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EGU General Assembly



Long-term legacy of delayed climate change mitigation in global glacier response

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vEGU21 display materials

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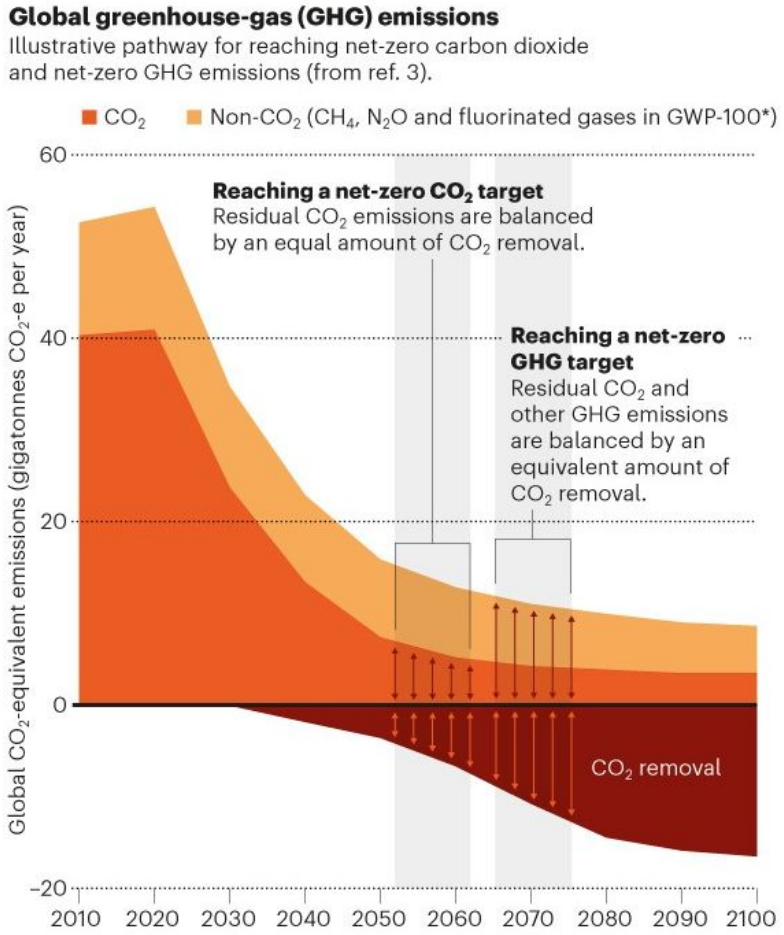
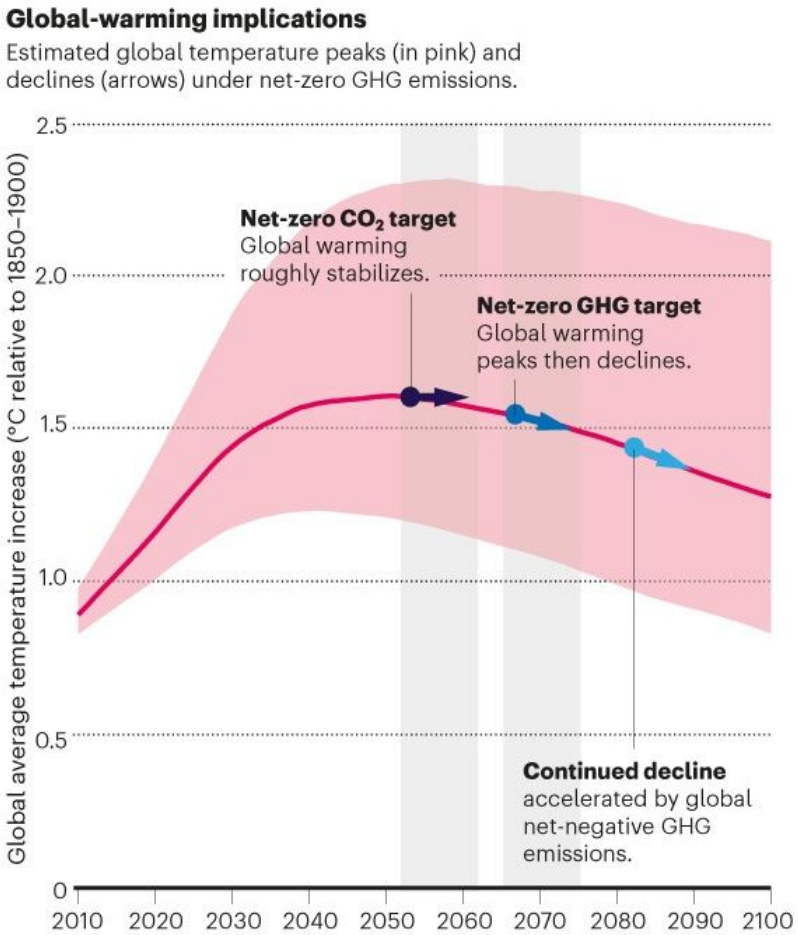
Context





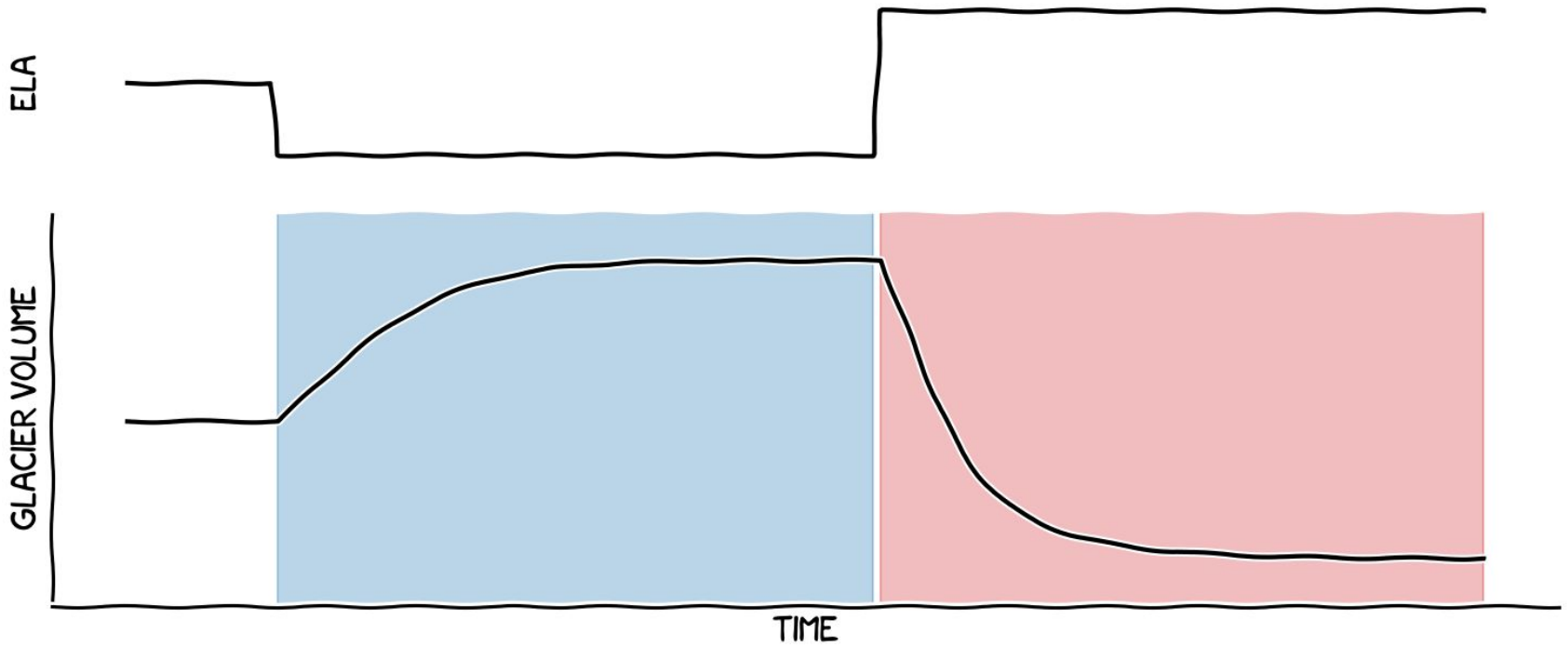
Meeting the Paris Agreement targets require stringent reductions of GHG emissions.

State commitments regarding emission reduction timelines are varied, often without a clear scientific basis.

Net-zero GHG can only be achieved with carbon removal, which if applied might lead to a global temperature decline.

Source: Rogelj et al. (2021)

Transient glacier response to climate change



Glaciers have a delayed response to climate change.

Even if emissions were to stop today, glaciers would continue to melt for decades or centuries (Marzeion et al., 2018).

ELA: Equilibrium Line Altitude ($\propto$ temperature)

Source: OGGM-Edu

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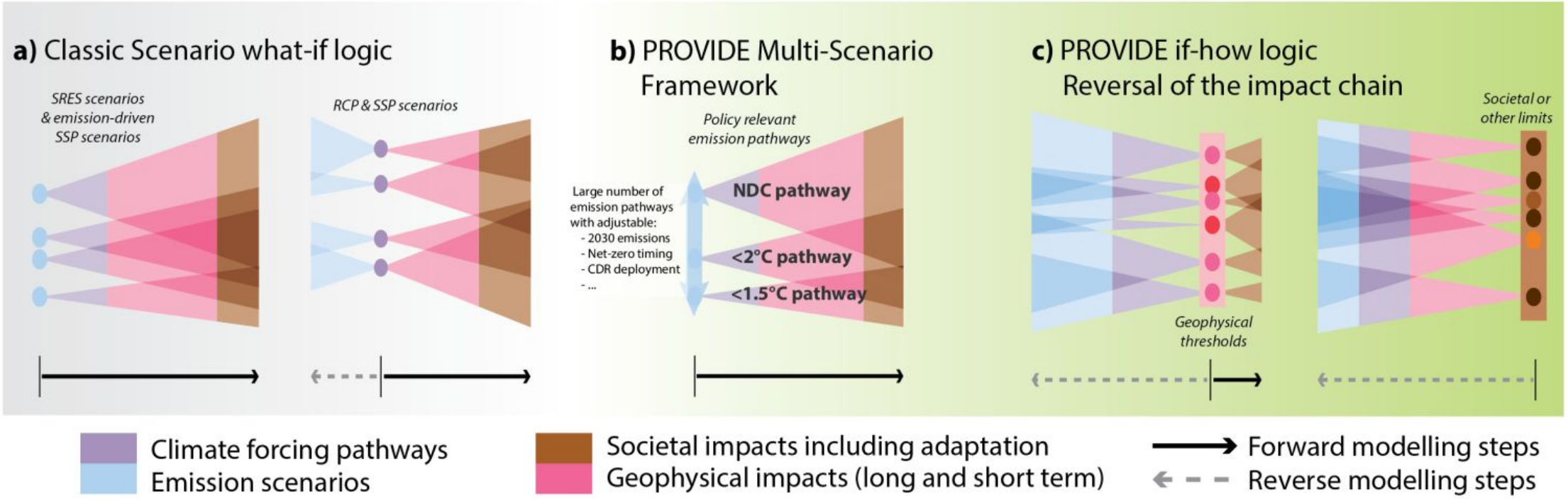
H2020 project: PROVIDE (start Sept. 2021)

Paris Agreement Overshooting – Reversibility, Climate Impacts and Adaptation Needs



"what if" (traditional RCPs/SSPs) complemented by "if how" (what is needed to stay below chosen societal thresholds) → **climate services based on reverse modelling of the impact chain**

See also: CL 3.2.18 (29 Apr 15:30) https://meetingorganizer.copernicus.org/EGU21/EGU21-15079.html

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- Climate targets (1.5°C, 2°C, …) can be achieved in various ways, with consequences for transient global temperatures (e.g. “overshoot”).
- SSP (or RCP) scenario based projections are “narratives”. They do not allow to link climate and glacier response to specific political targets.
- Most CMIP projections are limited to 2100, although glaciers will continue to respond long after climate stabilisation.
- Two well known, major impacts of glacier change (sea-level rise and regional water resources) have never studied together.

What is the short- and long-term influence of climate change mitigation policies on global and regional glacier change?

What are the consequences for (i) global glacier change and sea-level rise, and (ii) water resources in glacierized basins?

Methods

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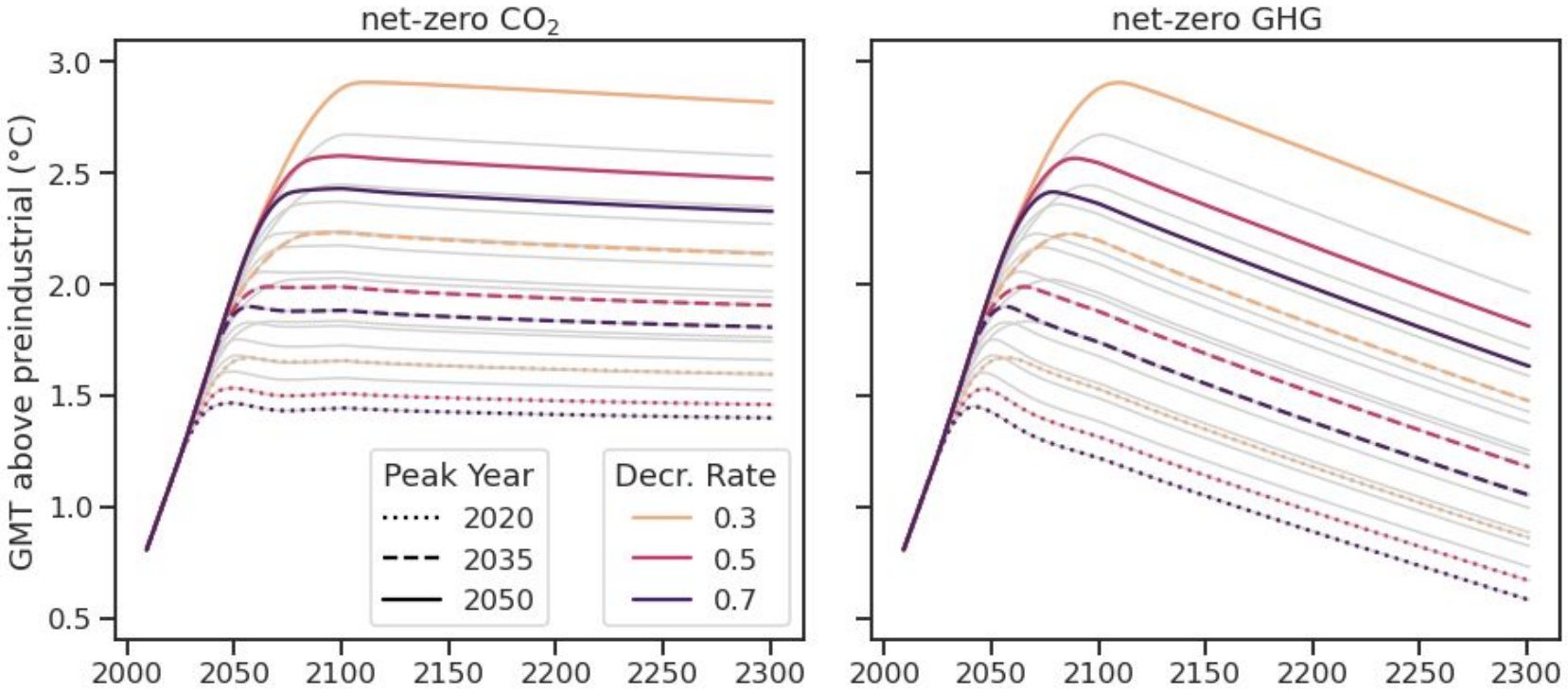
Global mean temperature (GMT) scenarios



GMT (global mean temperature) projections realized with an intermediate complexity climate mode (MAGICC).

Scenarios stylized from:

1. peak year of emissions: 2020 to 2050 in 5 years steps *(grey lines, 9 examples colorshaded)*
2. reduction rates after peak (0.3, 0.5, 0.7 GtC/yr)
3. Net-zero CO2 or GHG

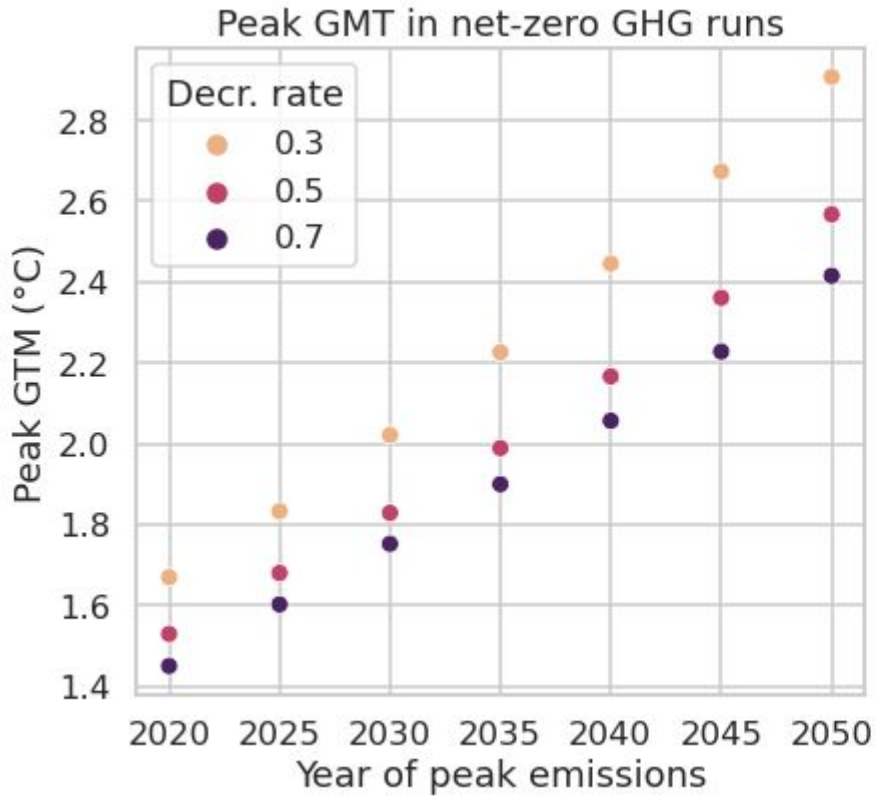
Peak year and decrease rate ⇒ impacts timing and amplitude of peak GMT

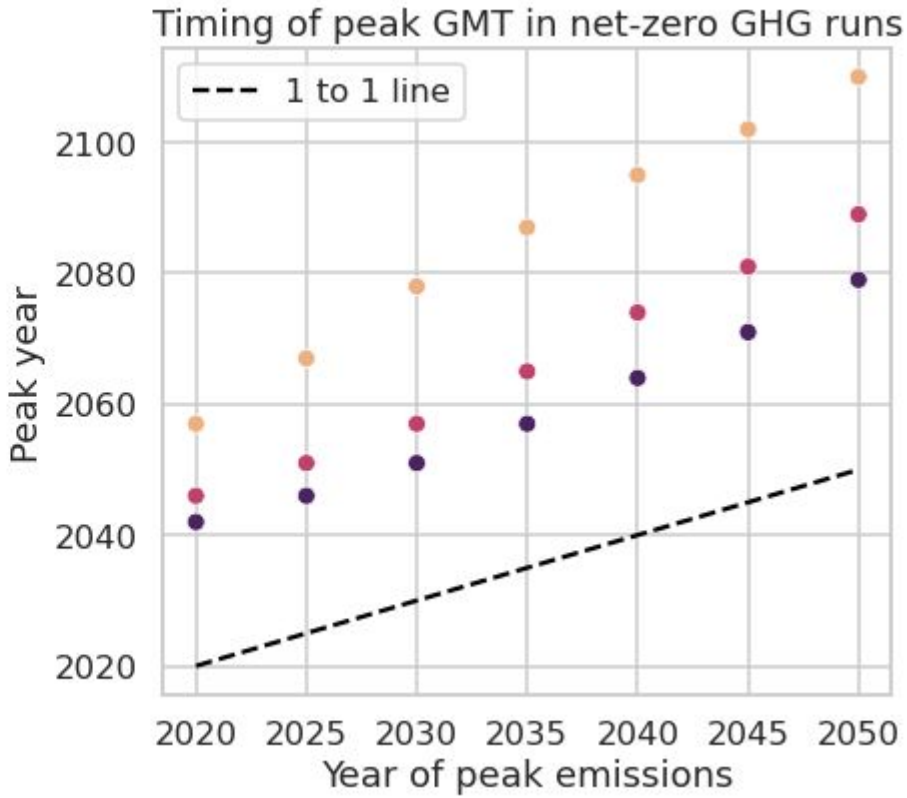
Net-zero CO2 or net-zero GHG ⇒ stabilization or cooling

Shown here is the mean of 600 simulations for each scenario (large variance!)

Data source: Mengel et al. (2018)

Global mean temperature (GMT) scenarios



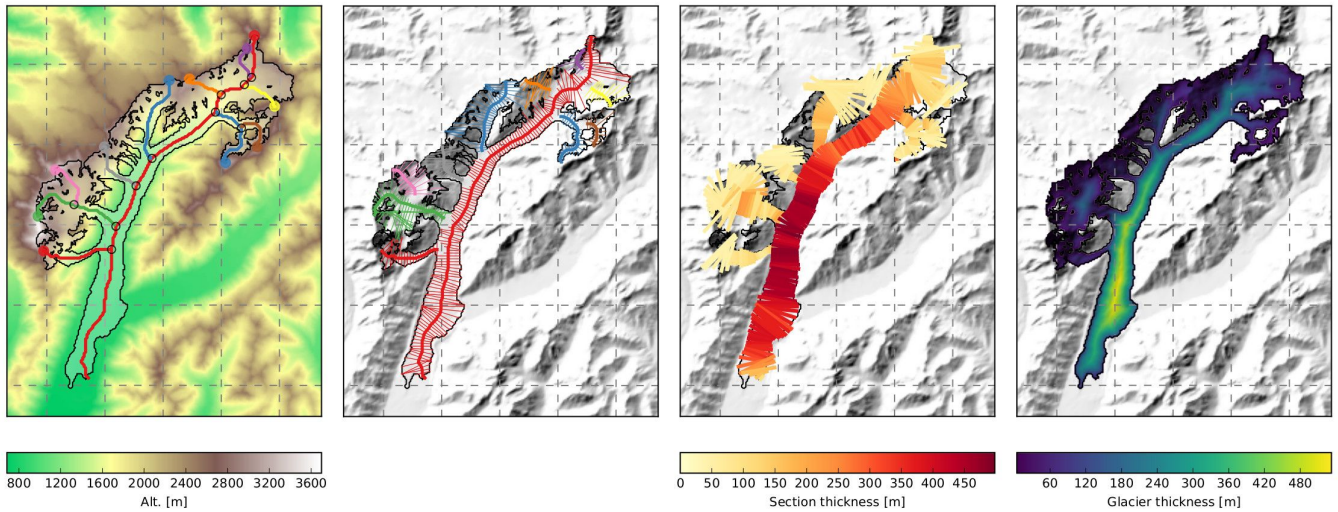


Peak year and decrease rate ⇒ impacts timing and amplitude of peak GMT

Net-zero CO2 or net-zero GHG ⇒ stabilization or cooling

Data source: Mengel et al. (2018)

Glacier evolution model



OGGM
Open Global Glacier Model

Source: OGGM.org

State of the art global glacier evolution model

Each of the 200k glaciers simulated individually.

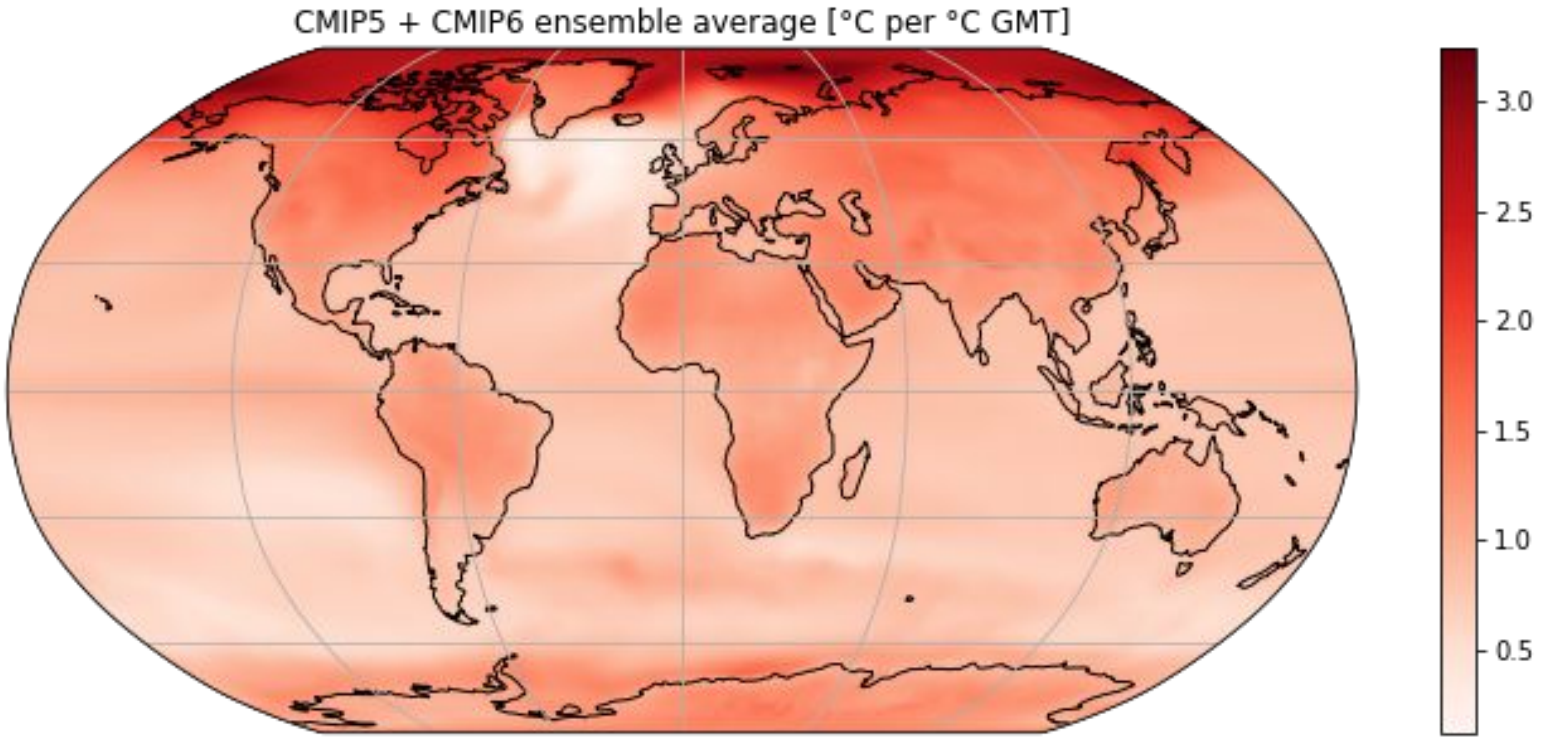
Calibrated to regional geodetic mass-balance observations from Hugonnet et al. (in press).

Monthly temperature index melt model
+ ice dynamics component
(glaciers can shrink and grow, model accounts for non-linear elevation feedbacks and response time)

Forced by MAGICC GMT series scaled by regional T° change signal.

GMT anomalies applied to the local glacier climate of 2009-2019: in simple words, **each year in the projections is an average of the last decade with changed temperature** (precipitation remains constant). Simulations span 2009-2300

Regional scaling of the temperature signal



Regional temperature change as a function of GMT change for 2081-2100 in 89 climate model projections (units: local temperature change (°C) per unit of global temperature change (°C)

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Take home: methods

Global glacier model driven by stylized global T° scenarios scaled by regional warming patterns and debiased at the glacier level

42 scenarios: peak emission year, decrease rate, temperature stabilization or cooling

No precipitation change, each year in the projections is an average of the last decade with updated temperature

This is a work in progress! No uncertainty quantification yet (will be done with ensembles)

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Results:
Global glacier change & sea-level rise

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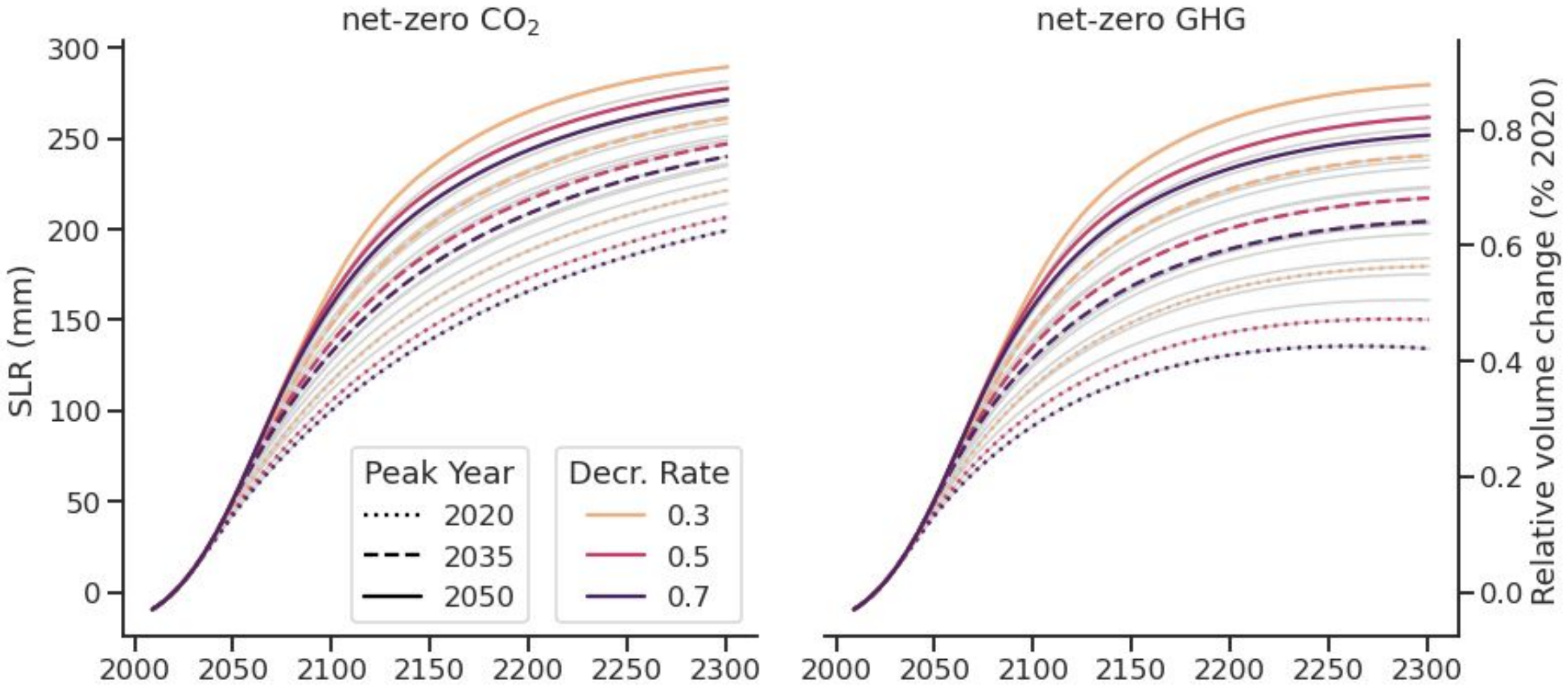

SLR: sea-level rise. Left: temperature stabilisation scenarios, Right: temperature decline scenarios

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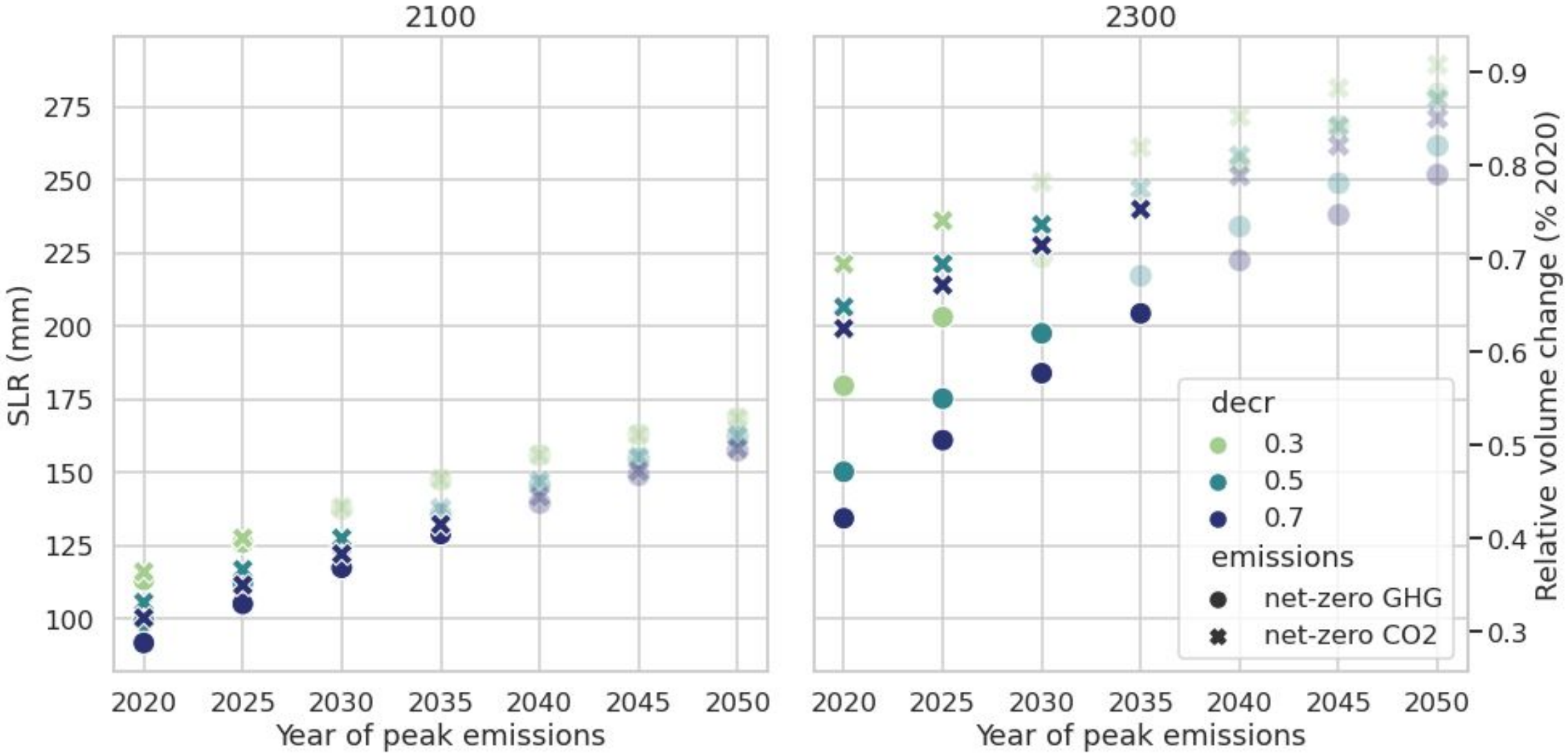
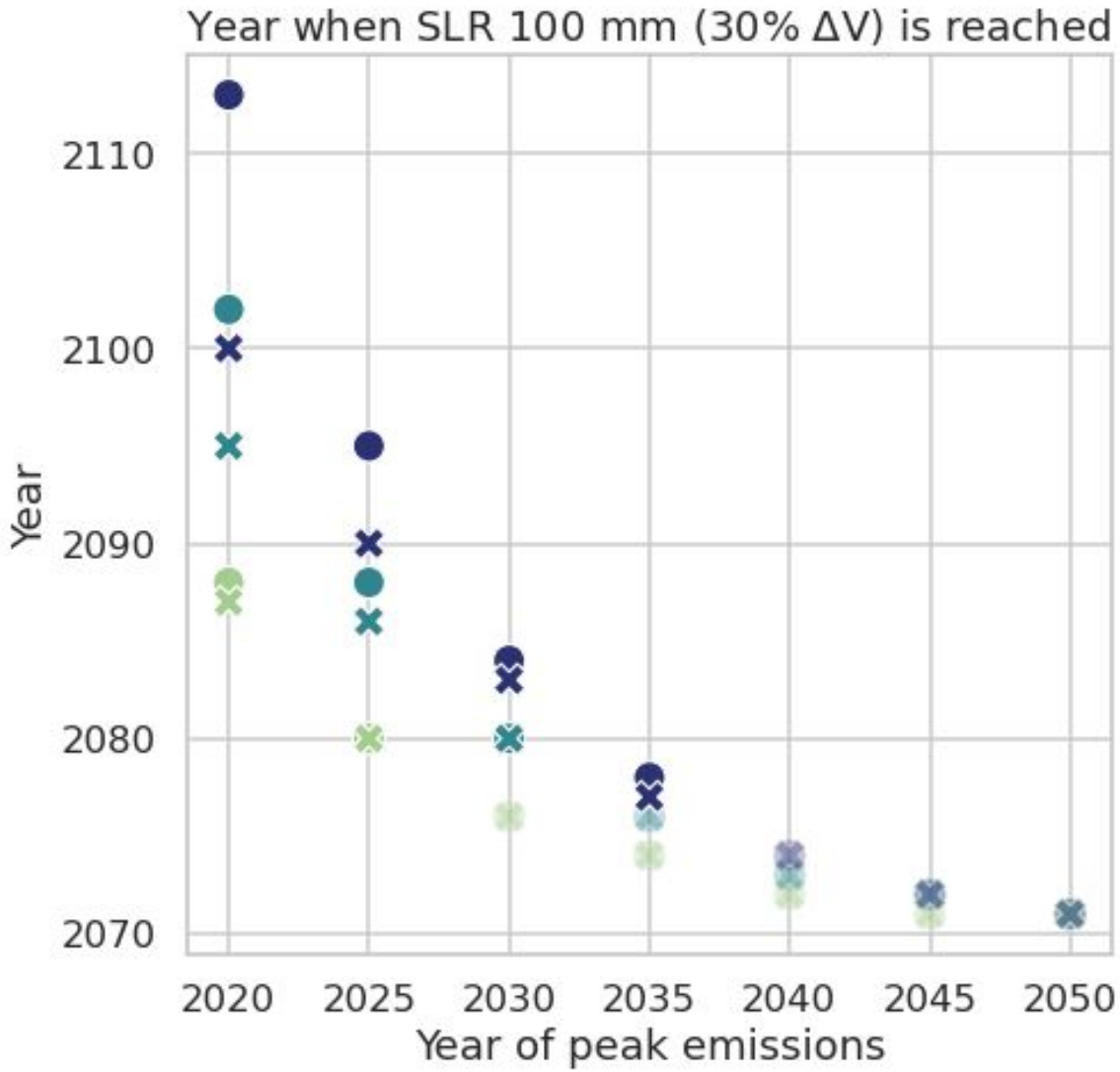
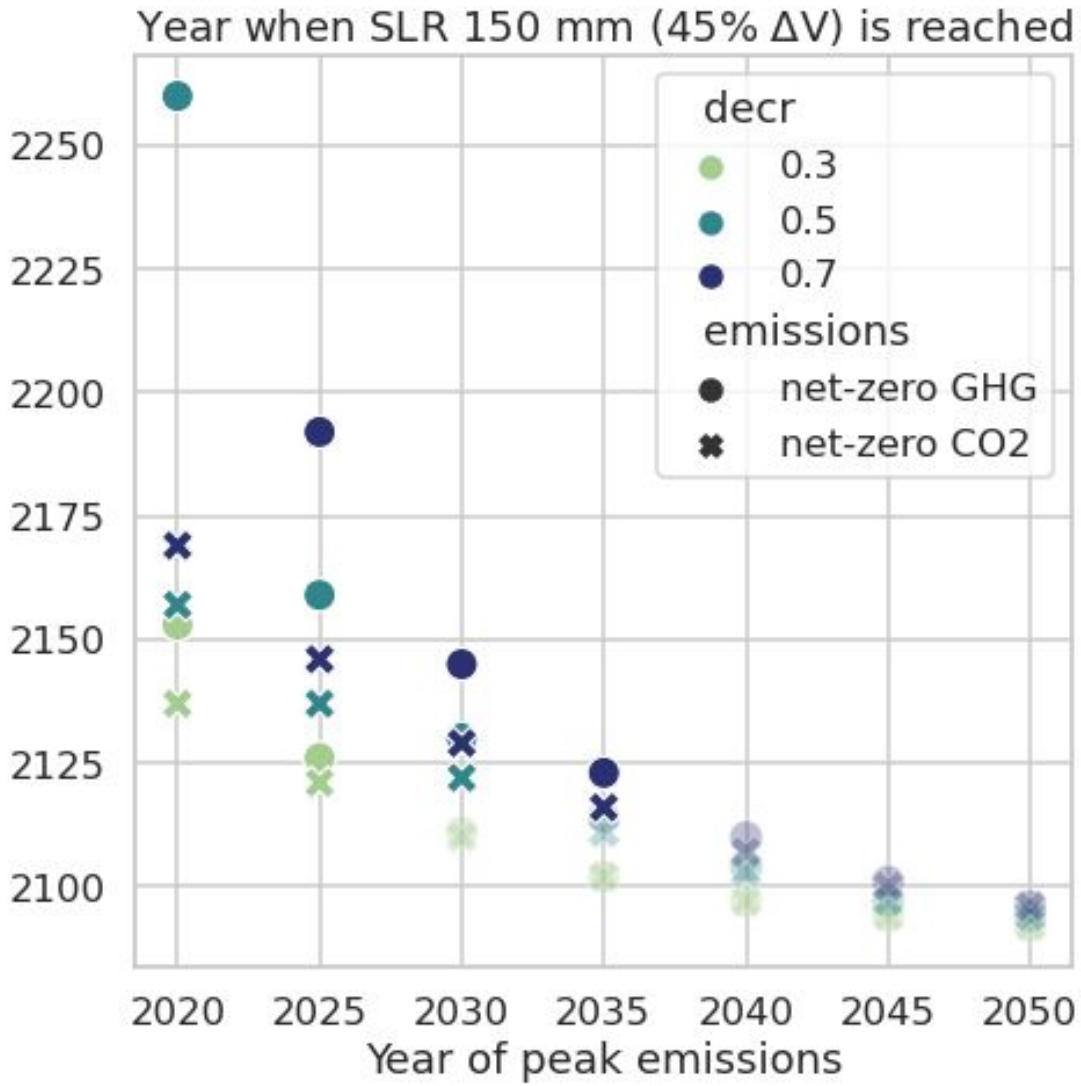


Brighter colors: < 2°C peak warming





2 early mitigation scenarios never reach 150 mm SLR

Take home: global glacier change & sea-level rise

Year 2100 glacier signal dominated by peak year of emissions, less from other characteristics:
Five year delay in peak CO_2 emissions reduces global glacier mass by 5% in 2100 and 10% in 2300.

Emission characteristics (decrease rate, net-zero GHG) become increasingly important with time and by 2300 they are as important as when peak emissions was reached.

By 2300, even if temperatures stabilize, mountain glaciers will continue to melt (more so in the stabilisation than the cooling scenarios). Only early and stringent mitigation measures (including carbon removal) might stabilize global glacier mass by 2300.

Example "threshold-based" application of our simulations:
we can gain from ~20 to ~50 years time to adapt to a mountain glacier related SLR of 100 mm (30% volume change) if we start reducing emissions now, instead of in 2050.

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Results:
Regional glacier runoff change

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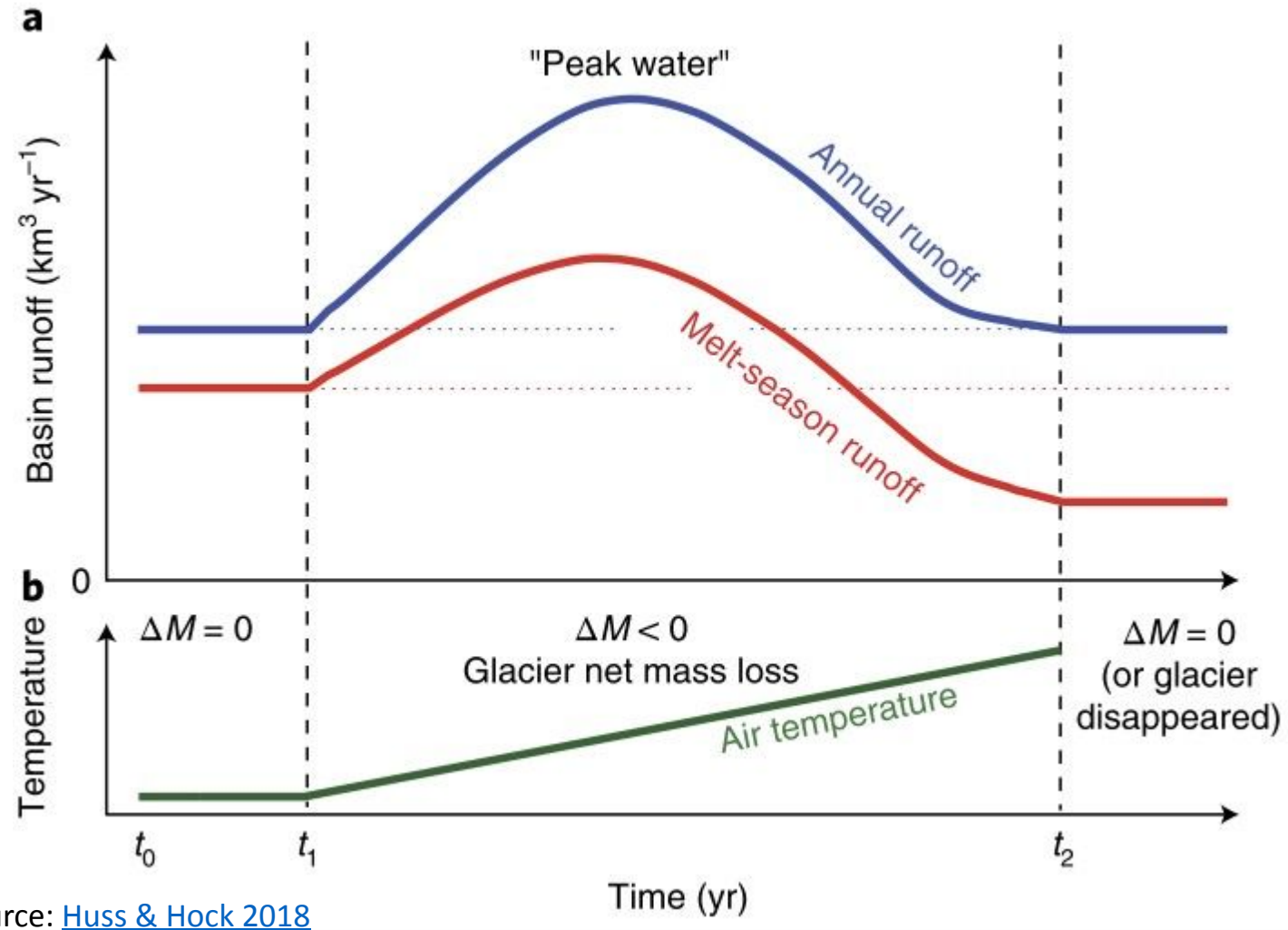
Glaciers as water “resources”



Source: Huss & Hock 2018

Glaciers are **temporary** reservoirs of freshwater, at seasonal and decadal or centennial timescales.

Glacier melt results in an increase of annual runoff followed by a decrease.

Seasonally, we expect a shift from (late) summer glacier melt to spring melt (seasonal snow).

Some regions are already past “peak water” (e.g. in the Alps). Other regions are still expected to reach peak water in the next decades (e.g. Himalayas). Our results are largely in agreement with Huss & Hock 2018.

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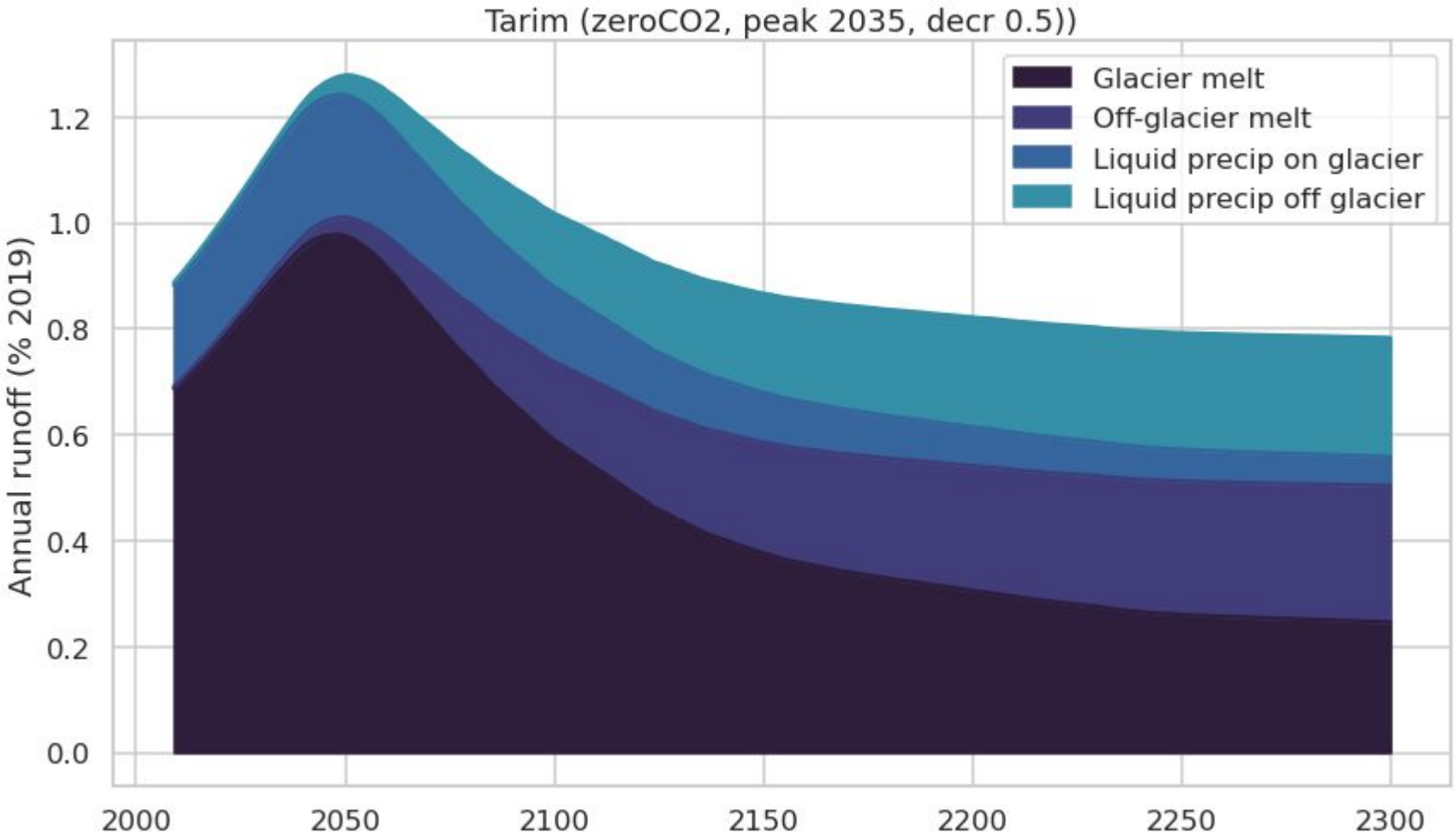
Example Central Asia: Tarim Basin



Example for a middle-of-the-road scenario (approx 2°C warming).

“Fixed gauge” runoff, i.e. the runoff originating from the area covered by the glacier in 2009.

As glaciers melt and areas free of ice increase, off-glacier components gain in importance.

Annual glacier melt increases then decreases as glaciers either stabilize or disappear.

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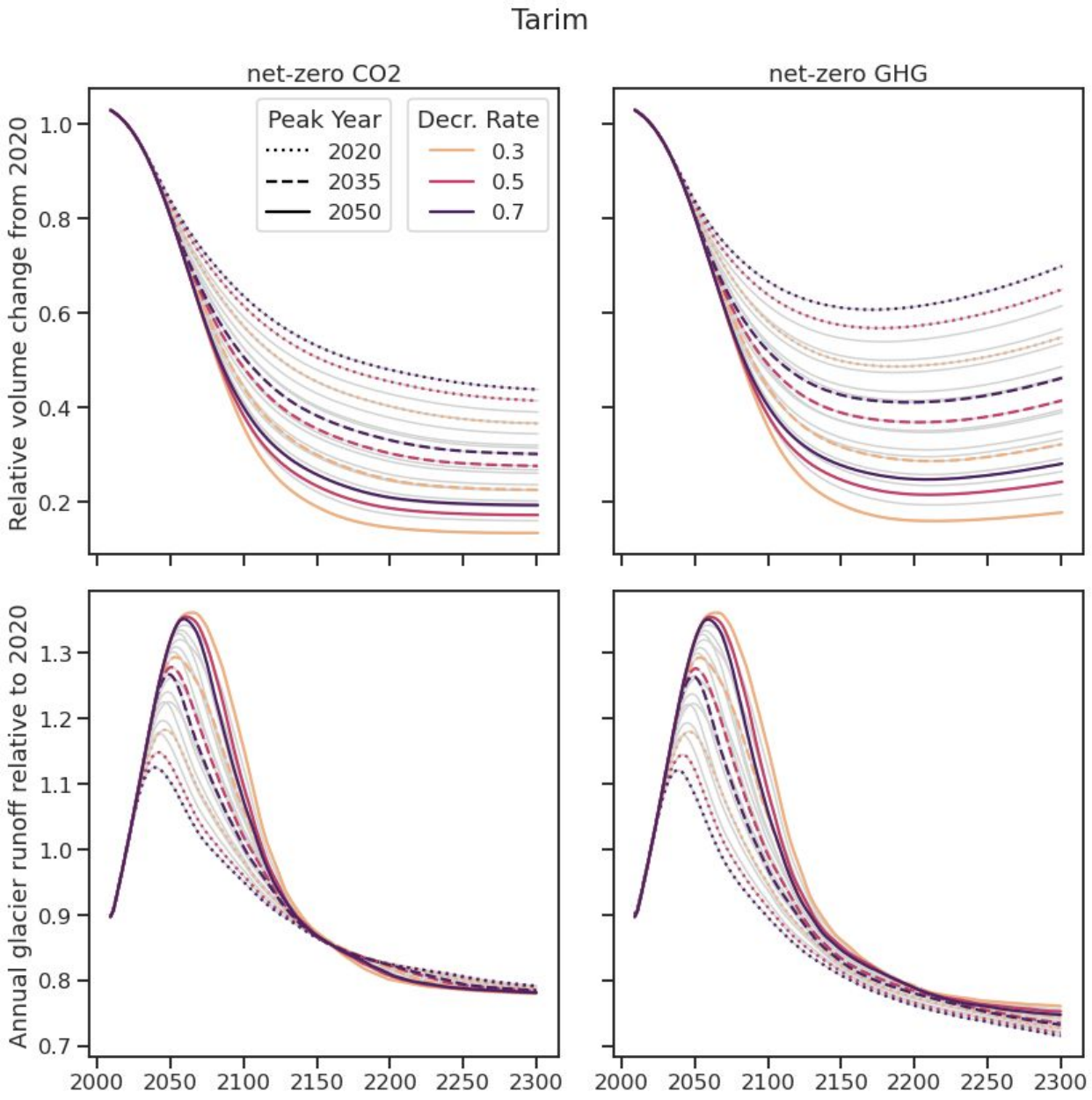
Glacier volume relative to 2020

Glacier runoff relative to 2020



"Peak water" can occur when temperatures stabilize (early mitigation) or when glaciers volumes become too low (late mitigation, in which case further warming does not change runoff much).

Stabilisation runoff (< 80% of 2020 levels) is largely independent of glacier stabilisation volume (here between 15% and 50% of 2020 volume).

If glaciers recover (cooling scenarios), glacier runoff further decreases as a result of new glacier ice formation. This process is slow.

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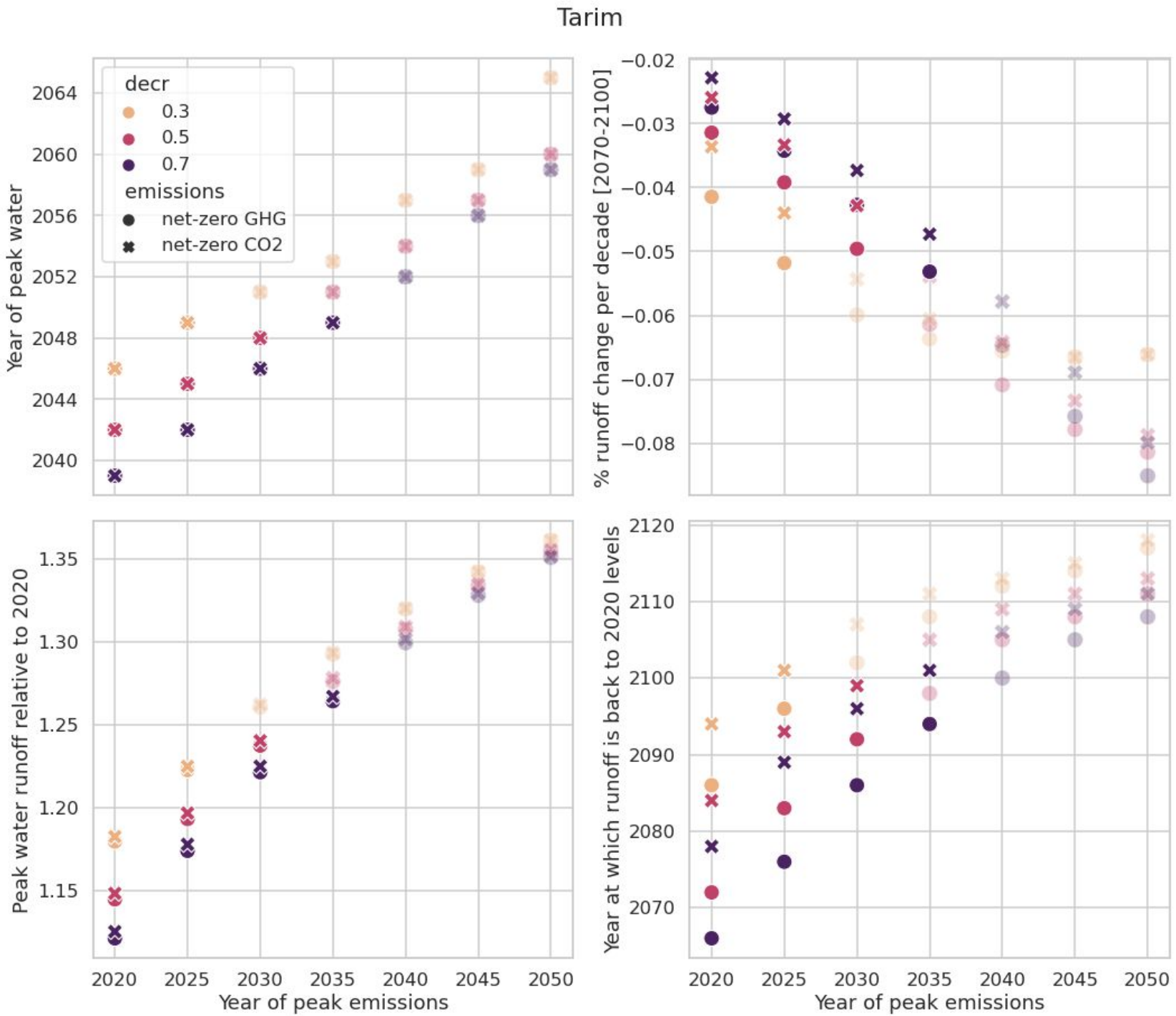
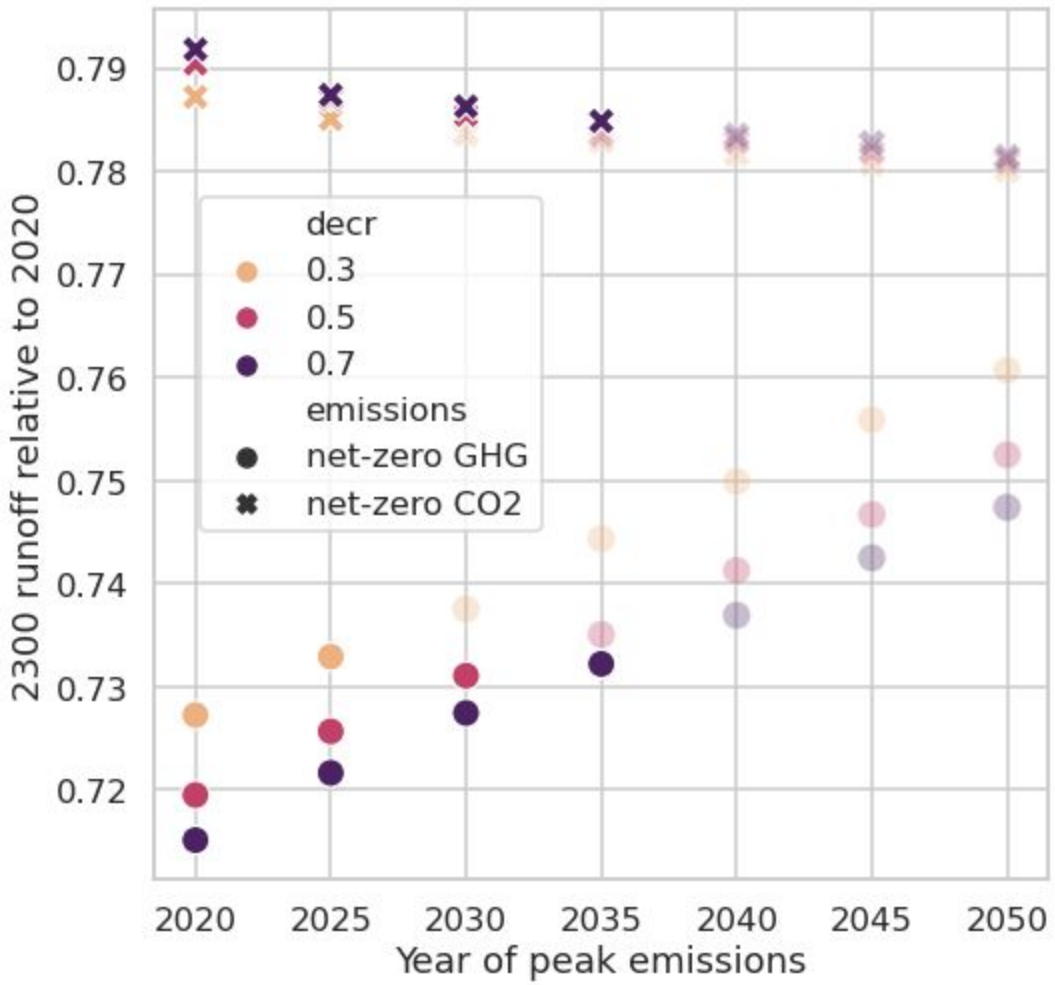


Late mitigation increases total runoff and extends the period with runoff above today's levels.

After peak water, rate of runoff decrease is considerably higher in late mitigation scenarios.

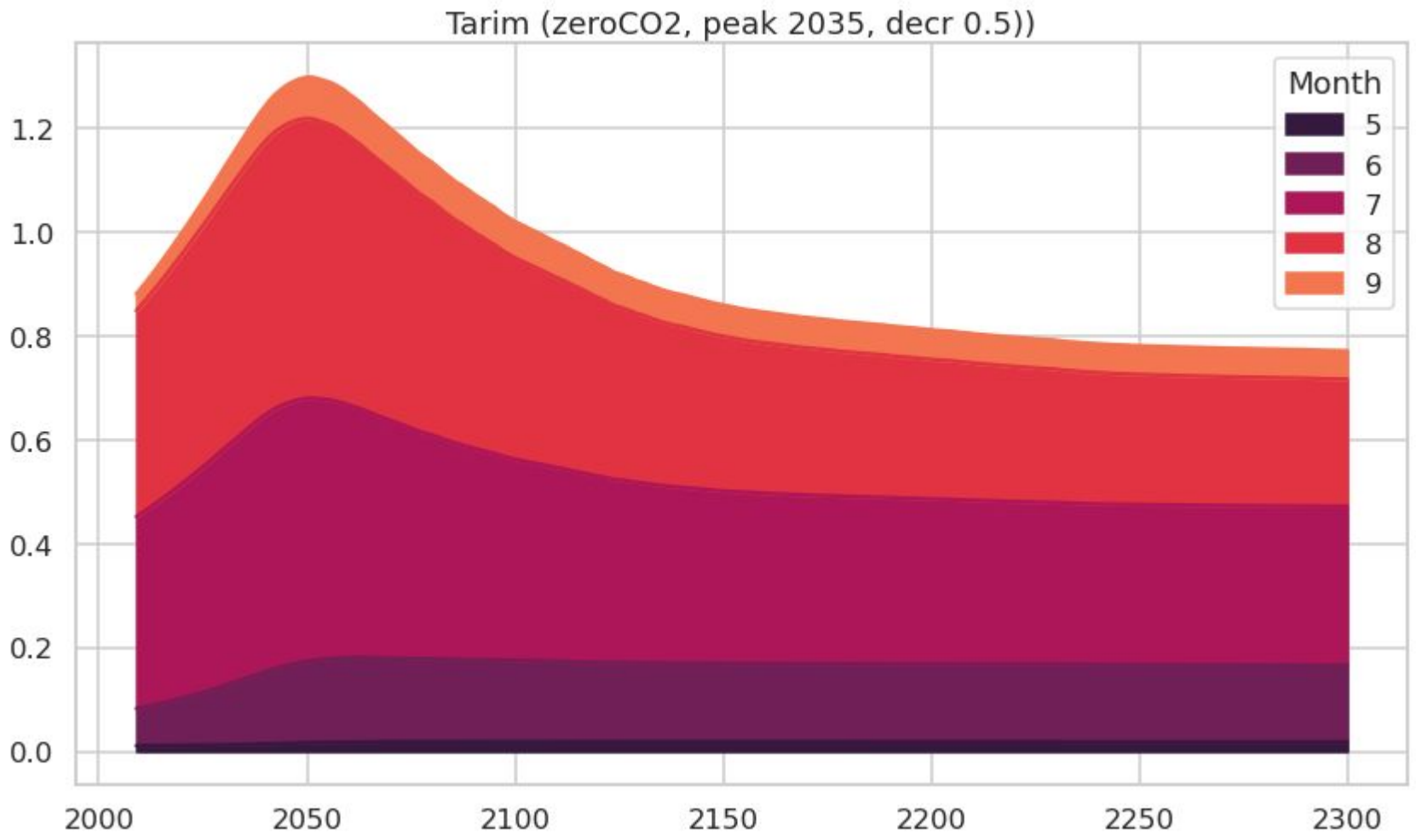
Brighter colors: < 2°C peak warming



No matter the scenario, long-term runoff will stabilize well below the levels of the last decade. If global temperatures decline, this will reduce long term runoff further.

Brighter colors: < 2°C peak warming

Monthly runoff



Monthly contribution to annual runoff for a middle-of-the-road scenario (approx 2°C warming), reference 2020.

Runoff increases for all months, then decreases for summer months and stabilizes in spring.

Seasonal shift towards spring melt (May-June).

Monthly runoff

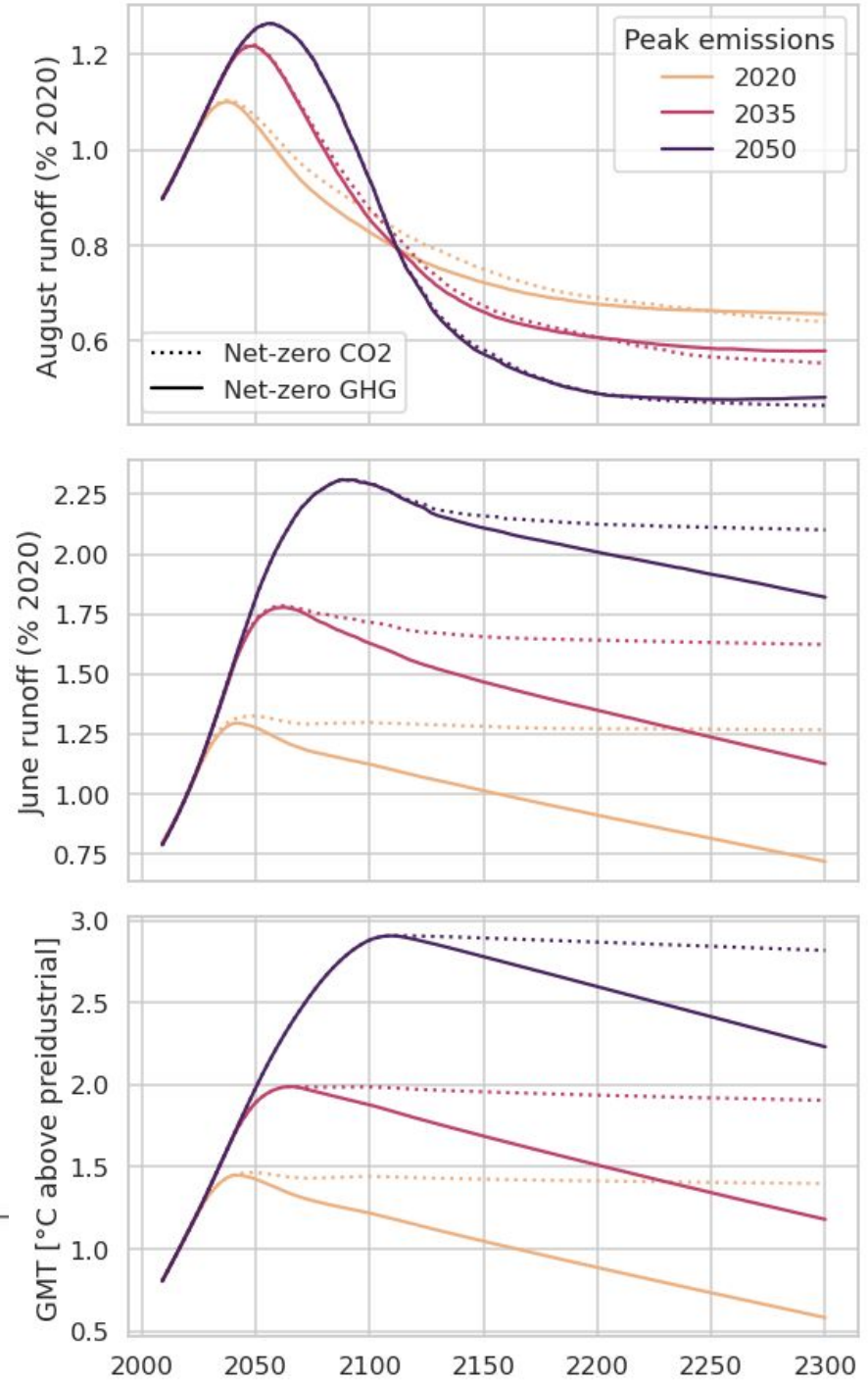
Example runoff for 6 scenarios
(peak emissions 2020, 2035, 2050 and net-zero CO2 or GHG).

August runoff is driven by glacier melt: decrease is strong in all cases, but is less important for early mitigation scenarios. Peak water in August not necessarily driven by peak temperature (glacier volume as limiting factor).

June runoff is driven by seasonal snow melt, precipitation and precipitation phase: it is strongly related to temperature.

Early mitigation scenarios lead to smaller and less disruptive changes in general:

- less reduction of summer melt, and
- smaller increase in spring runoff



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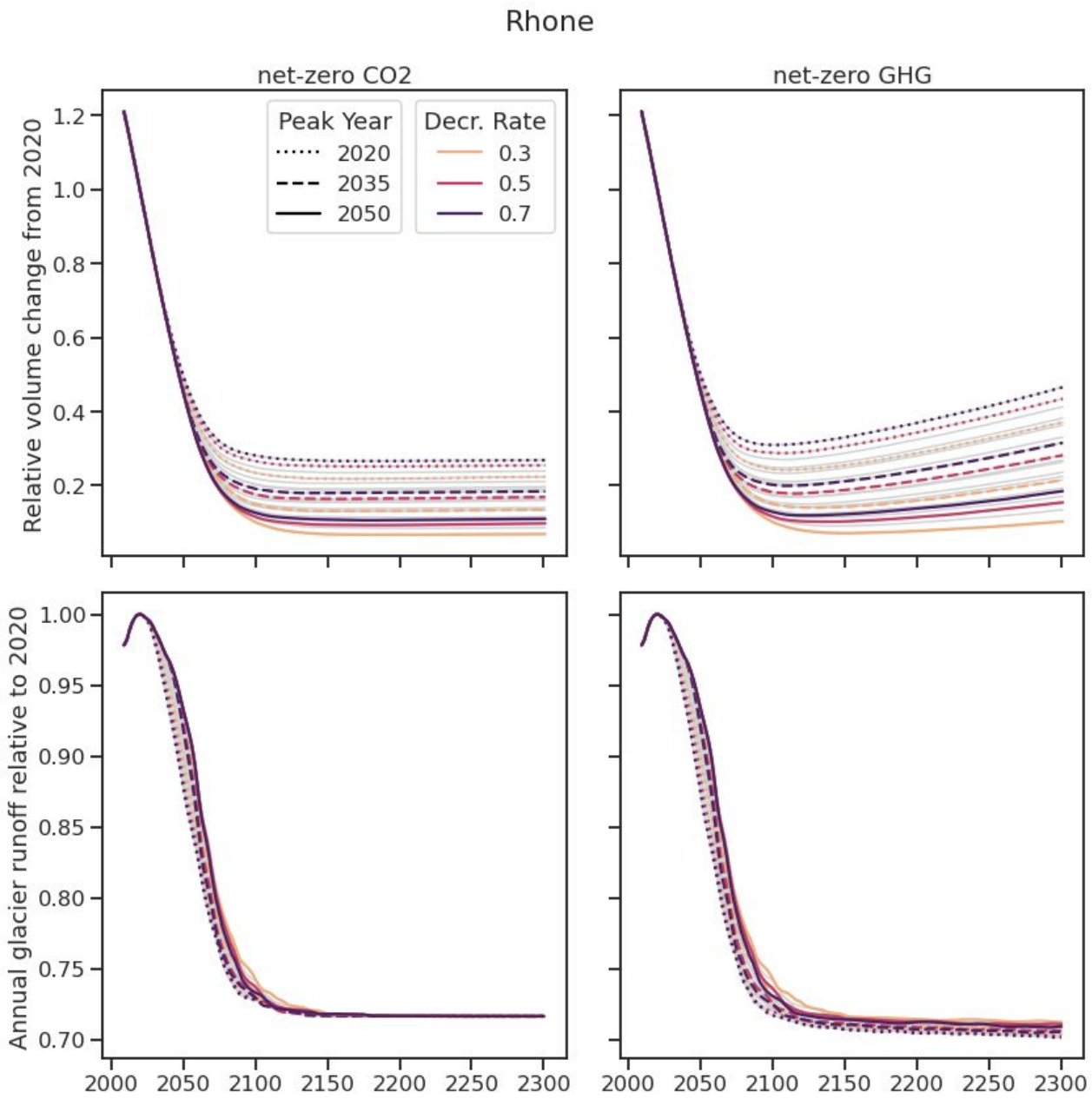
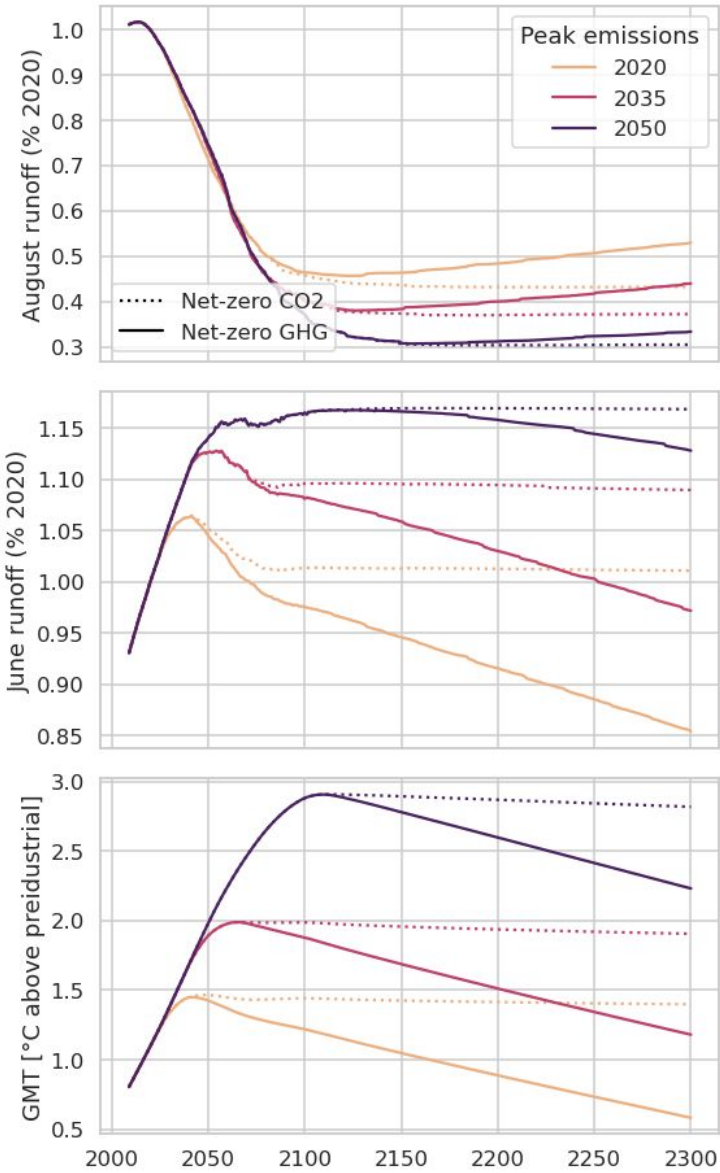
Example past peak water: European Alps



Currently right past or at peak-water.

Current increase in spring runoff compensates for summer decrease.

Annual runoff largely independent of scenario, but seasonal runoff does depend on it.



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Take home: regional glacier runoff

Some major river basins in Asia (Tarim, Aral Sea, Indus, Ganges…) but also in high latitudes (e.g. Yukon) currently experience an increase of runoff because of glacier melt.
For these basins, early climate mitigation reduces amplitude and duration of peak water (e.g. Tarim Basin peak water can last from ~ 50 in an early mitigation scenario to ~ 100 years in a late mitigation one).

Longer periods of increased runoff might have potential benefits (e.g. hydropower, water) and also risks (floods, increased glacier retreat and related hazards). After peak water, the rate of runoff decrease is considerably higher in late mitigation scenarios, and adaptation measures might be harder to put in place after decades of increased runoff. Early mitigation policies also lead to the least disruptive changes in runoff seasonality.

Other basins (e.g. Rhone in the Alps, Rio Santa in Peru) are already past "peak-water" and experience a decreasing glacier contribution.
For these basins, mitigation scenarios have comparatively little influence on annual runoff (committed mass loss dominant), but they do influence seasonal runoff and stabilisation glacier volume.

Net-zero GHG scenarios (cooling) will lead to a negative glacier contribution to total streamflow, but at relatively slow rates.

Conclusions

We could compute glacier contribution to both sea-level and regional runoff based on stylized climate change mitigation scenarios, allowing to put climate policies in direct relation to glacier response.

Early mitigation will have large positive outcomes for sea-level rise, long term glacier volume, and will be less disruptive for annual and seasonal runoff in glacierized basins. Late mitigation actions will lead to a strong mid-term increase in runoff in major basins, with small potential benefits but high risks, and will require faster adaptation to decreasing water resources after peak water.

Glacier recovery in temperature decline scenarios will lead to a further long term reduction of runoff, albeit at slower rates.

There is a strong potential for a new type of climate service information, reverting the usual impact chain ("from scenarios to impact") and putting societal limits first.



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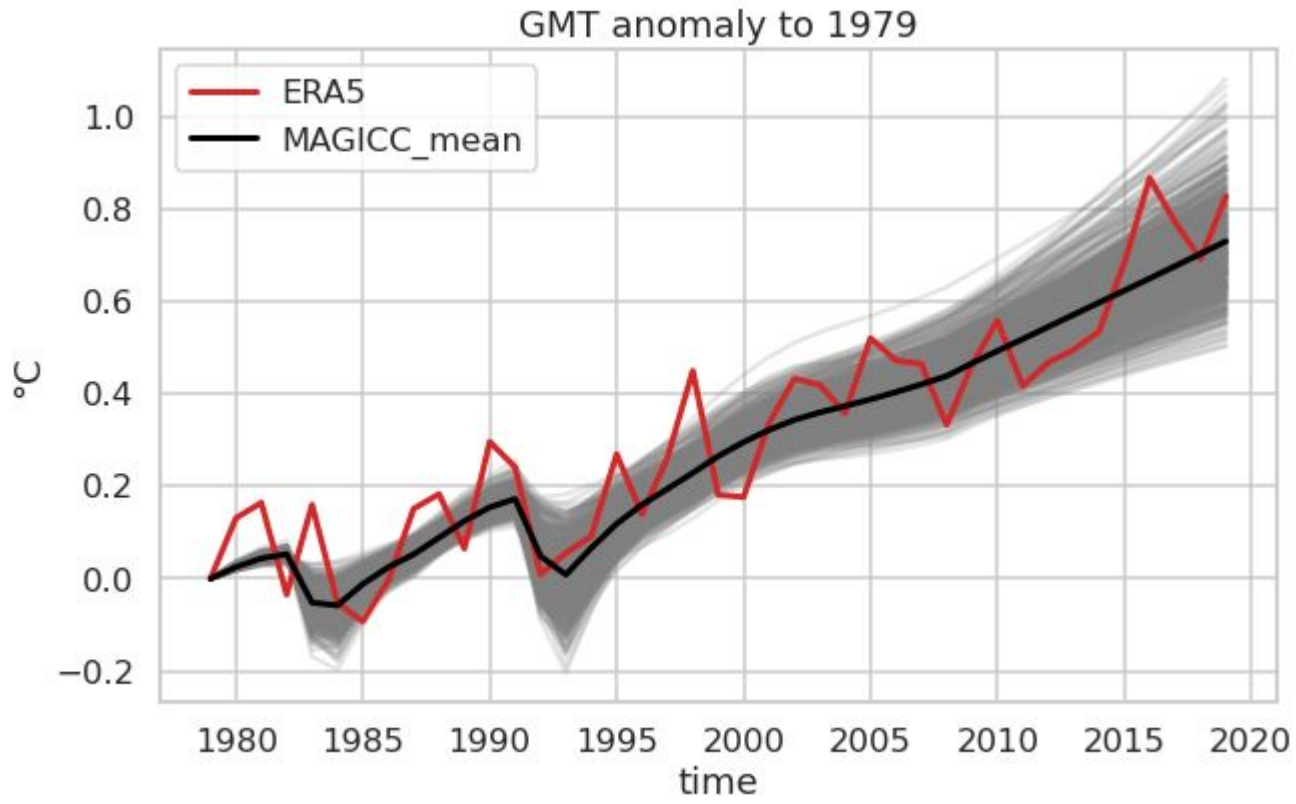

MAGICC GMT compared to ERA5 data

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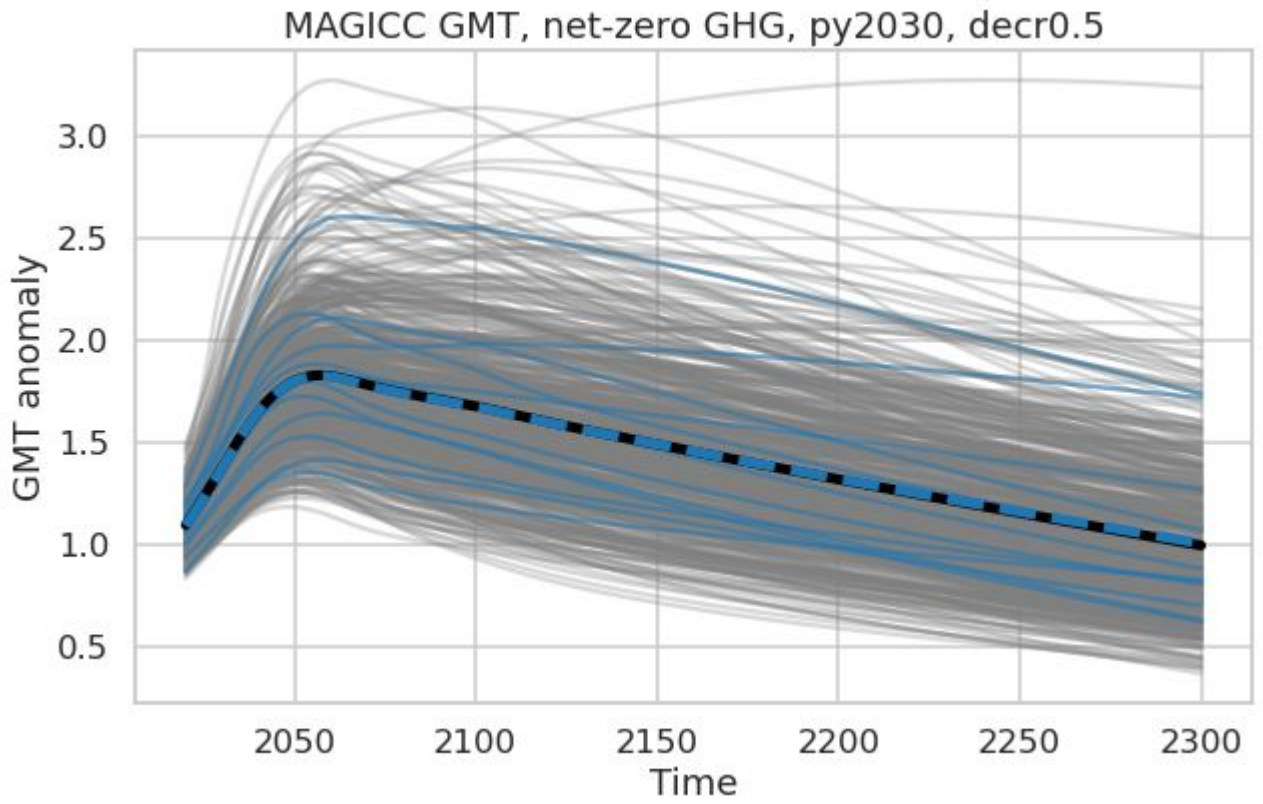
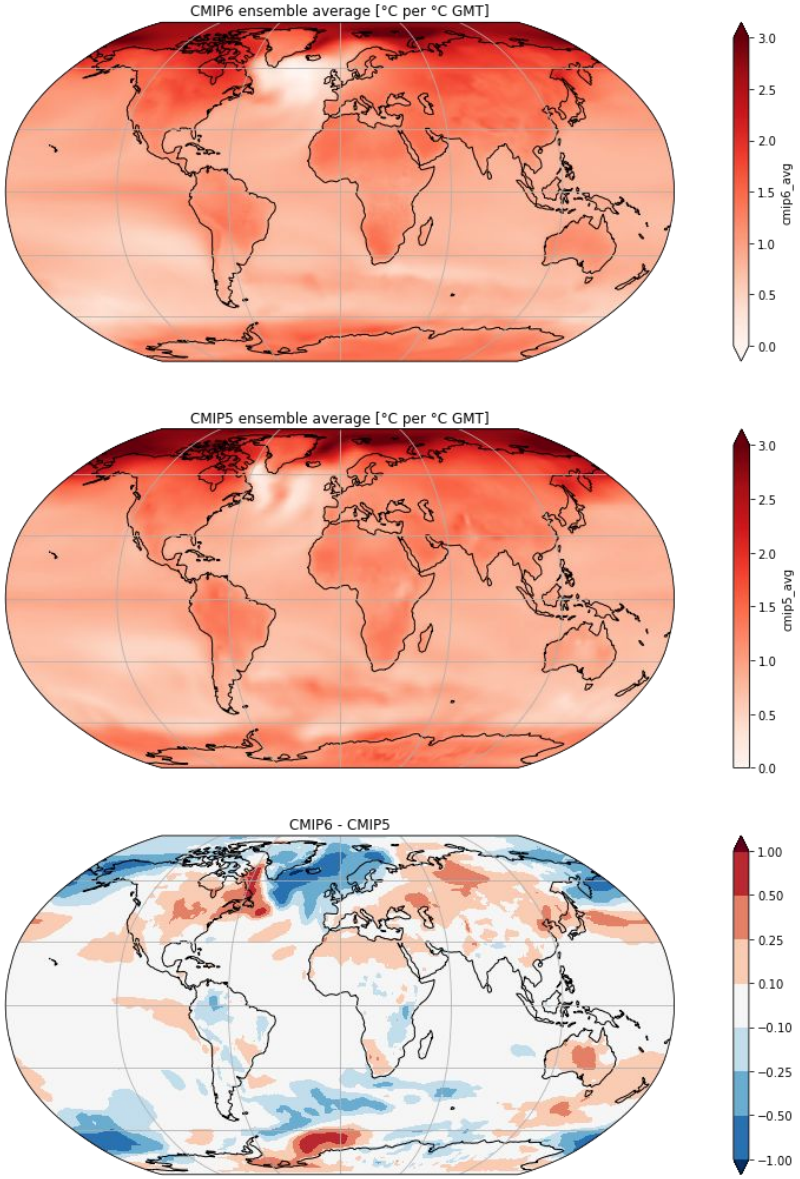
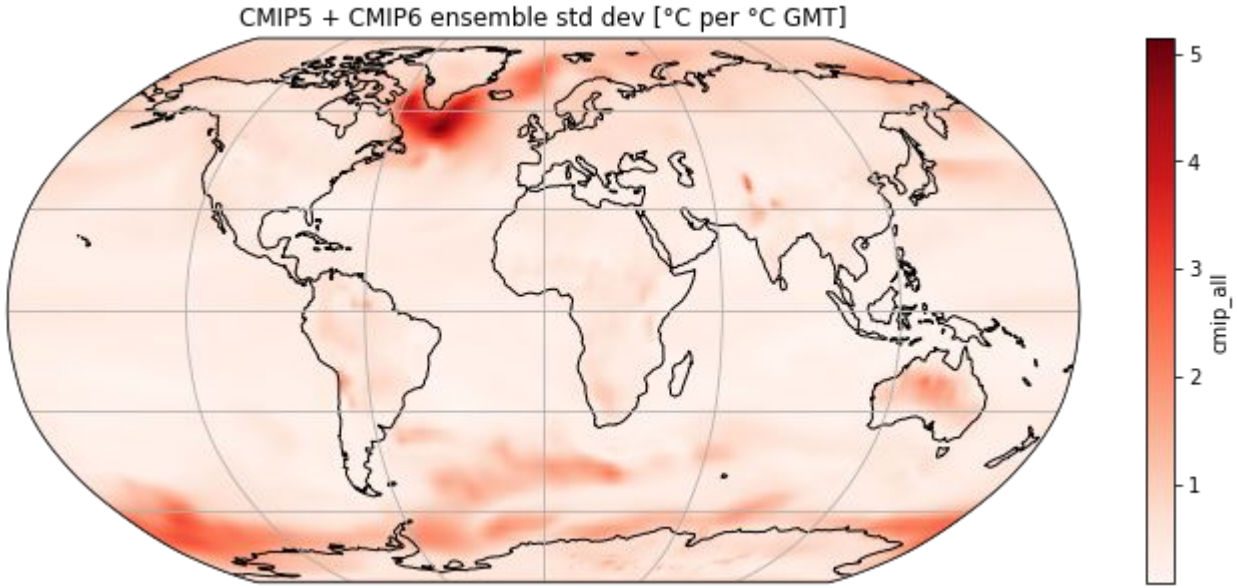


MAGICC GMT 600 member ensemble for one single scenario - this uncertainty will be taken into account in the final study.





Robustness of the dT per dT patterns