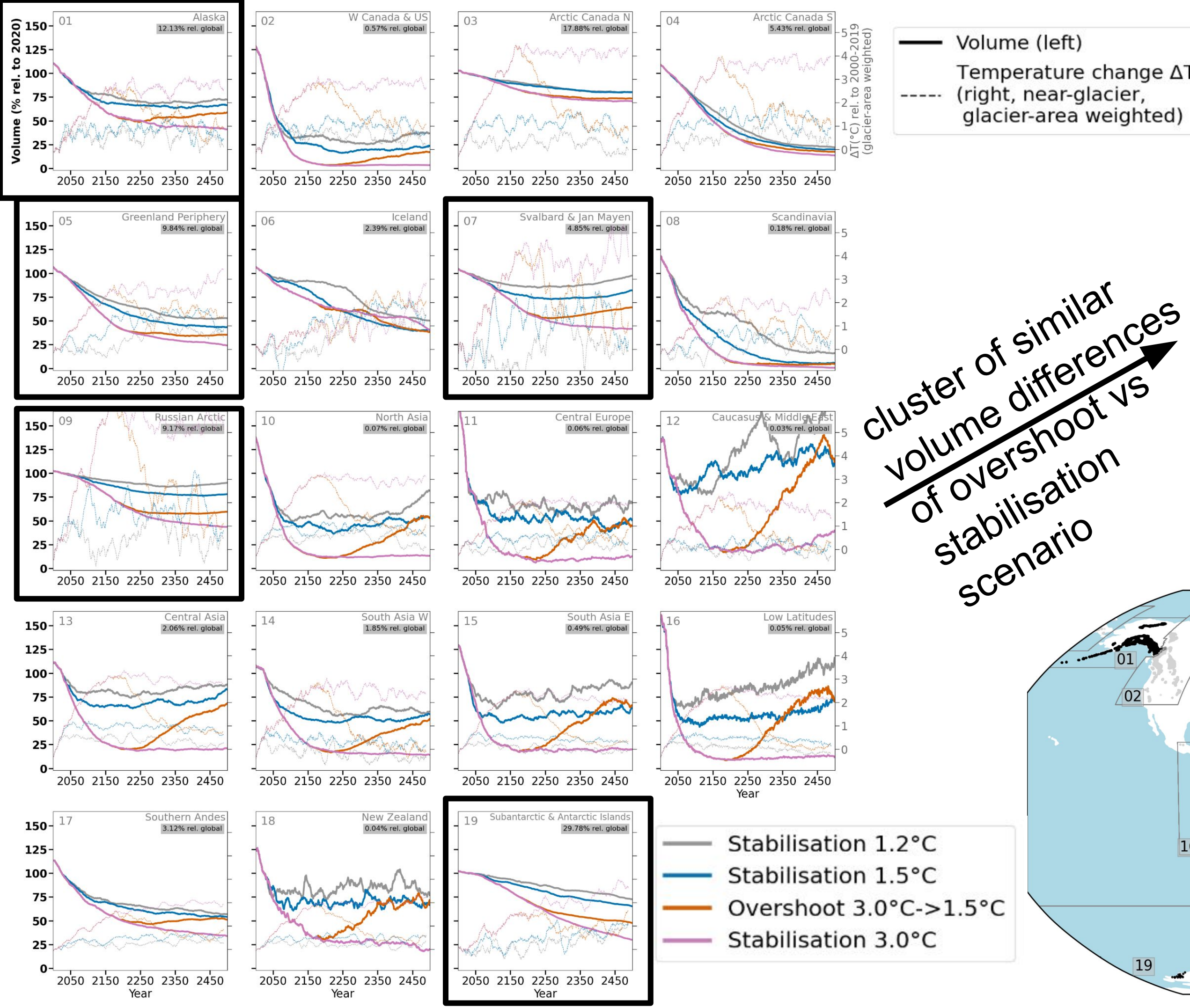
For the used OGGM **model** setup: glacier loss from temperature overshoots is **globally** basically **reversible after millennials**

More research necessary to assess influence from non-included feedbacks

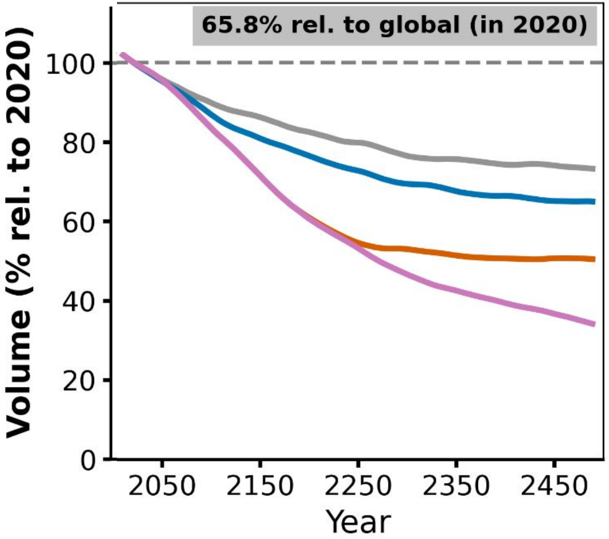
3c Regional glacier volume evolution until 2500

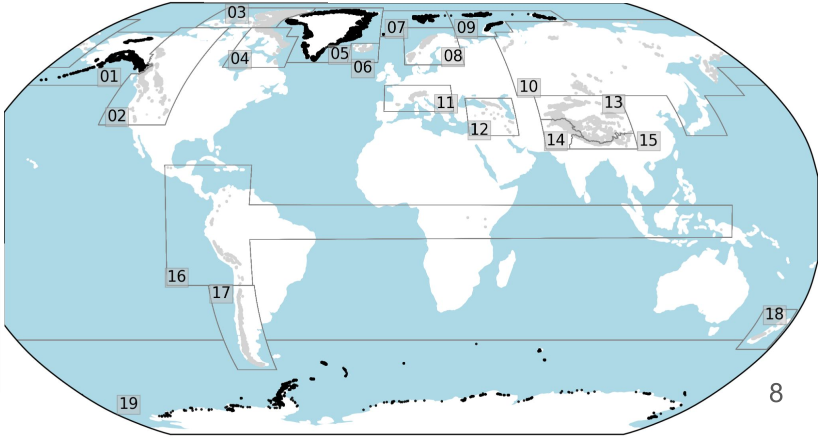




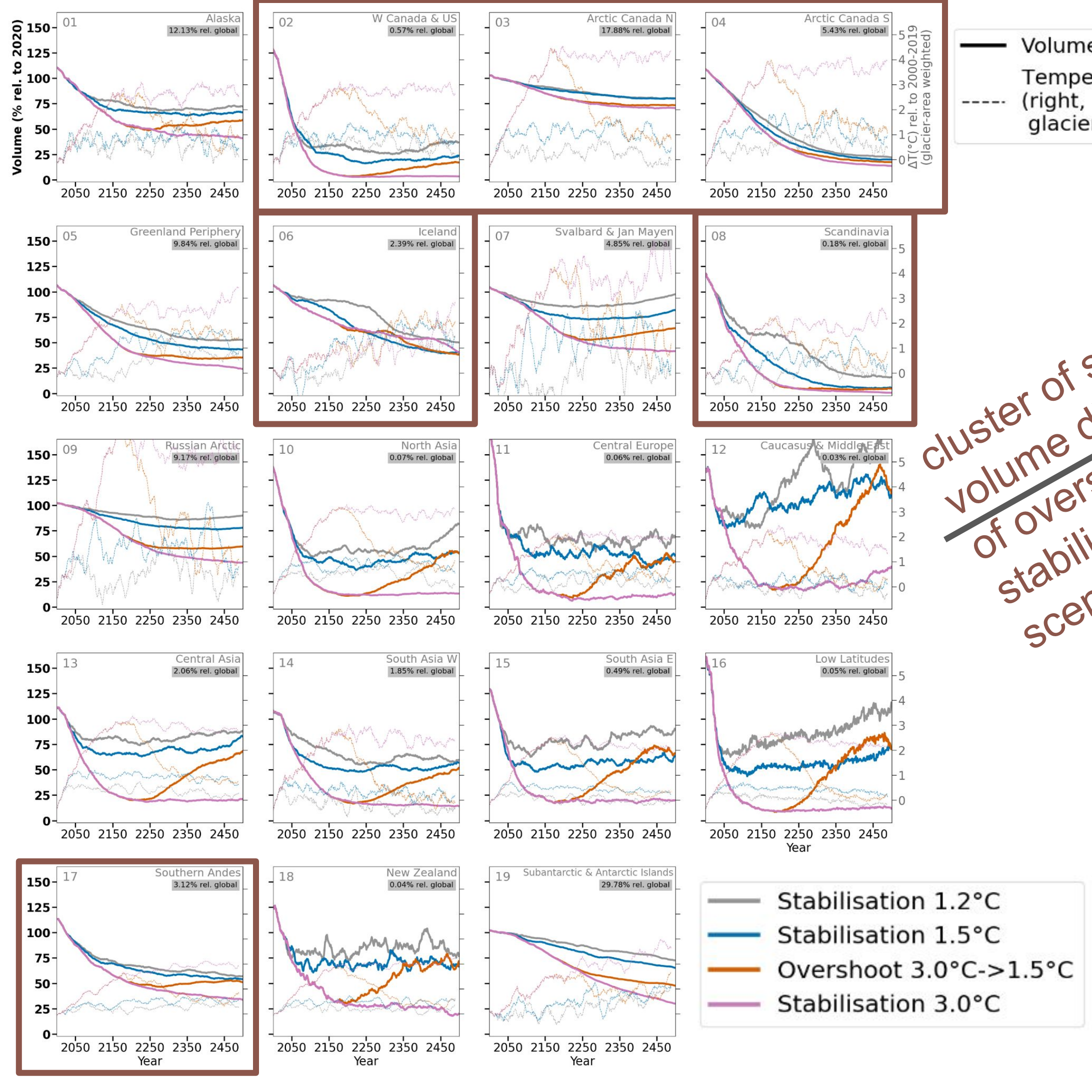


(i) large overshoot influence until 2500, slow glacier response

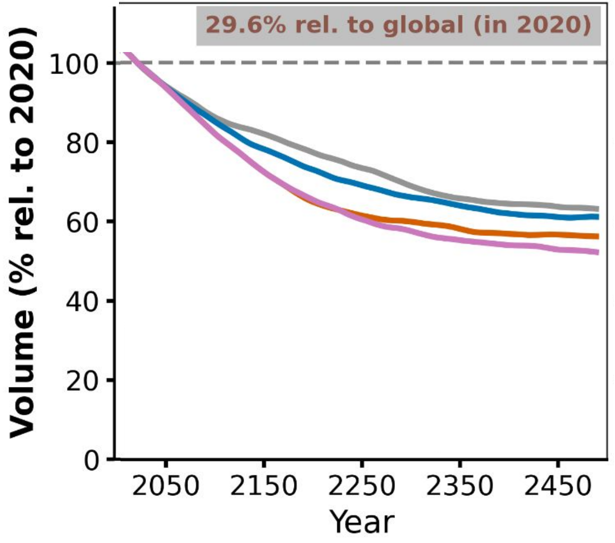


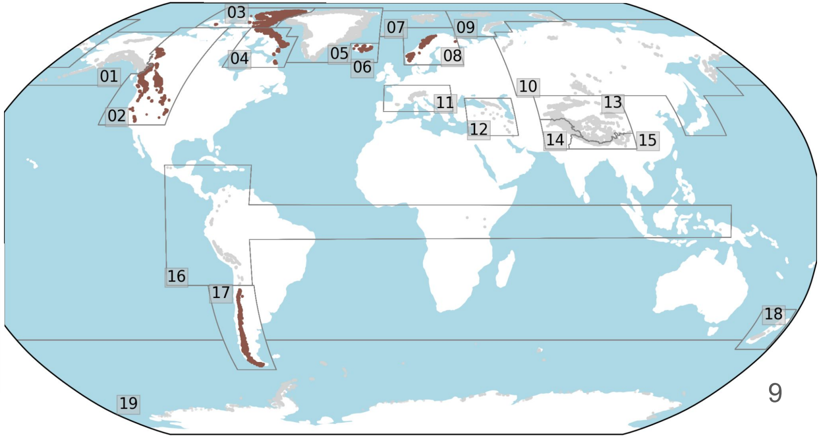


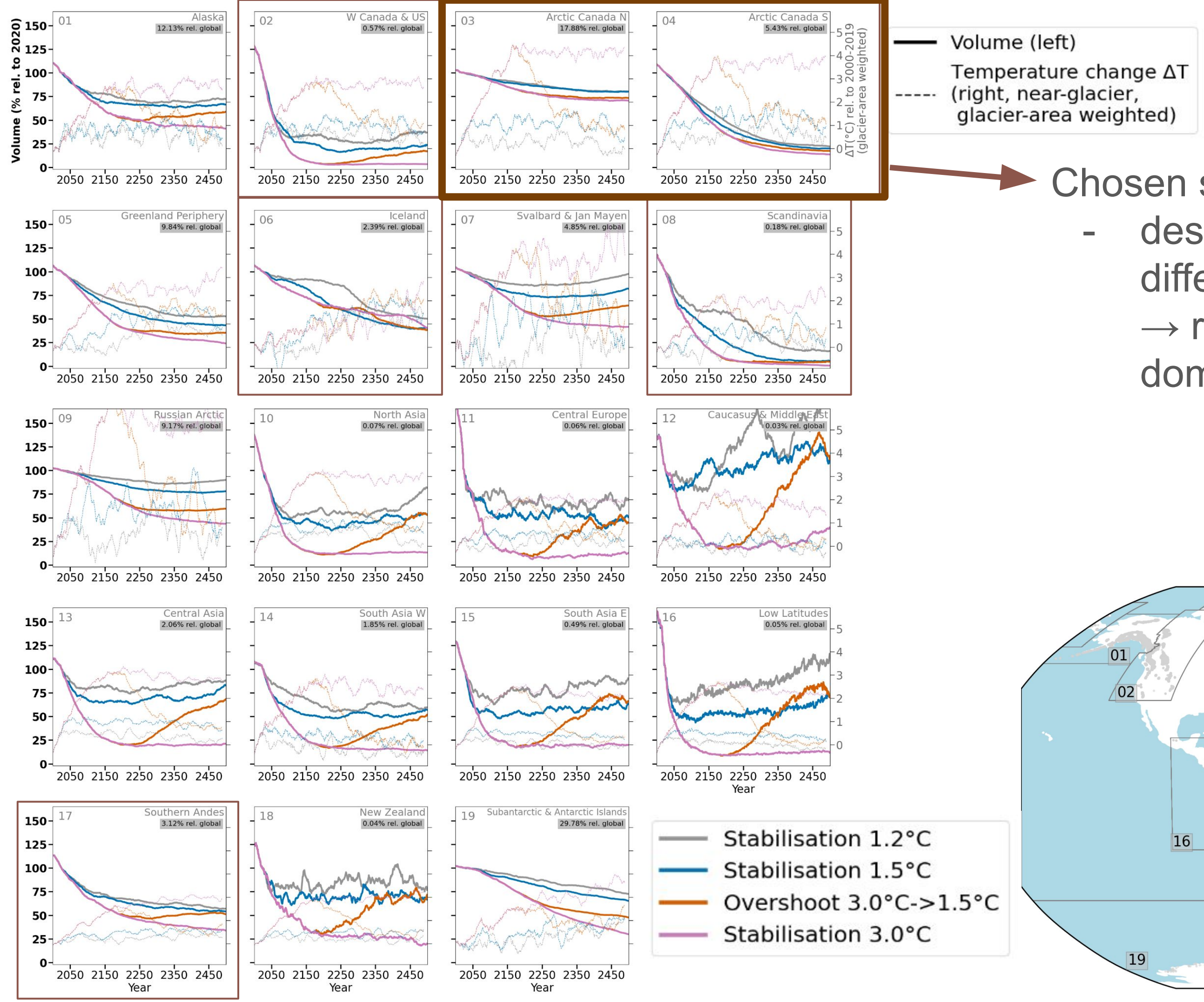
(ii) small overshoot influence in 2500, medium influence before



cluster of similar volume differences of overshoot vs stabilisation scenario



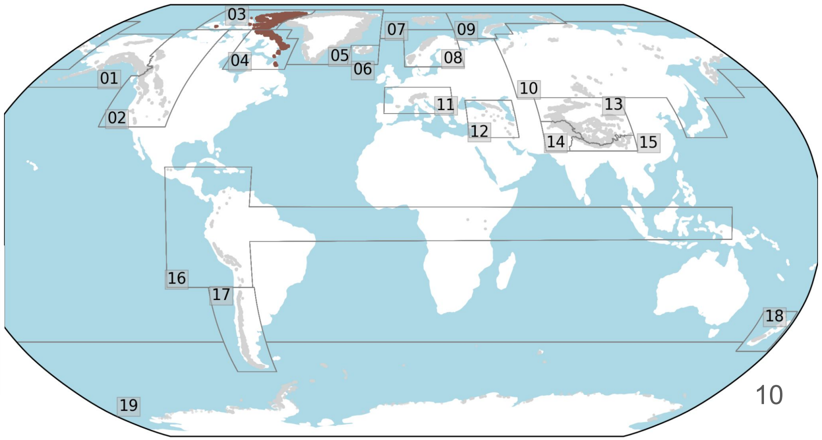




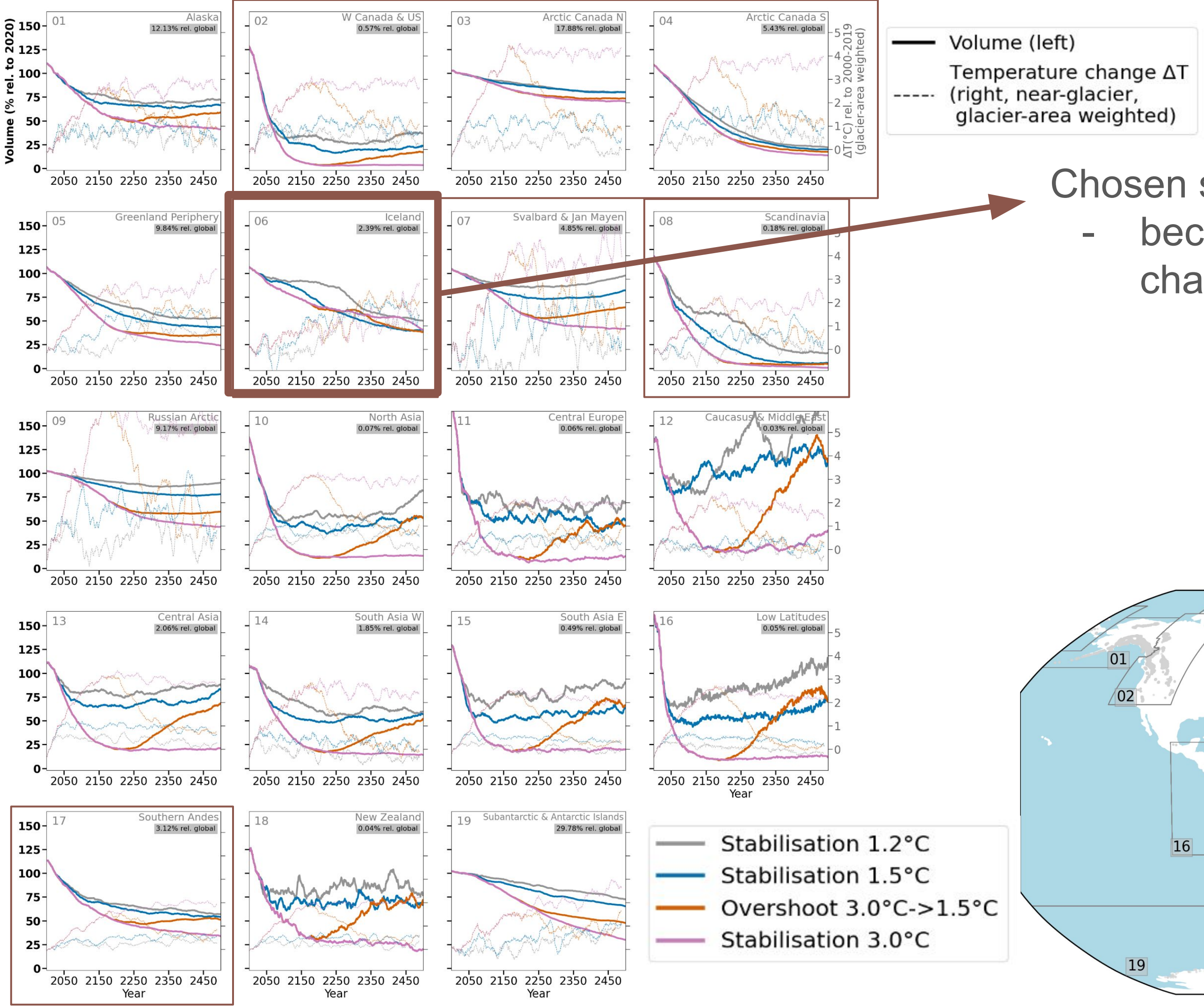
(ii) … special case Arctic Canada North & South (03-04) …

Chosen scenarios differ little:

- despite large regional temperature differences
  → reason: committed warming dominates response until 2500

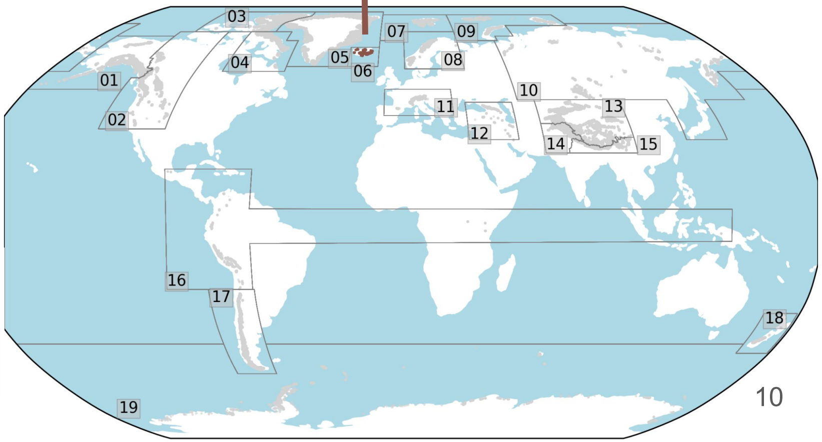


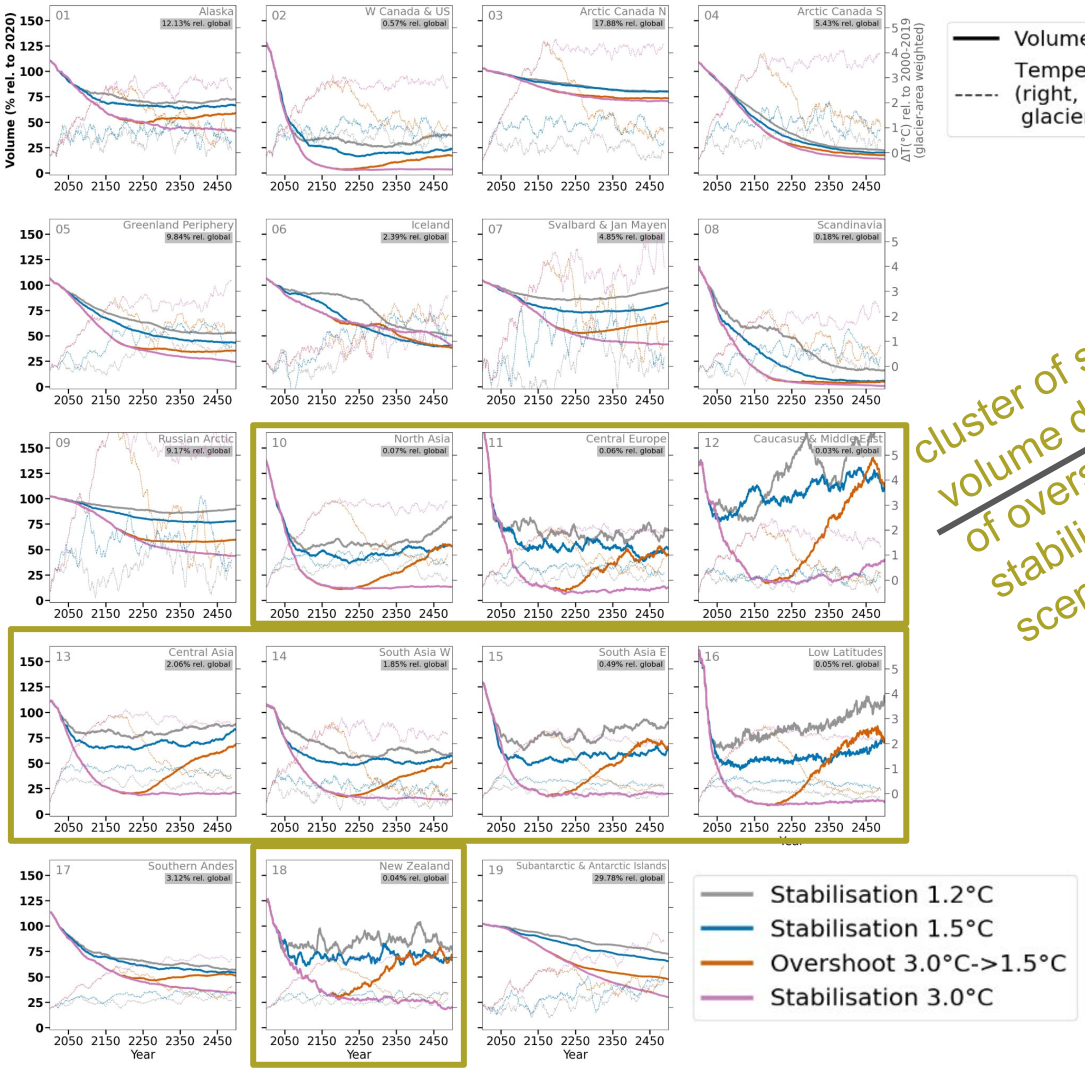
(ii) … special case Iceland (06) …

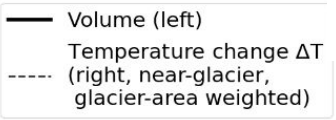


Chosen scenarios differ little:

- because regional temperature change is similar for that ESM

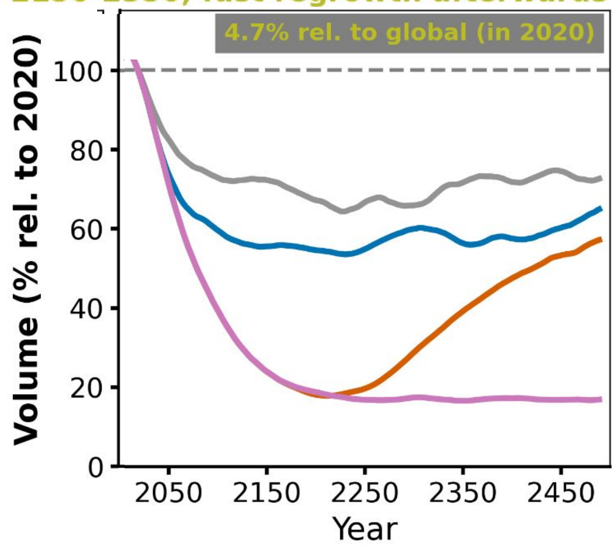


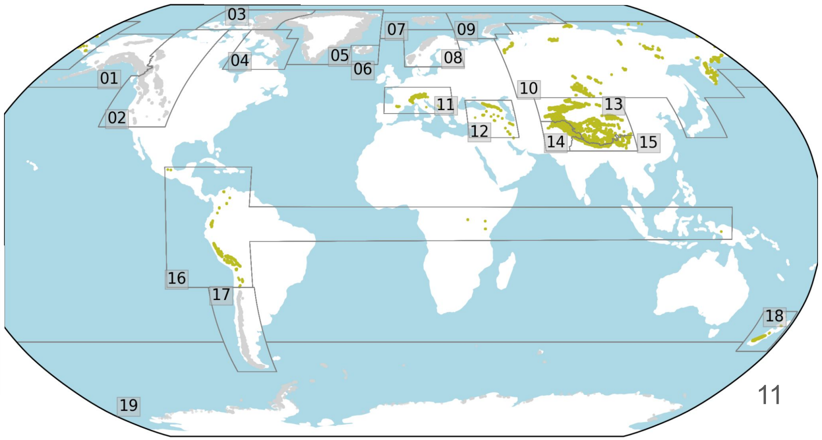


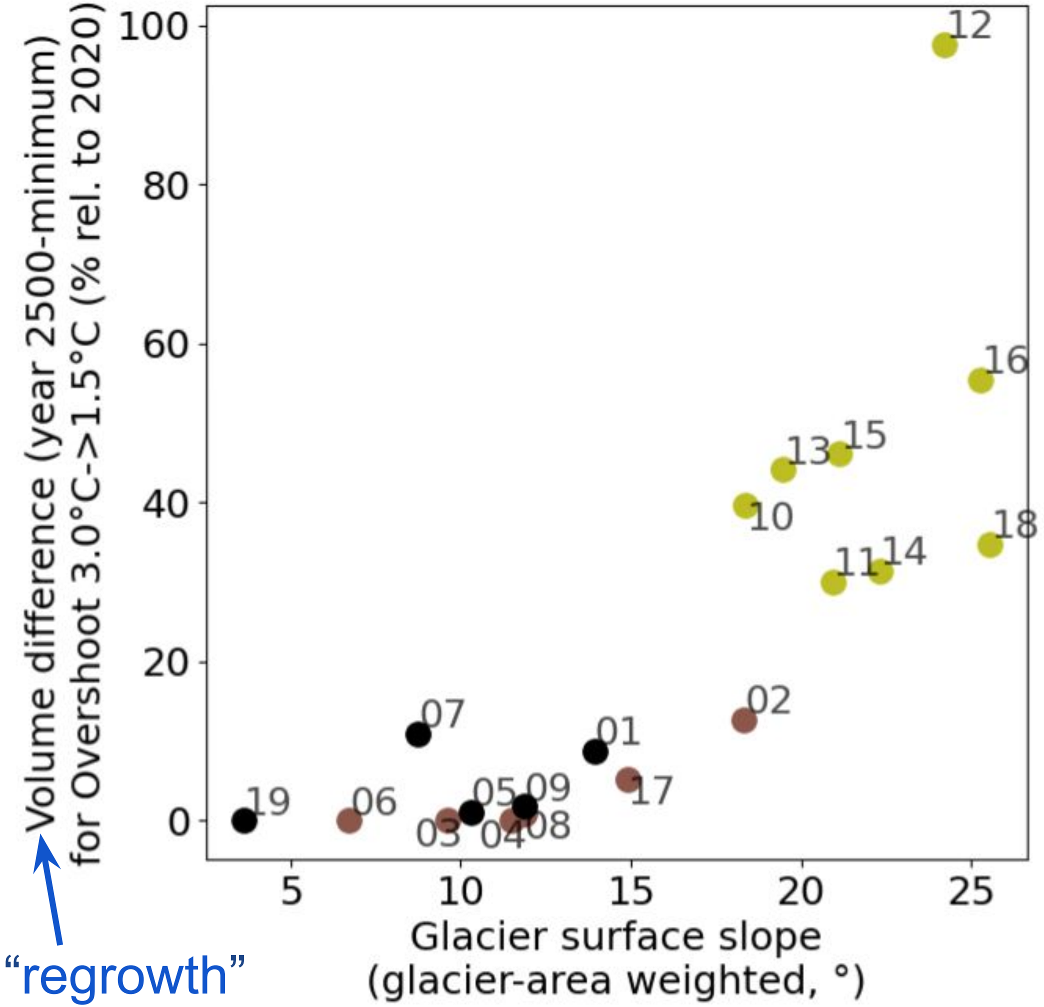


cluster of similar volume differences of overshoot vs stabilisation scenario

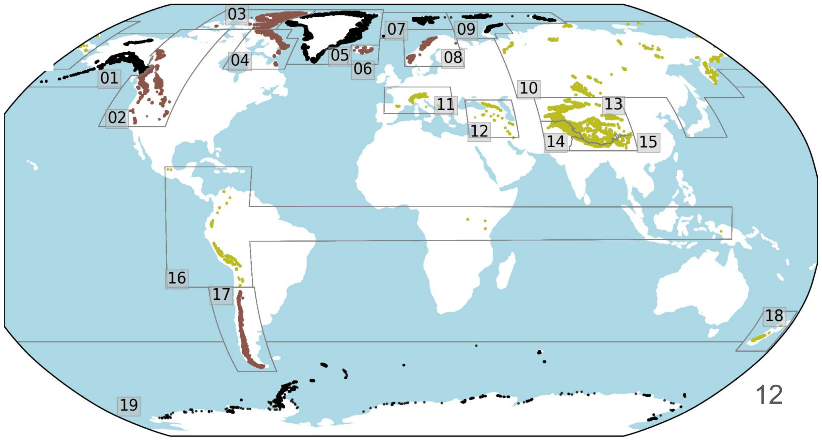
(iii) large overshoot influence in 2150-2350, fast regrowth afterwards







Regional differences in "regrowth rate" partly explained by the glacier regions' slope

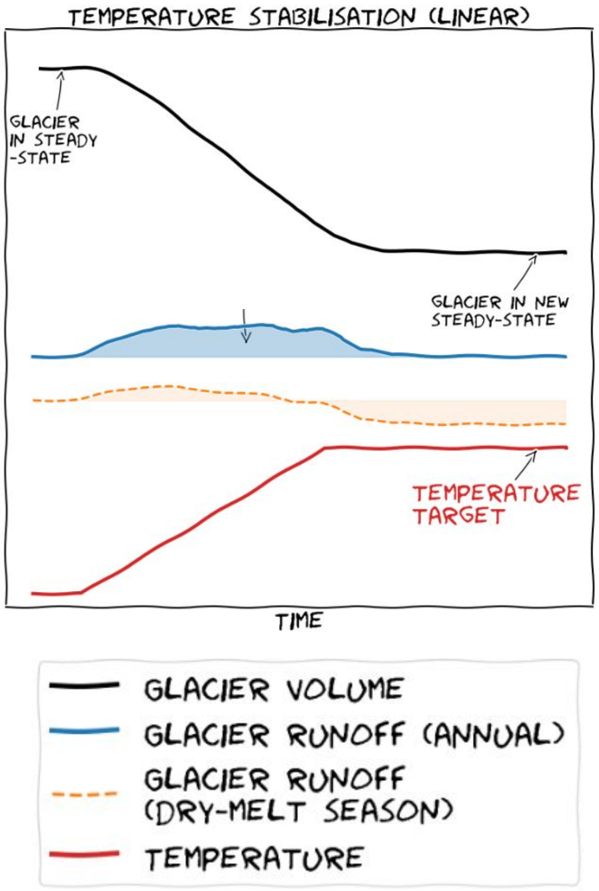


4 Overshoot influence on glacier runoff

4a Idealised experiments: glacier runoff

Glacier runoff:
liquid precipitation and snow & ice melt tracked through a constant area (glacierised area at simulation start)

… idealised experiment uses Aletsch glacier in the background (precipitation kept constant!)



4a Idealised experiments: glacier runoff & “peak water”

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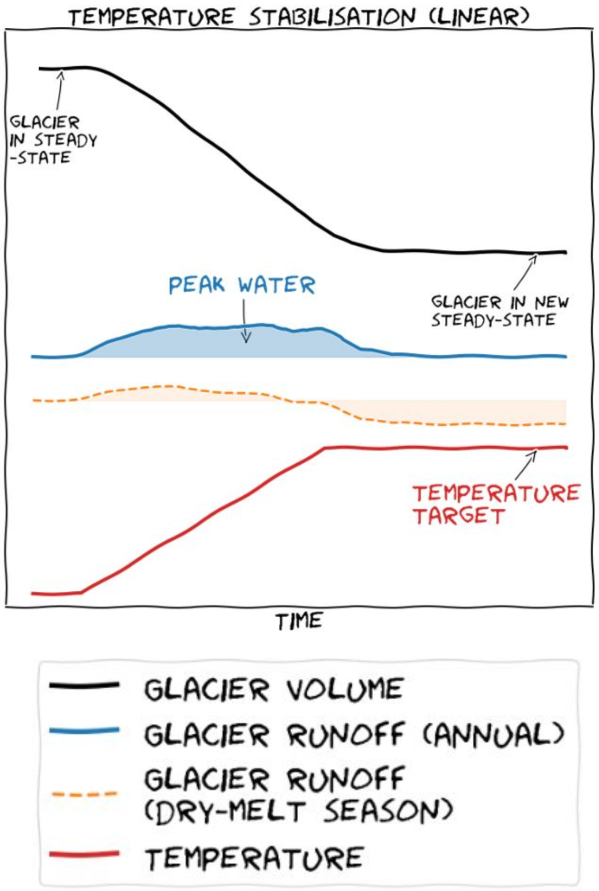
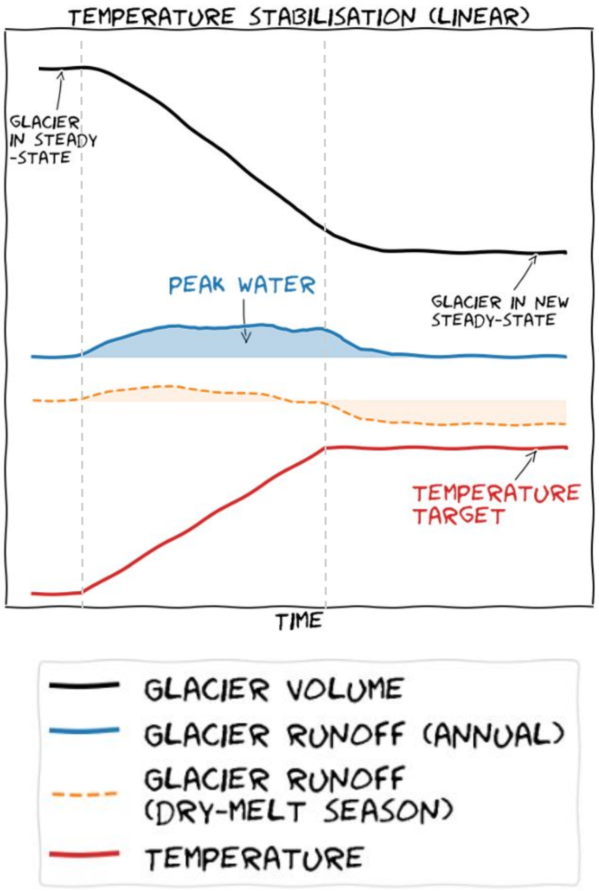


Peak water:
balance between increased melt & reduced glacier volume to melt the glacier

Annual runoff reaches in new steady state same level as in previous steady state, since tracked area and precipitation do not change!

… idealised experiment uses Aletsch glacier in the background (precipitation kept constant!)

4a Idealised experiments: glacier runoff & "peak water"[1]



←modelled reproduction of sketched Fig. 1 of ref.[1]↓

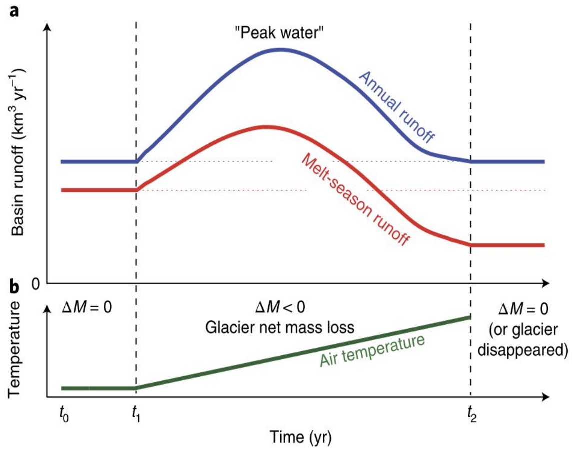


Fig. 1 | Schematic illustration of the changes in runoff from a glacierized basin in response to continuous atmospheric warming.

… idealised experiment uses Aletsch glacier in the background (precipitation kept constant!)

[1] Huss, M. and Hock, R.: Global-scale hydrological response to future glacier mass loss, Nat. Clim. Chang., 8(2), 135–140, doi:10.1038/s41558-017-0049-x, 2018

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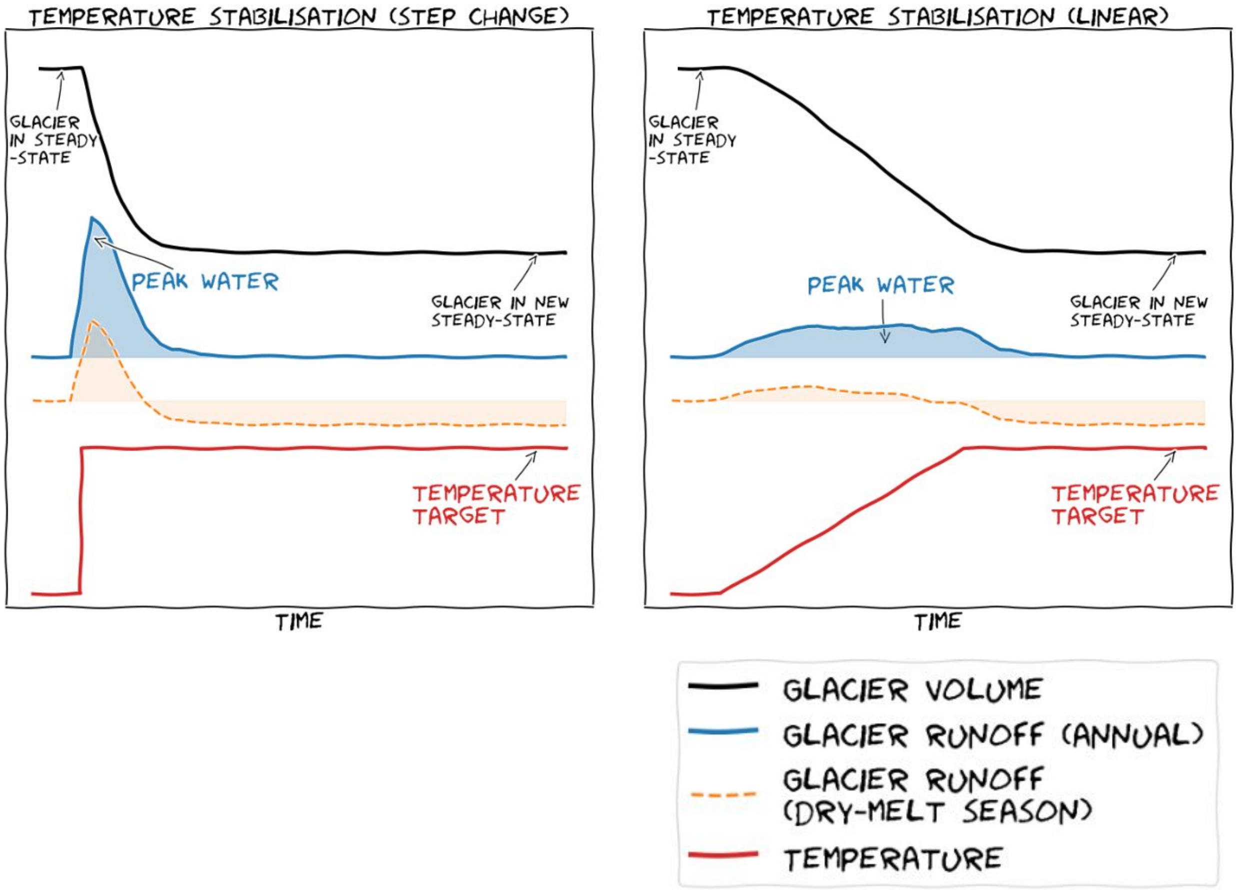
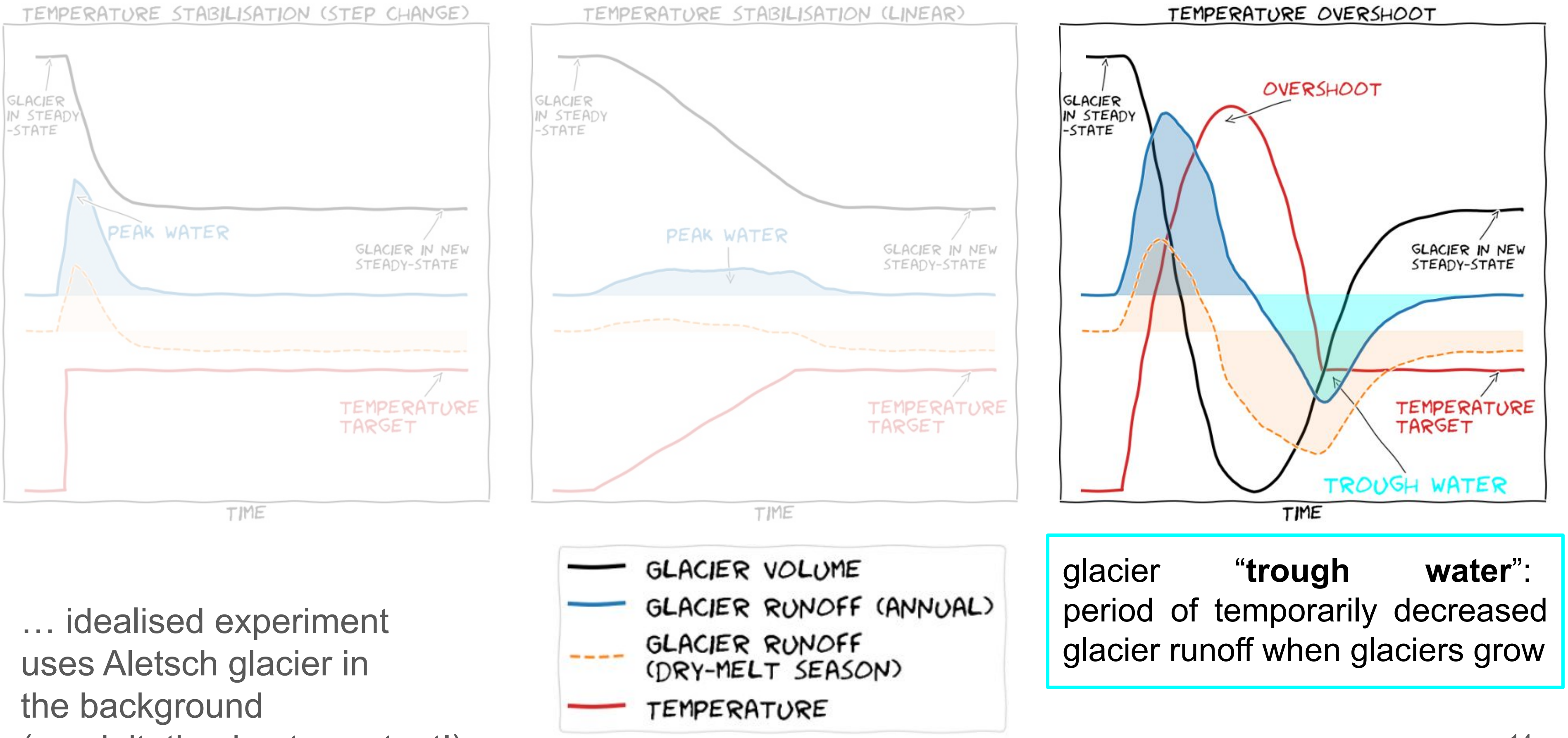


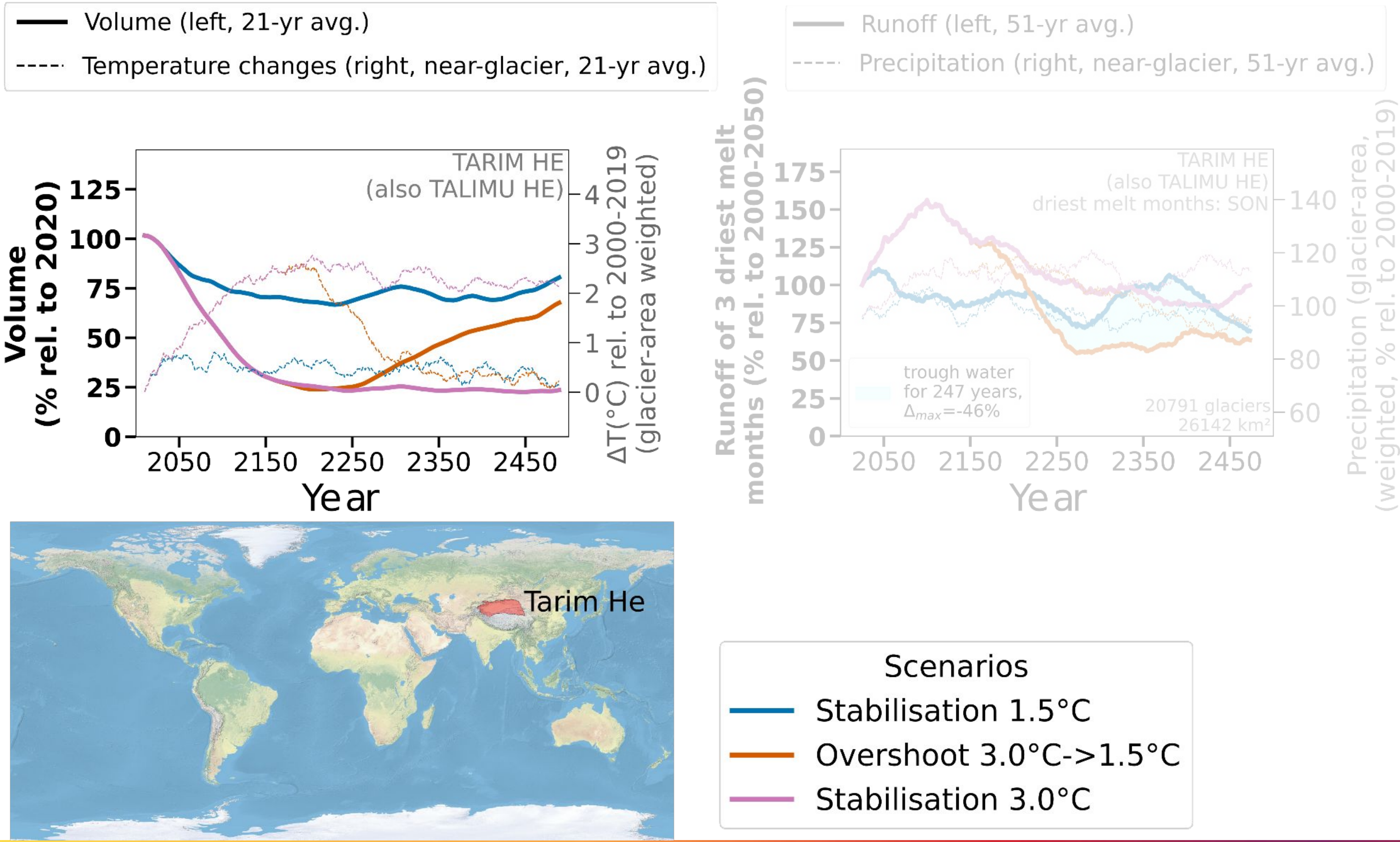
4a Idealised experiments: **new** concept of **“trough water”**



… idealised experiment uses Aletsch glacier in the background (precipitation kept constant!)

glacier **“trough water”**: period of temporarily decreased glacier runoff when glaciers grow

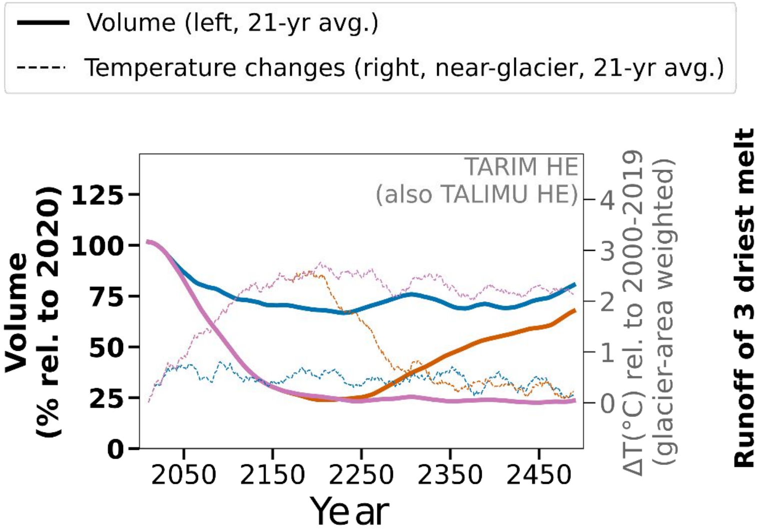
4b Basin-wide glacier runoff & “trough water” with ESM stabilisation & overshoot scenarios

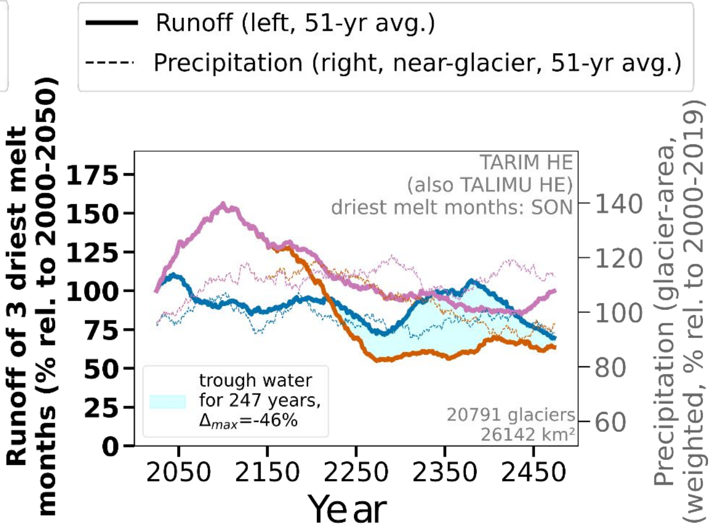


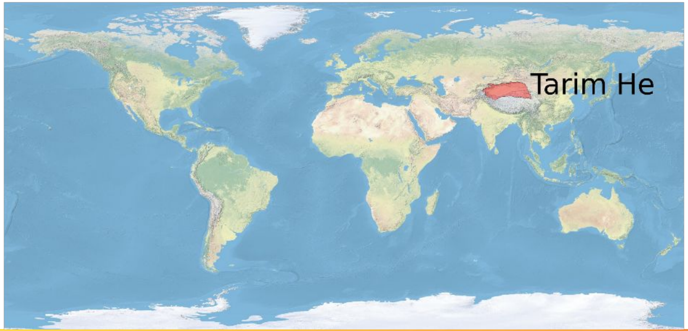
<u>Definition:</u> “Trough water” occurs if 51-year average glacier **runoff from “Overshoot 3.0°C -> 1.5°C”** scenario is ≥5% **smaller than in “Stabilisation 1.5°C”** scenario for ≥ 20 years.

For the Tarim basin & this ESM:
- significant and long “trough water”
- precipitation increases with warming
→runoff largest for 3.0°C scenario

4b Basin-wide glacier runoff & “trough water” with ESM stabilisation & overshoot scenarios







Scenarios
- Stabilisation 1.5°C
- Overshoot 3.0°C->1.5°C
- Stabilisation 3.0°C

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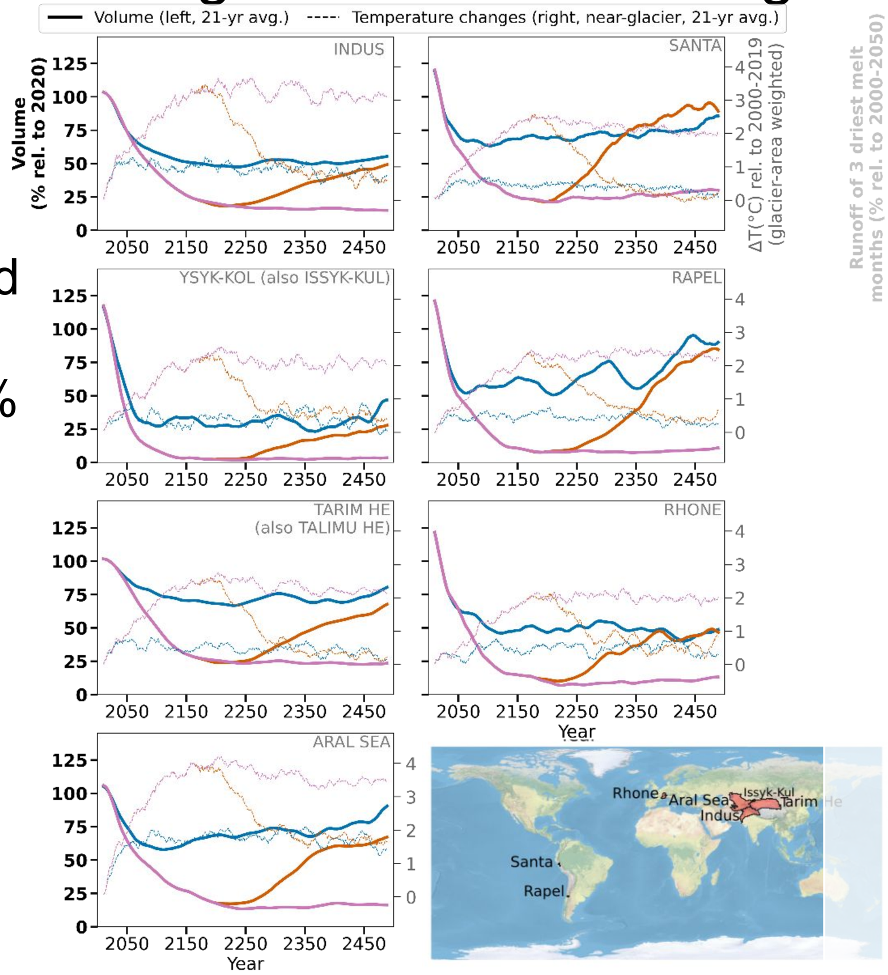

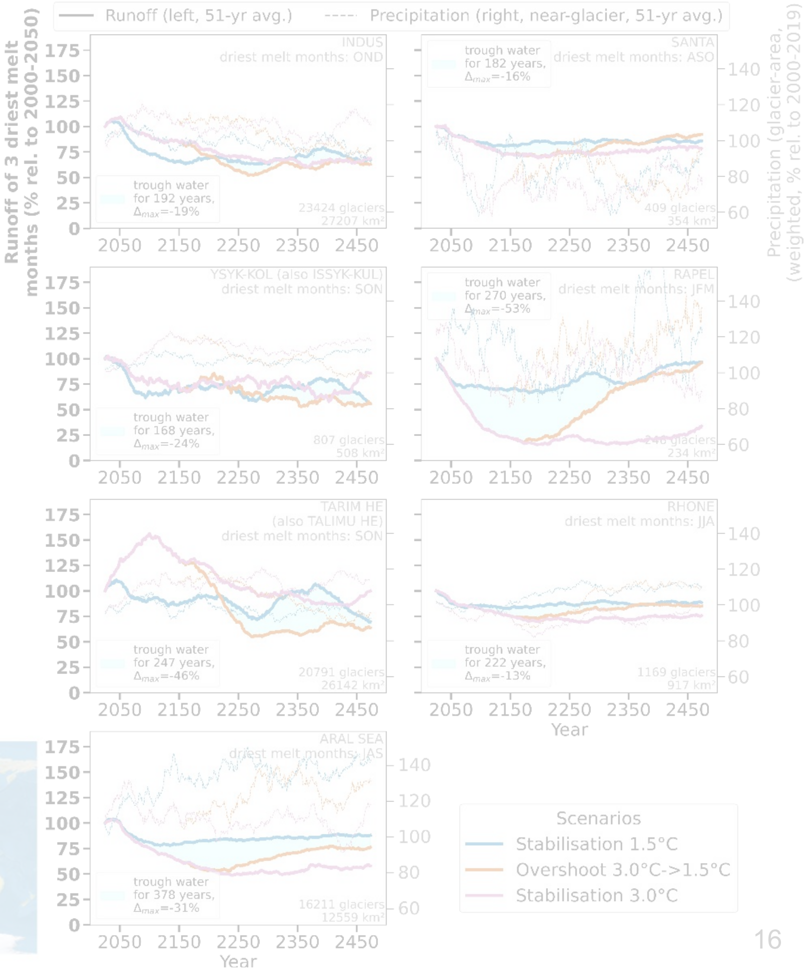

7 most arid basins* with >0.9% glaciation

*Ultee et al. (2022): Glacial runoff buffers droughts through the 21st century

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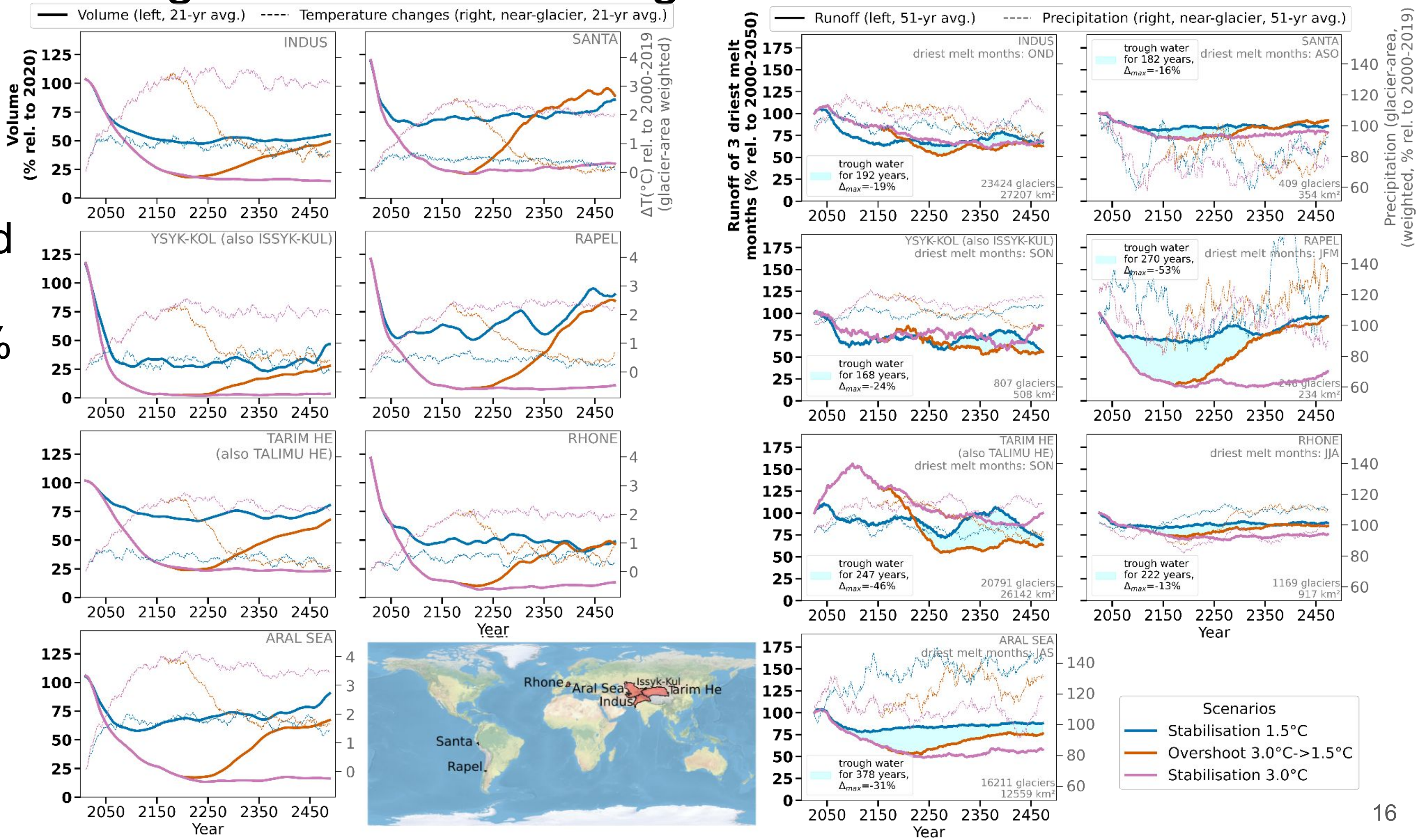

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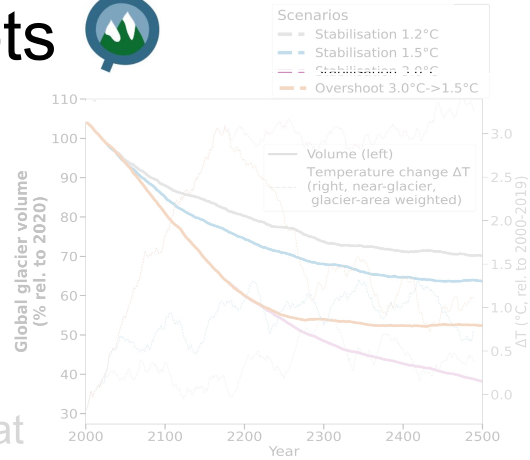
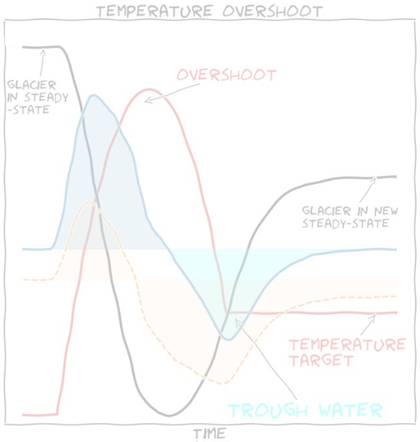
5 Conclusions - glacier impacts of overshoots

- Slow global response results in irreversible ice loss over centuries
    - In 2500, overshooting 1.5°C temporarily by a peak at 3°C results in 11% more global glacier loss than directly stabilising at 1.5°C
- In fast-responding glaciated basins (mostly steeper mid-latitude regions) overshooting temperature targets creates growing glaciers that reduce glacier runoff ("trough water")
    - Impact & timing depends on local characteristics:
      e.g., magnitude of local temperature overshoot & future precipitation changes, melt vs precipitation seasonality, initial state (pre- or post peak water), glacier response time
- Further realisations of ESMs and coupling with a hydrological model imperative for detailed regional analyses of potential downstream impacts
- No confidence on carbon dioxide removal technique scalability & trough water is just one out of many uncertain overshoot impacts !!!





←slides

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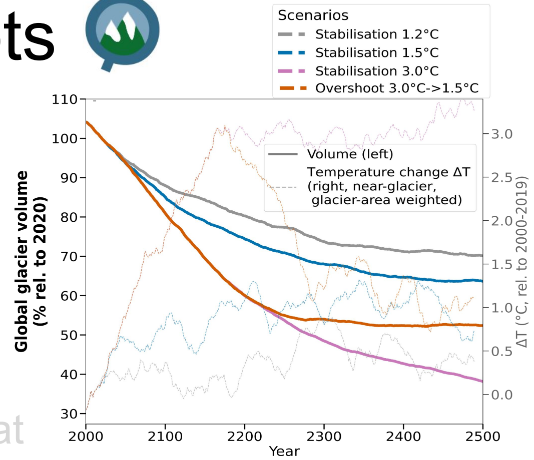

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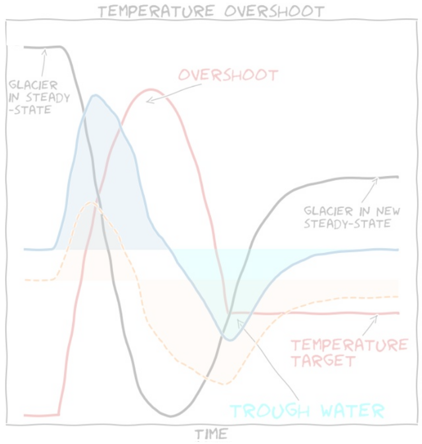

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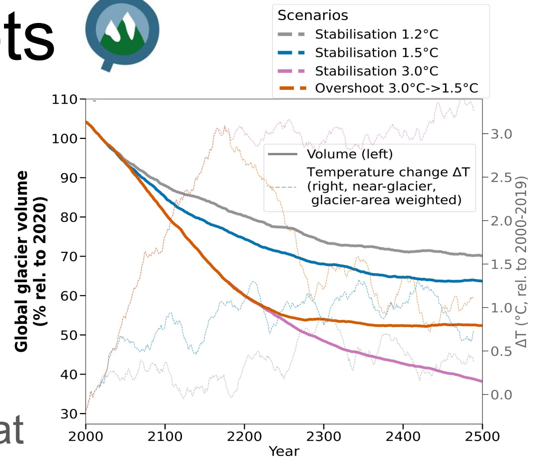

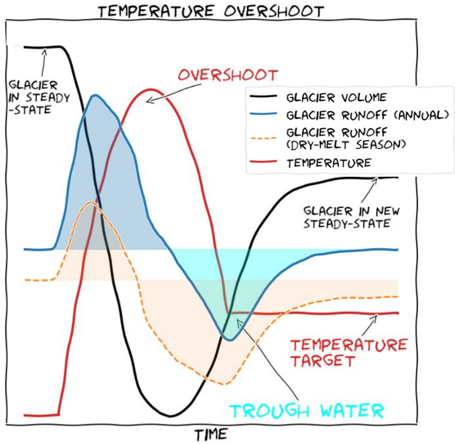

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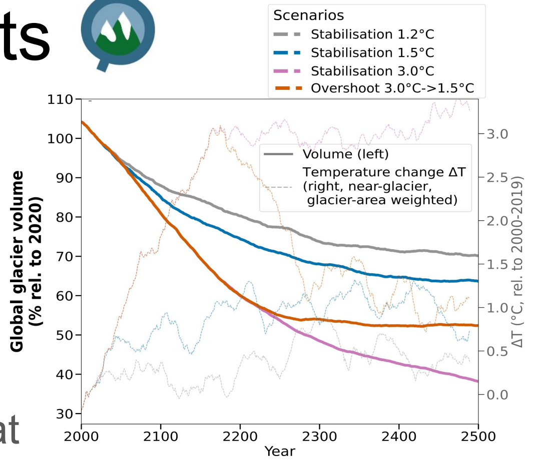
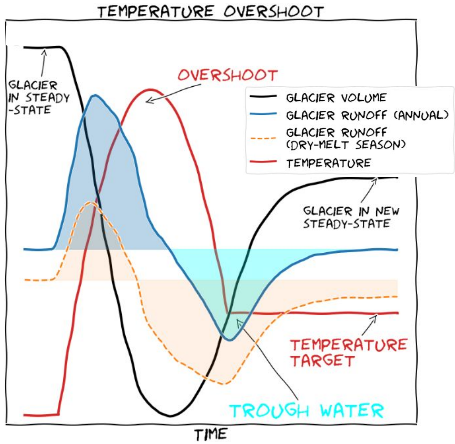
- Further realisations of ESMs and coupling with a hydrological model imperative for detailed regional analyses of potential downstream impacts
- No confidence on carbon dioxide removal technique scalability & trough water is just one out of many uncertain overshoot impacts !!!

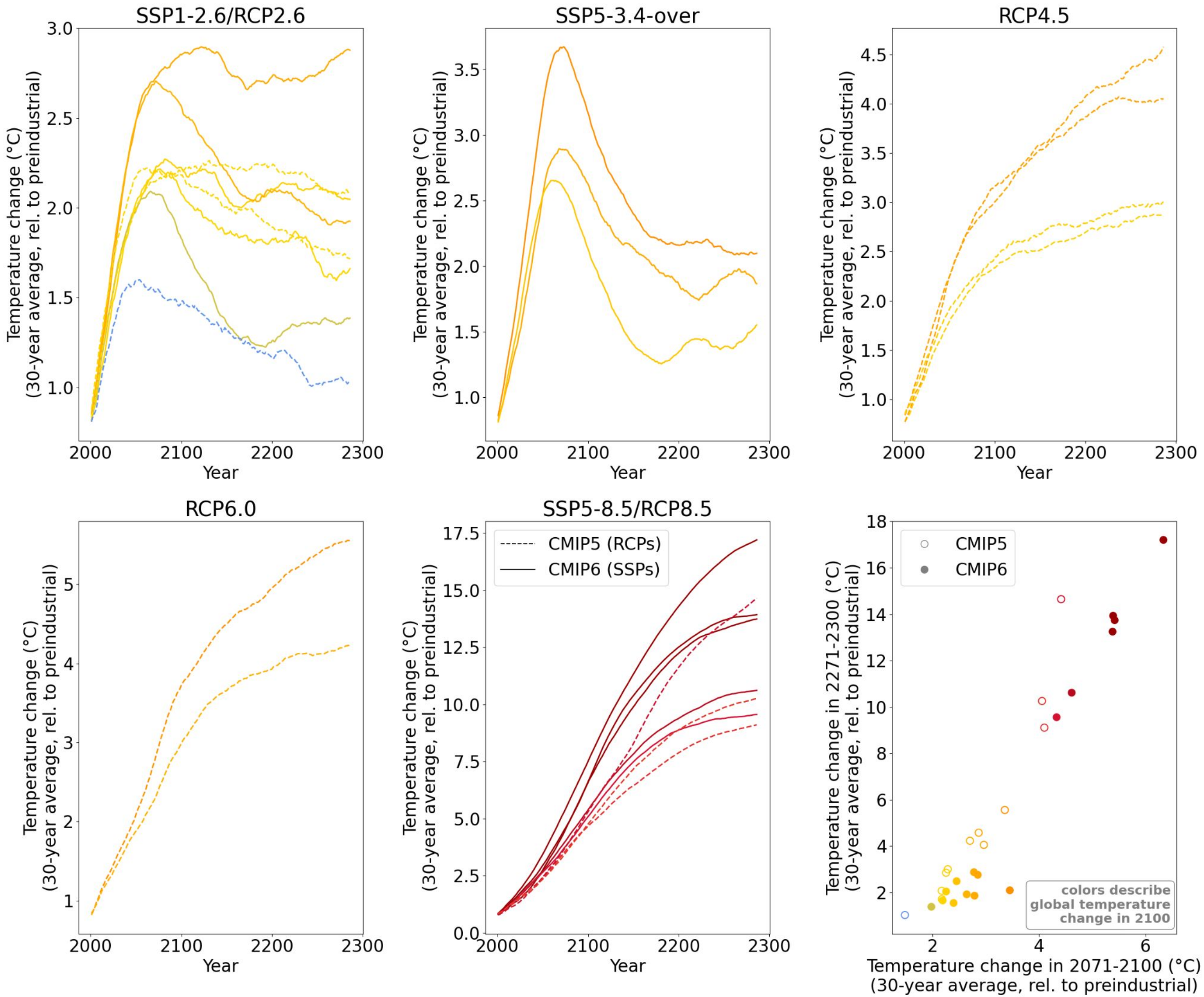




←slides

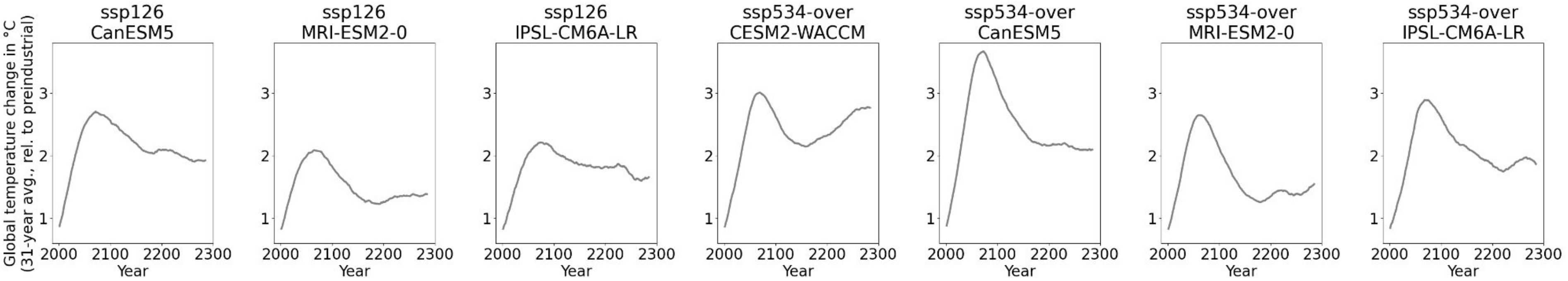
Appendix

Appendix A: Glacier volume projections



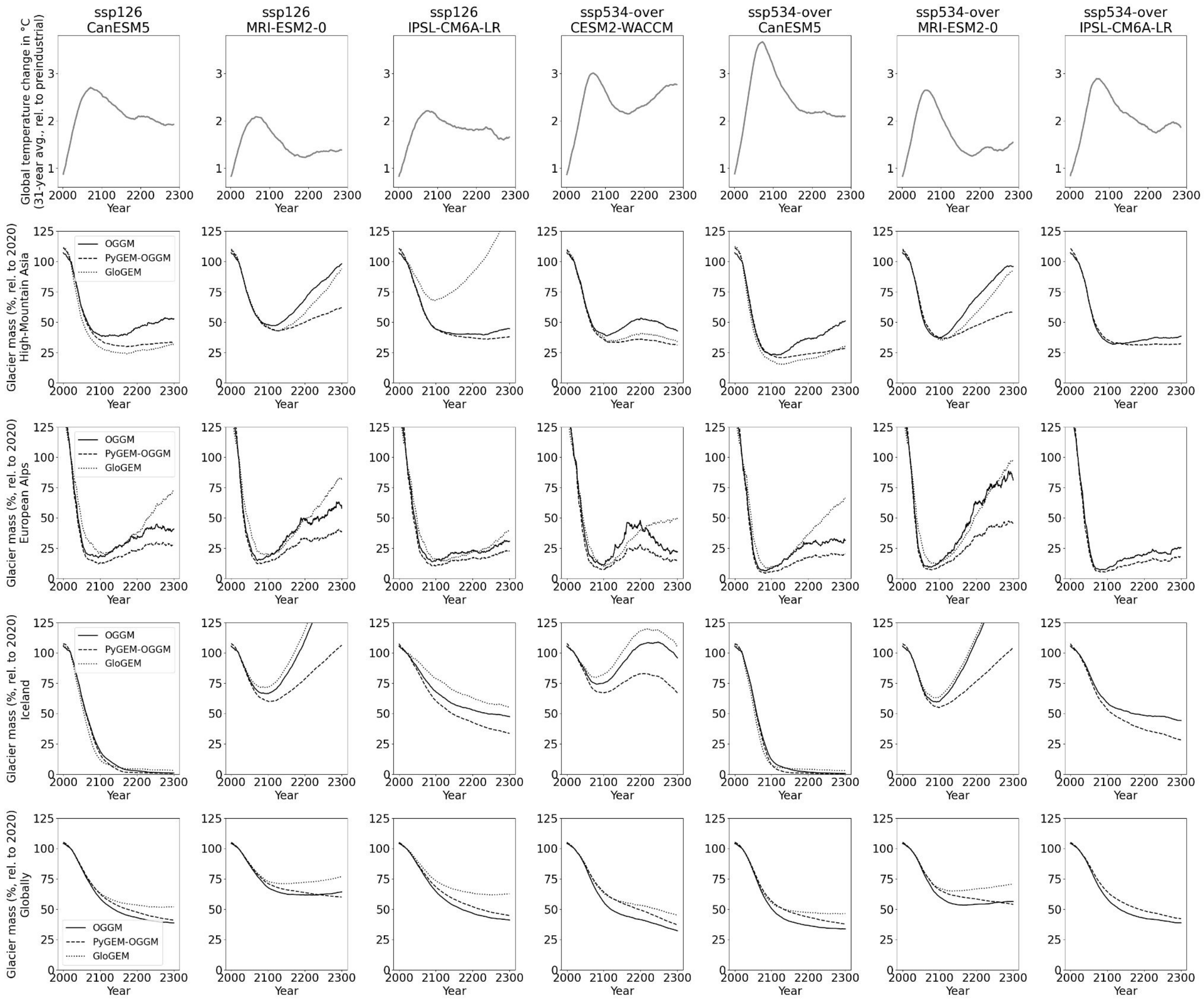
Global mean temperature changes from CMIP GCMs until 2300

Existing published climate scenarios & GCM/ESMs from CMIP6 until 2300 with an “overshoot behavior”



- very few GCMs with overshoots and they only go until 2300
- **lack a comparison target / a temperature stabilisation scenario**

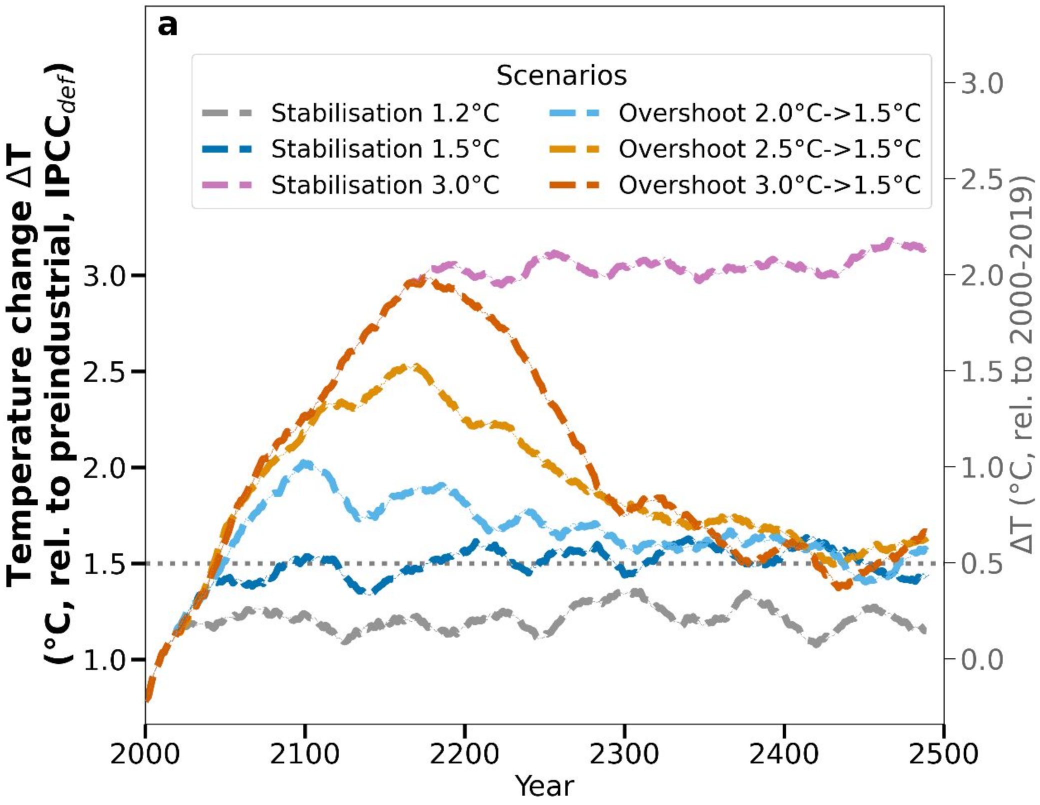
→ We use instead new idealised overshoot scenarios …



Glacier volume projections with CMIP6 under global mean temperature overshoots (where temperatures increase and then drop)

… we see growing glaciers in fast responding regions… but strong glacier model differences!

Data: Schuster et al., 2023, Zenodo, glacier-model-projections-until-2300
https://github.com/lilianschuster/glacier-model-projections-until2300

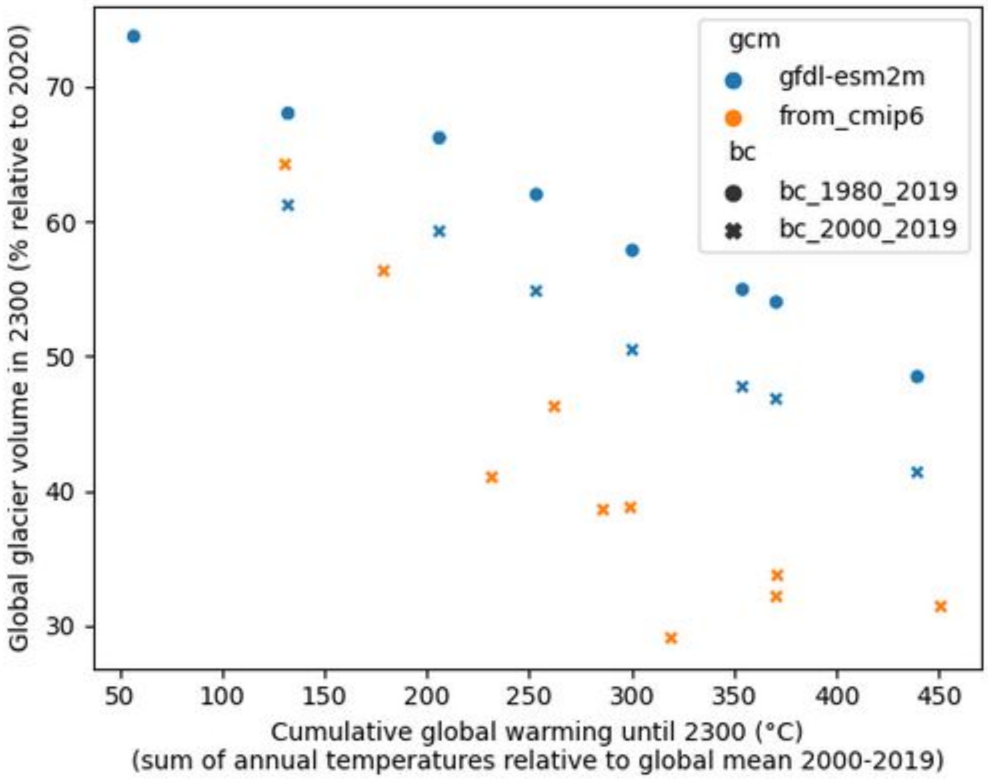


Other used scenarios of that ESM [1] for our study:

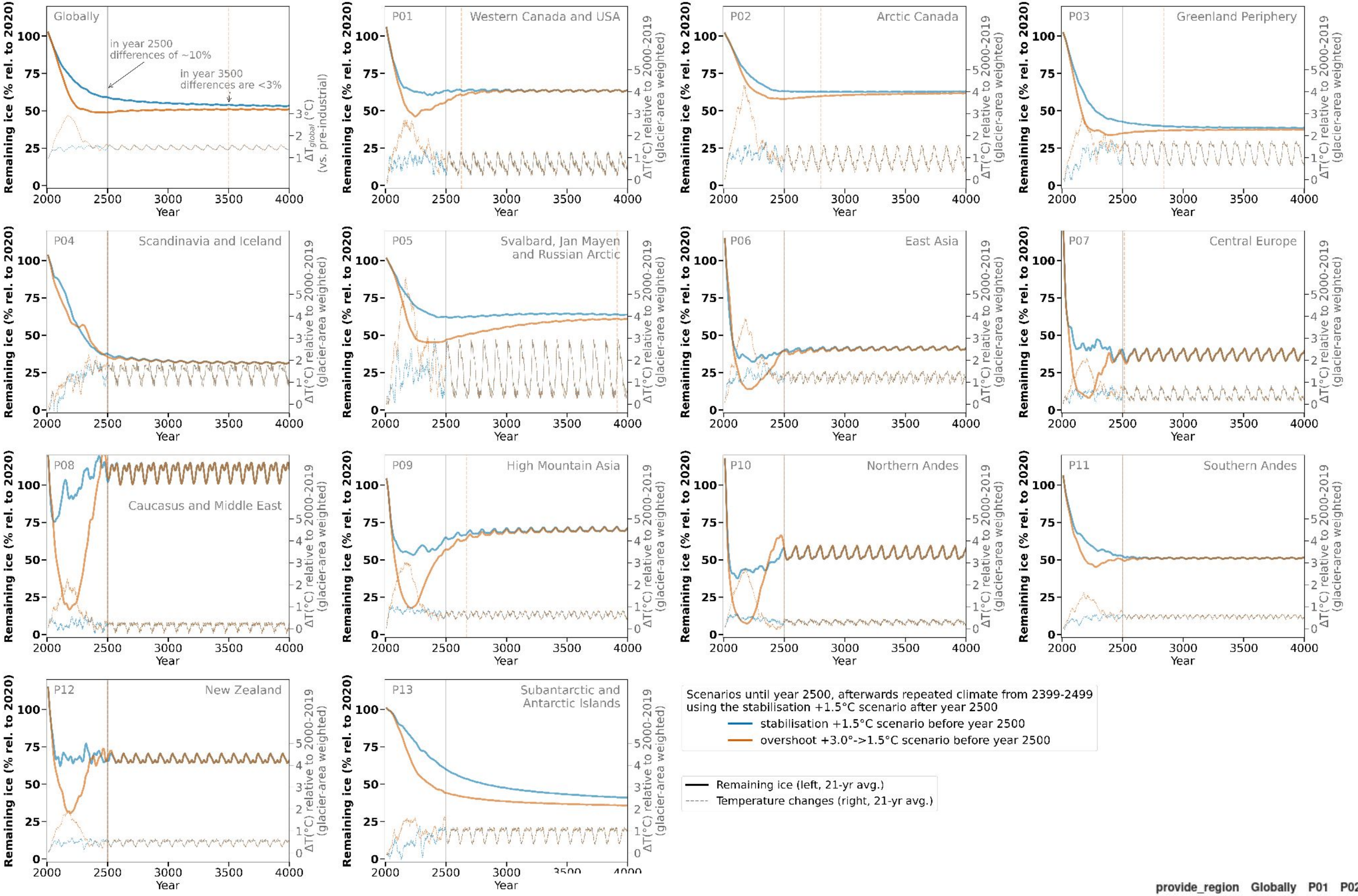
- GFDL ESM2M Earth system model (ESM, 2.5° resolution) from 2000-2500
- applies Adaptive Emission Reduction Approach to match prescribed temperature targets.

[1] Lacroix, F. et al., in preparation: High-Latitude Surface Ocean Warming Following Recovery of Meridional Transports in Overshoot Scenarios

Comparison to other GCMs until 2300 and influence of bias-correction method



What happens after 2500 regionally ?



provide_region	Globally	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13
Volume differences between initial states from overshoot +3.0°C->+1.5°C and stabilisation +1.5°C scenario (% relative to 2020)	-1.5	-0.0	-0.4	-0.7	-0.0	-0.1	0.0	-0.0	0.0	-0.0	0.1	-0.0	-0.0	-4.4
Volume differences between initial states with zero volume and stabilisation +1.5°C scenario (% relative to 2020)	-4.7	-0.1	-1.1	-2.1	-2.4	-1.7	-0.0	-0.0	0.0	-0.0	-0.1	-2.9	-0.0	-12.9

Local evidence for completely irreversible tipping dynamics on mountain glaciers exist:

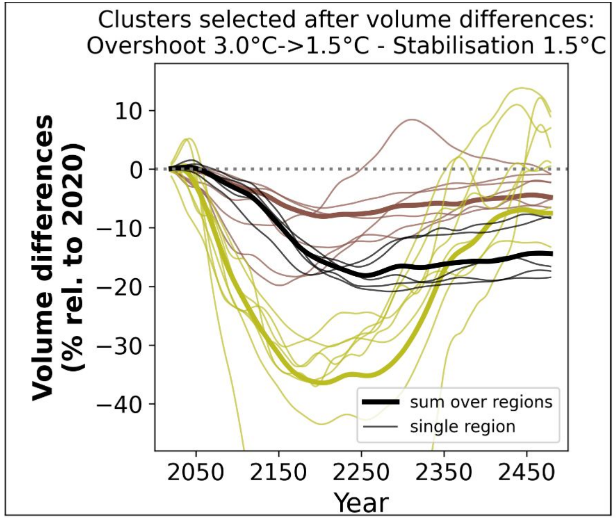
However, feedbacks are small, simplified, only implicitly or neglected in global glacier models.

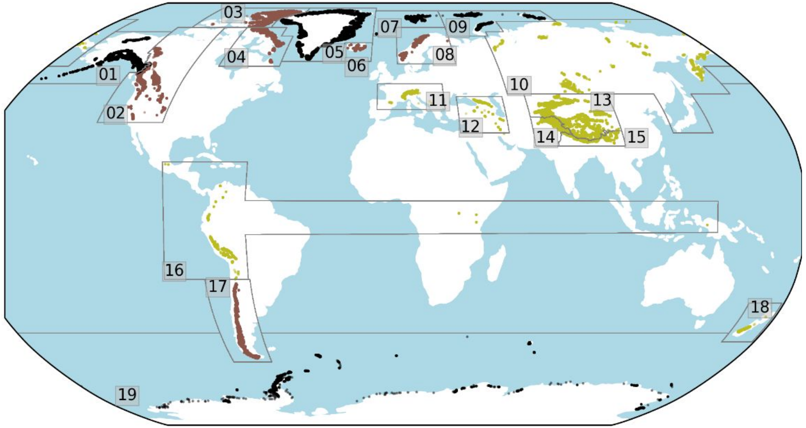
- positive feedbacks: e.g. climate-independent retreat of calving glaciers if destabilisation threshold reached, surface-darkening, local warming due to retreating glaciers, elevation-melt feedback, glacier-related slope failures, thermokarst processes, increased ice flow?, …
- negative feedbacks: glacier retreat to higher elevations, more insulating debris, decreased ice flow?

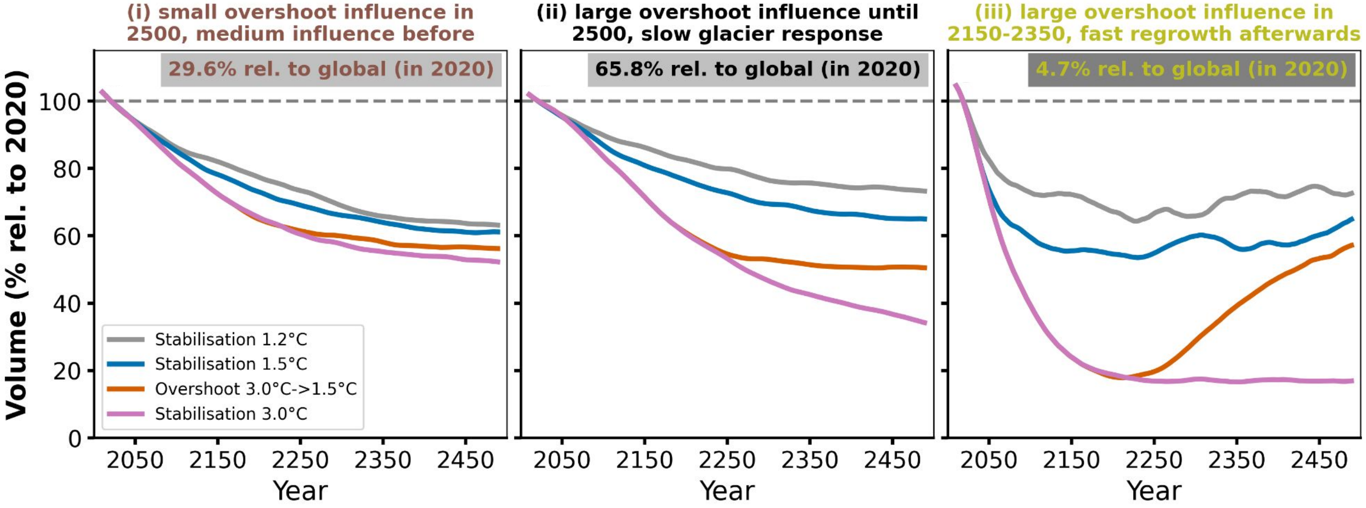
→ integrated influence of local feedbacks is unknown. First studies including individual feedbacks regionally indicate limited influence on regional projections.

more in the Global Tipping Points Report 2023
https://global-tipping-points.org/

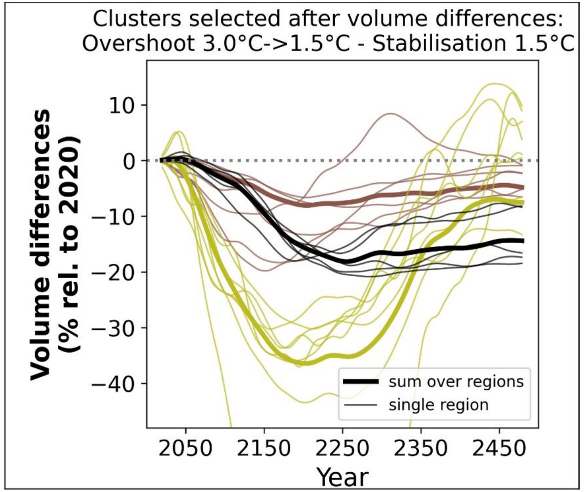
Regional glacier volume evolution until 2500

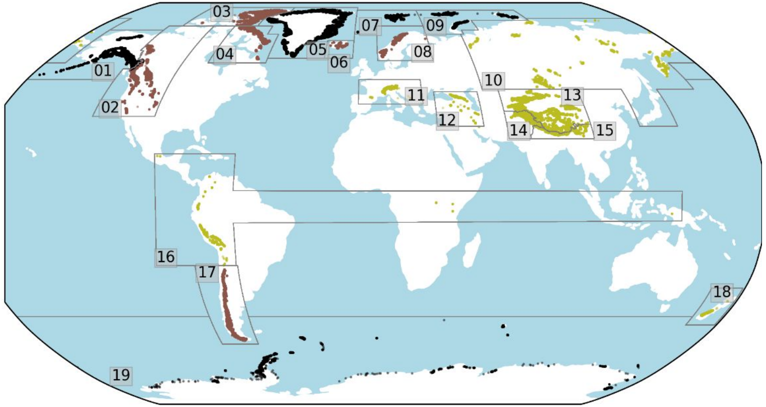


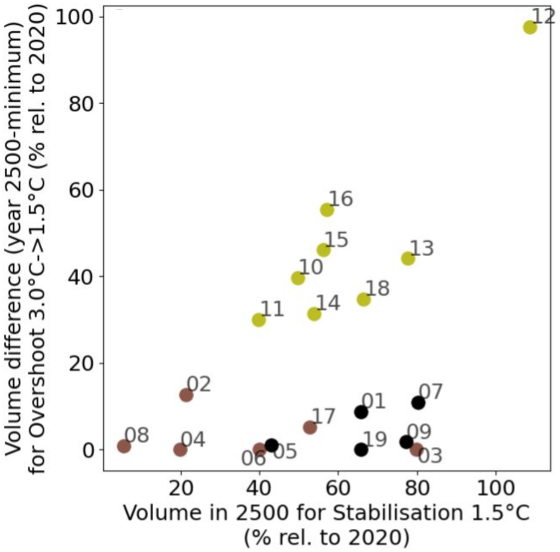


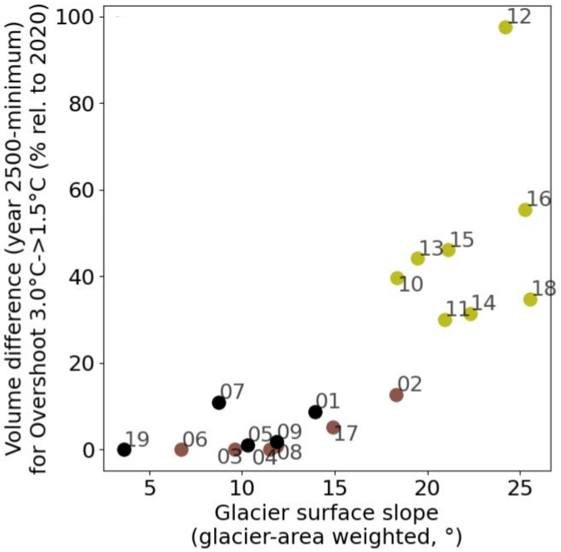


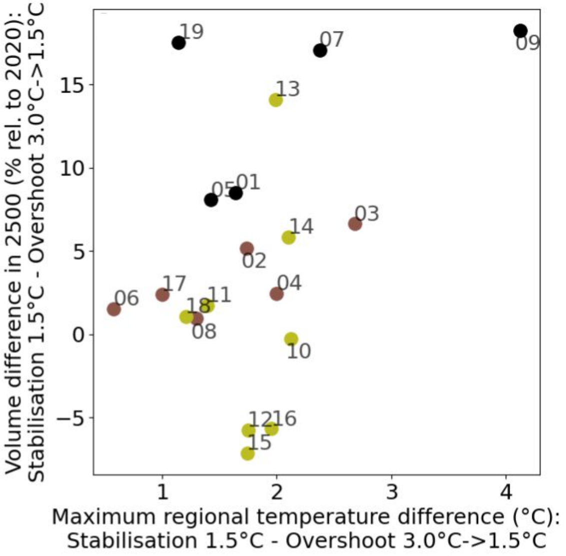
Regional glacier volume evolution until 2500



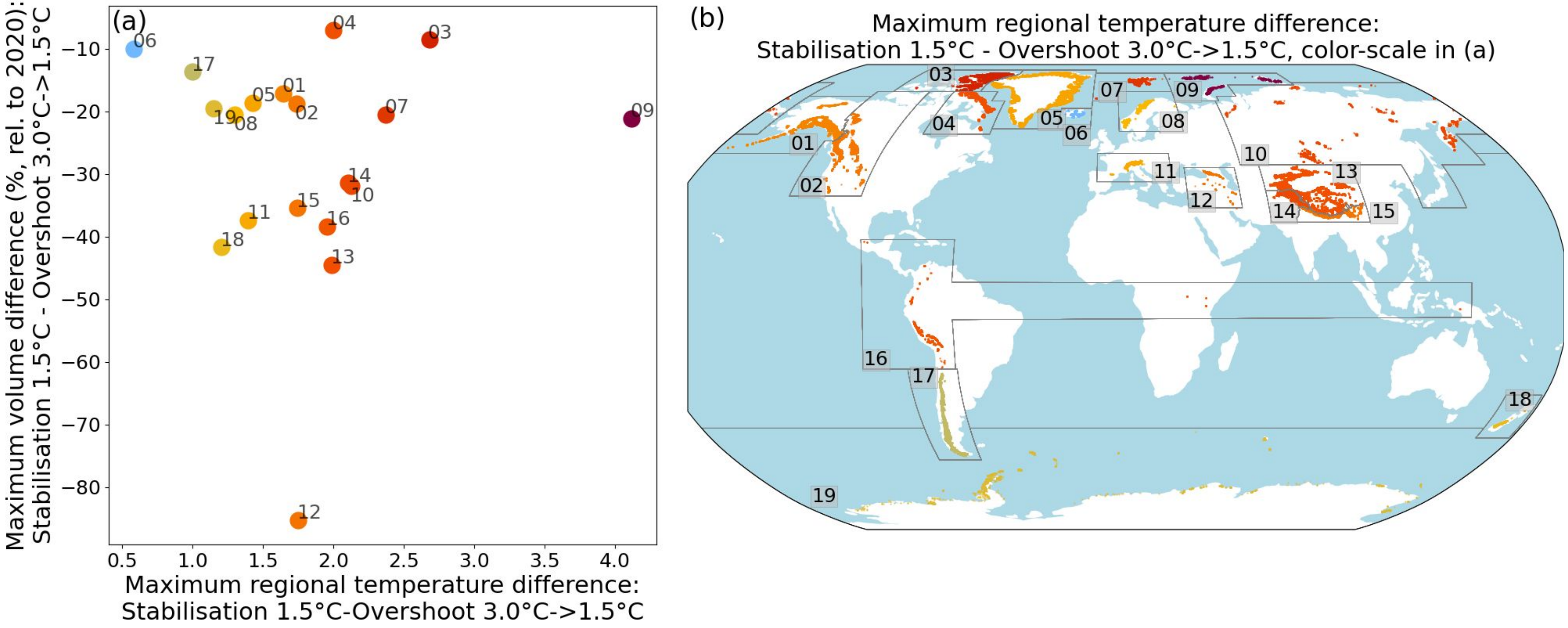




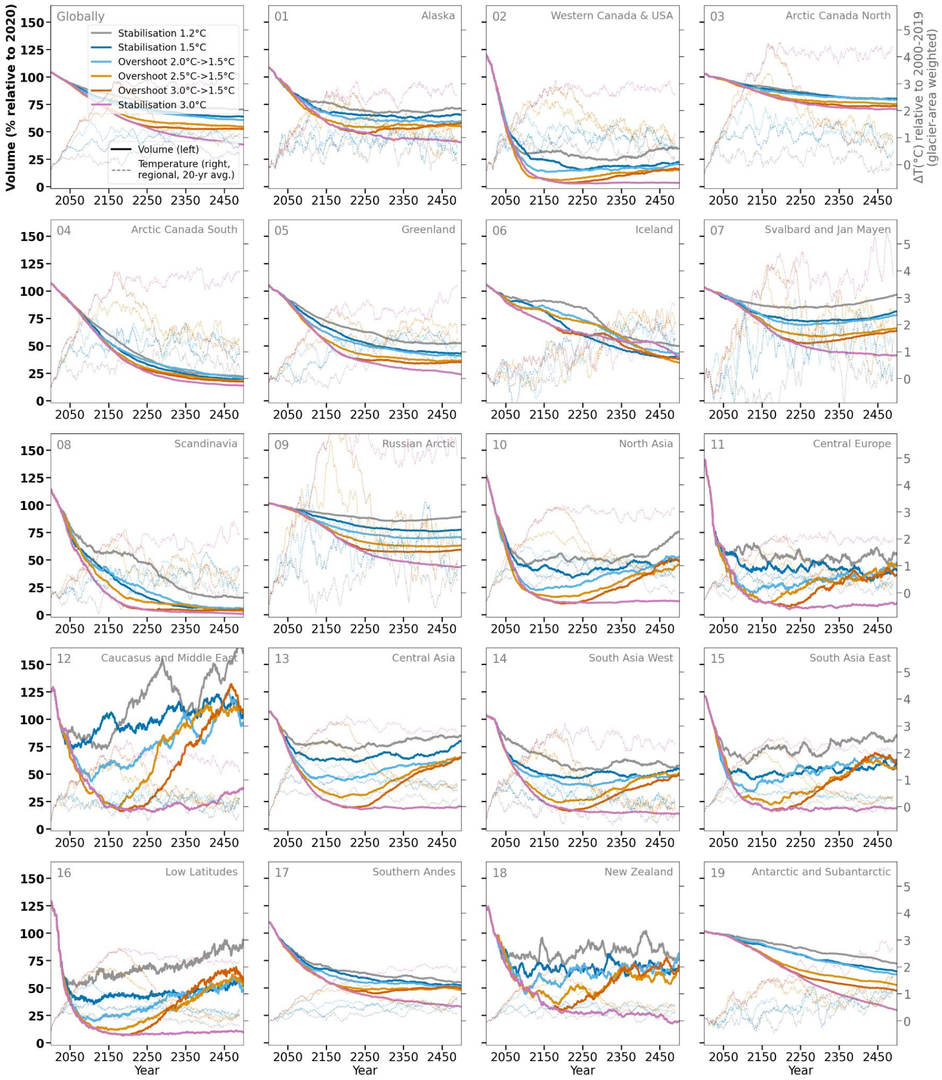




Regional temperature change differences …

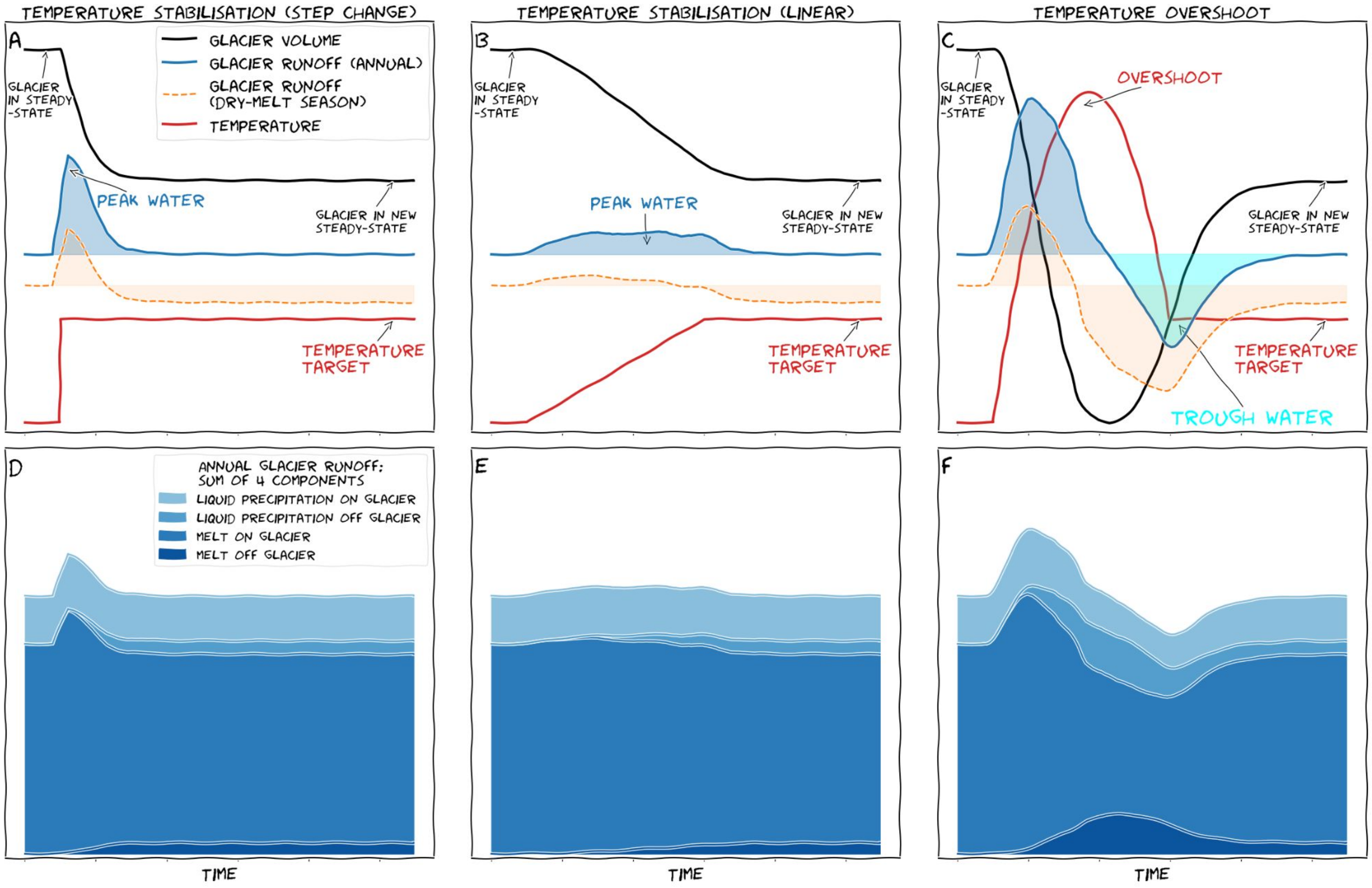


Glacier projections with additional overshoot scenarios of the GFDL-ESM2M Earth System Model

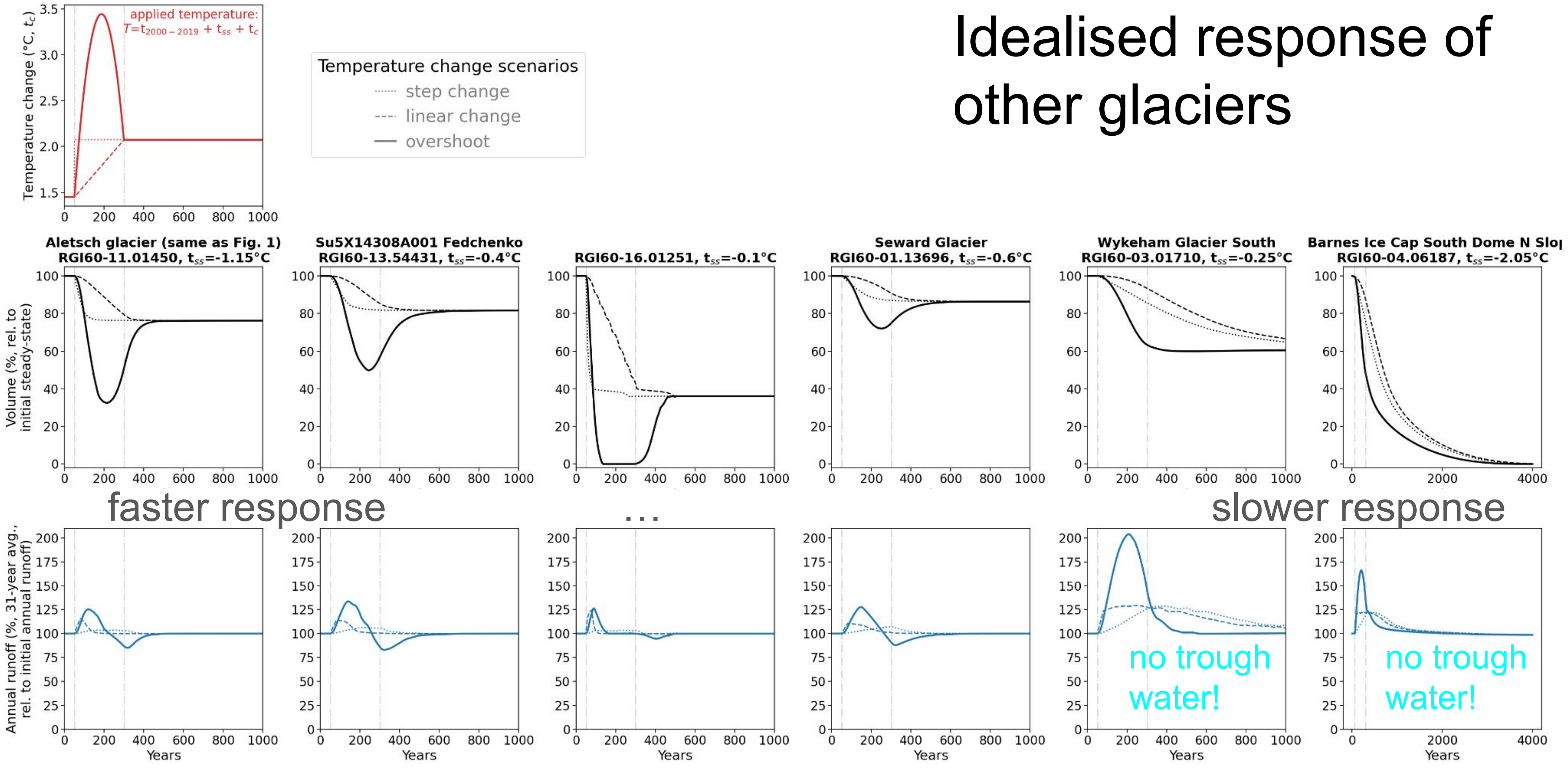


Appendix B: Glacier runoff

Idealised experiments -> additional figures:

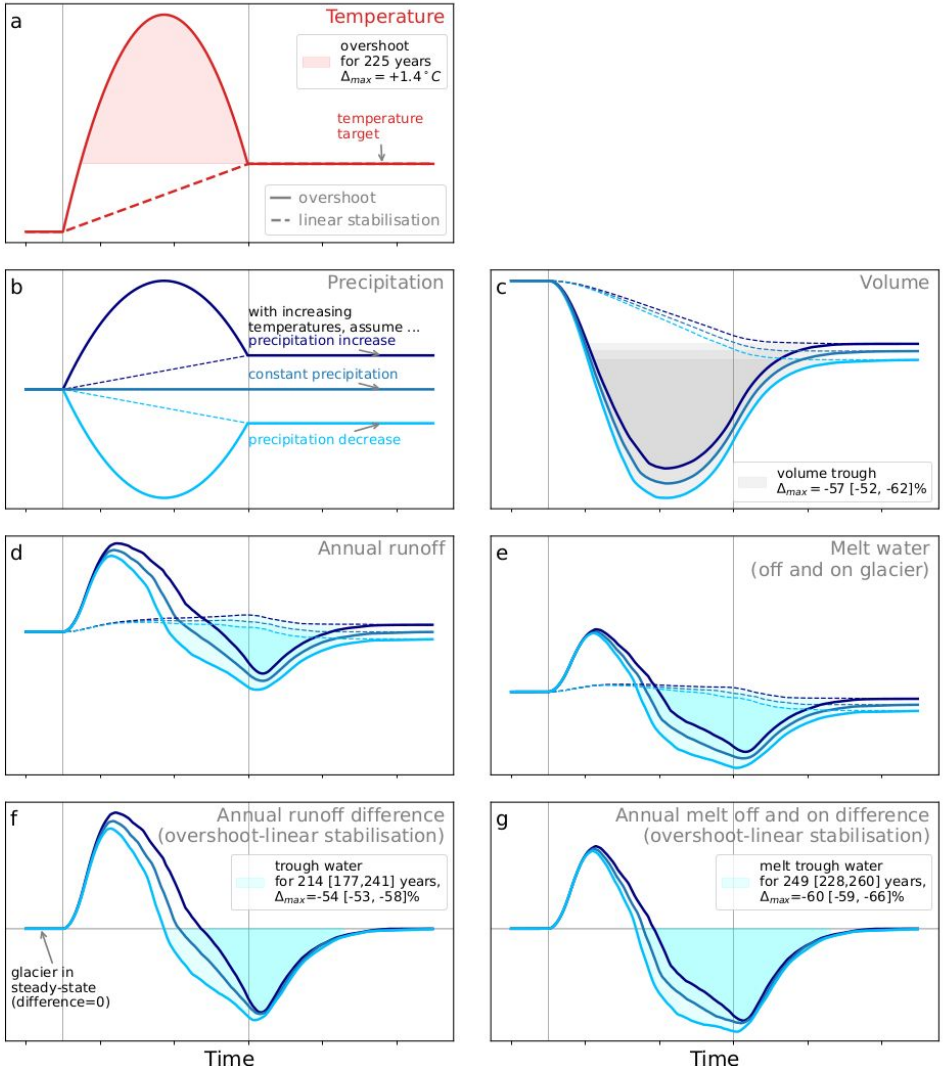


Idealised response of other glaciers



Influence of a temperature overshoot is glacier-specific. If glacier response is longer than temperature overshoot, no trough water will occur.

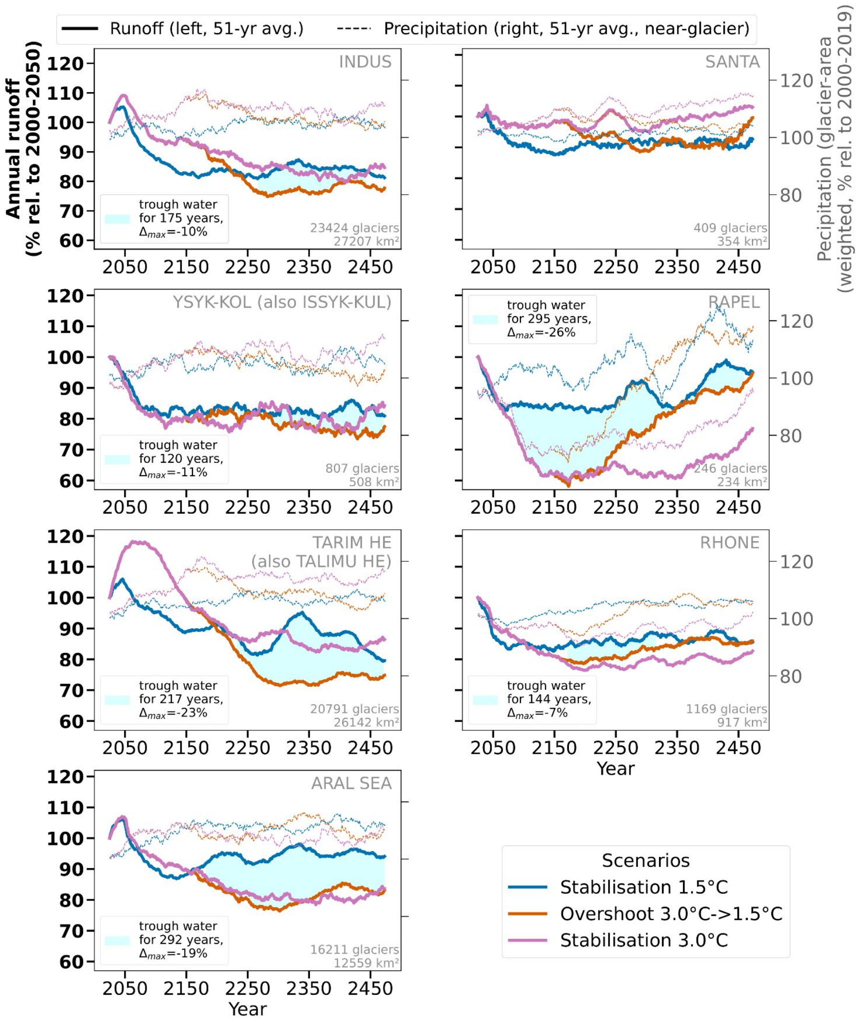
Precipitation change influence:
- on idealised glaciers -



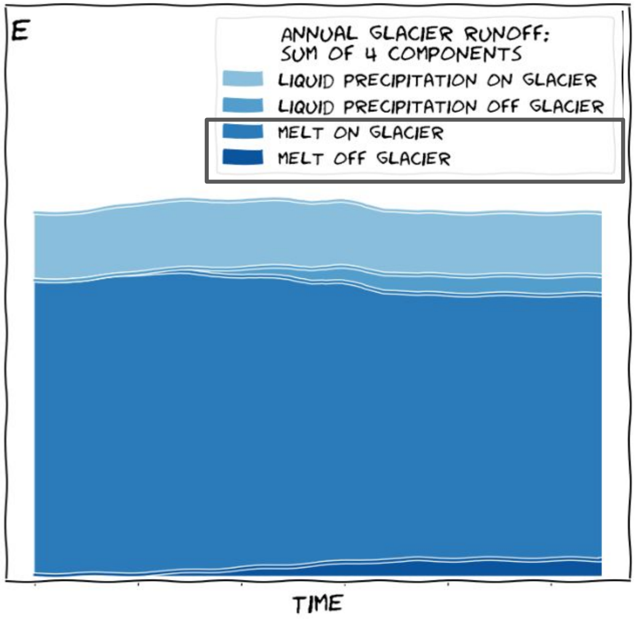
For regions with precipitation decrease with warming:
→ longer and more intense trough water

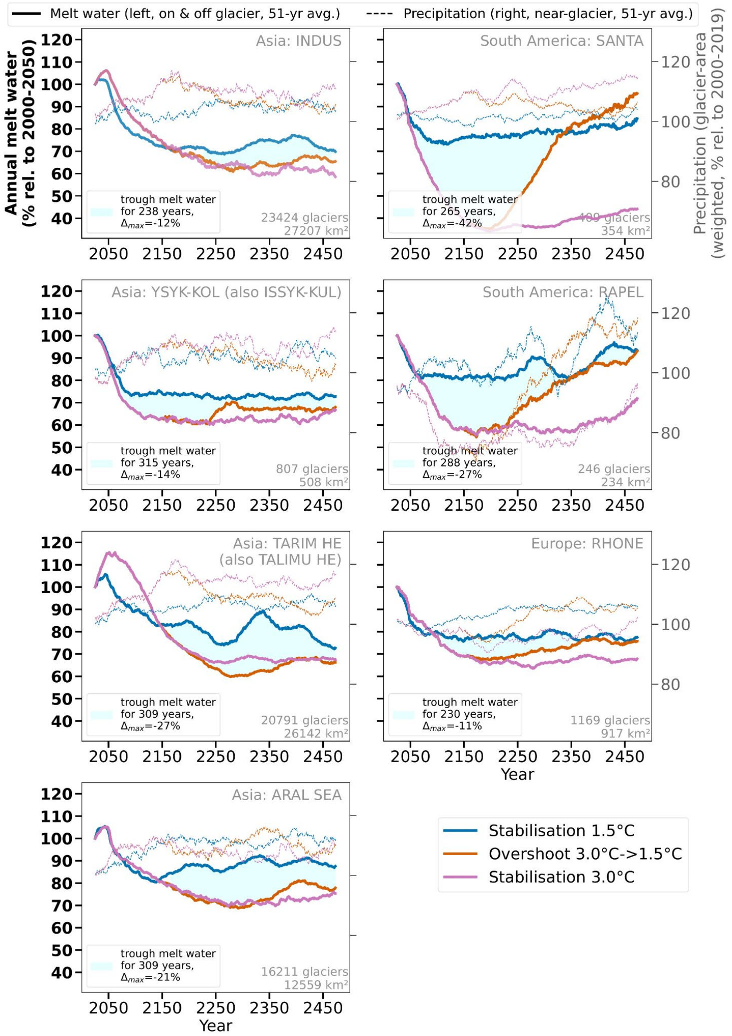
Idealised influence of precipitation changes along temperature changes on glacier volume, runoff and melt on and off the glacier The idealised simulations were done on the Aletsch glacier (Switzerland), where we set the temperature increases between the two steady-state to +0.62°C, and the overshoot scenario peaks at +2.0°C relative to the initial climate. The precipitation changes were set to ±5% °C−1.

Annual glacier runoff projections for selected basins

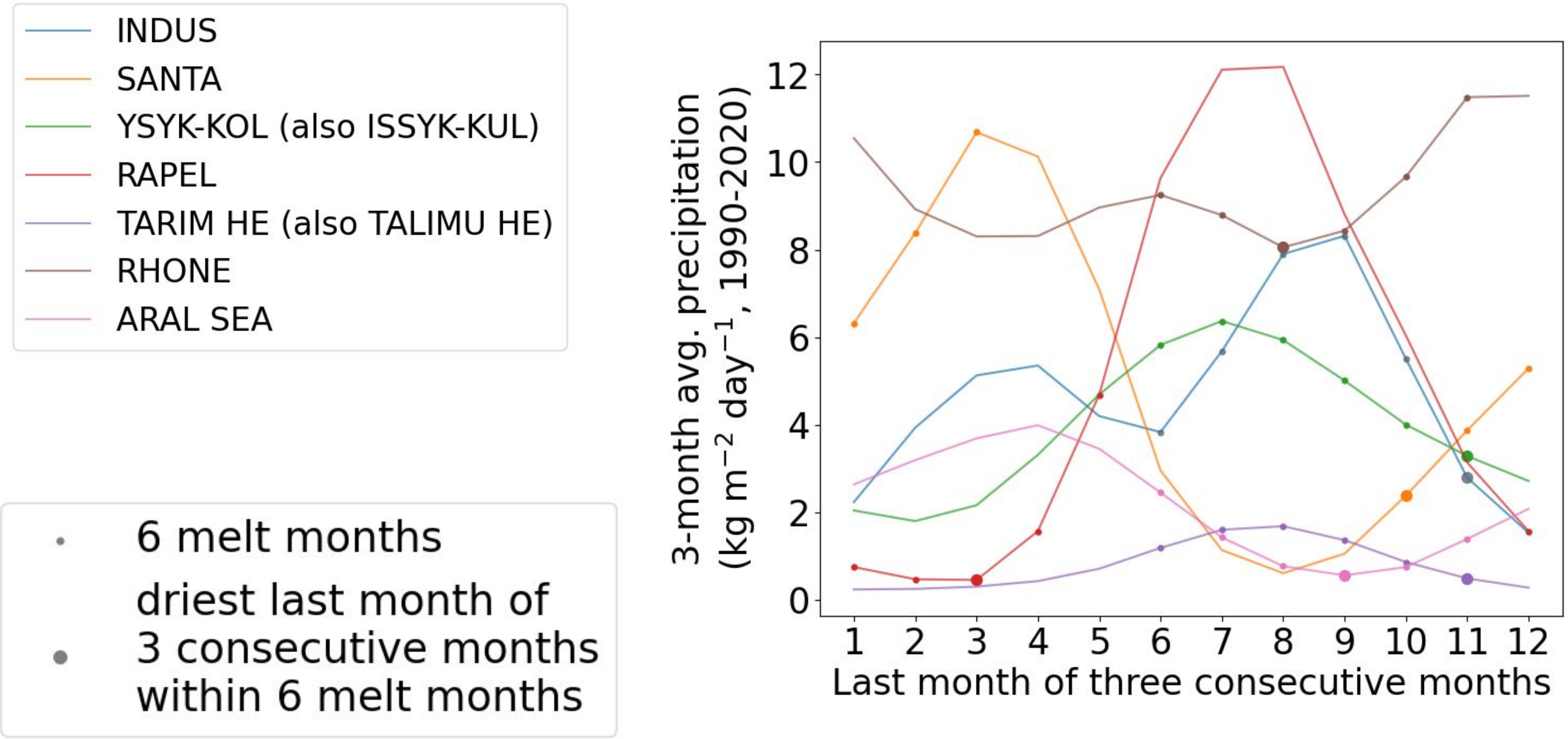


Annual melt water projections for selected basins

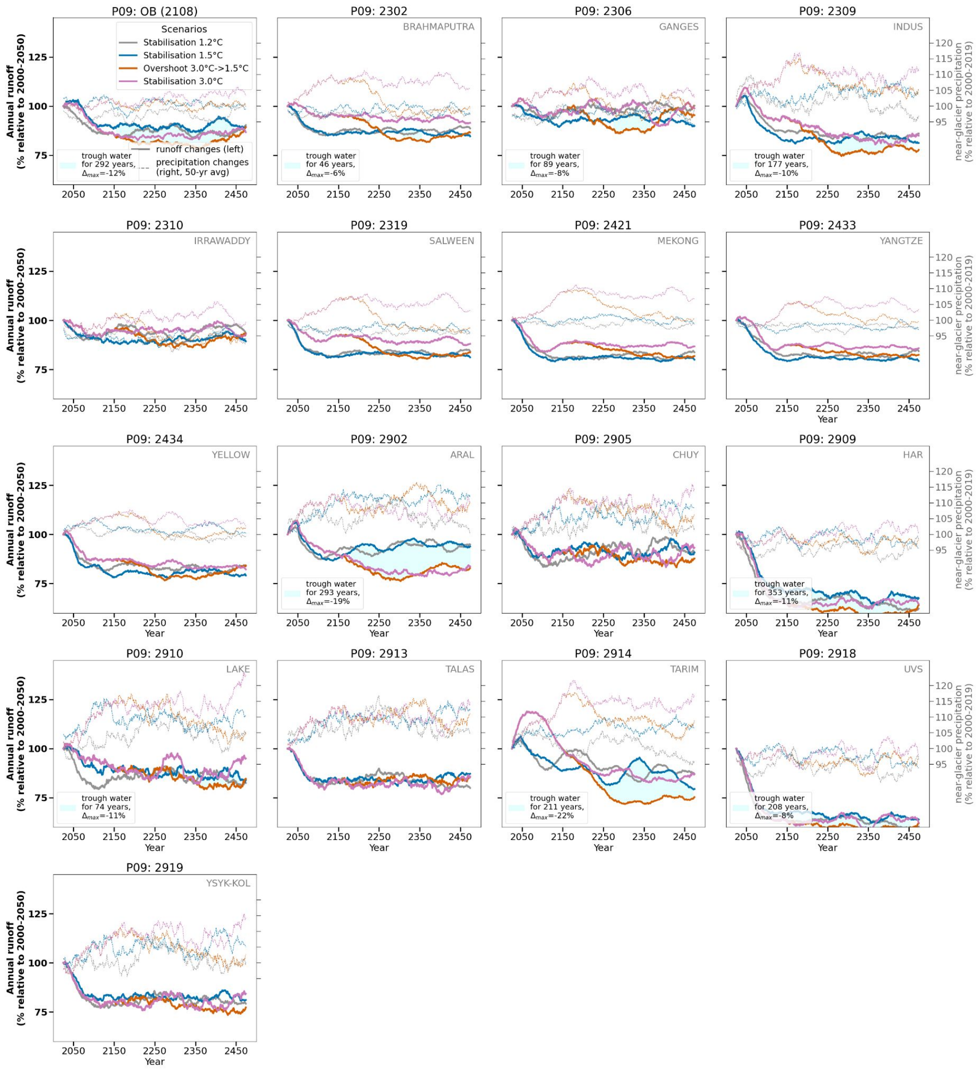




Selection of the dry-melt season for the seven basins:



all basins in HMA



Some basin statistics: