Supplement of The Cryosphere, 18, 5045–5066, 2024
https://doi.org/10.5194/tc-18-5045-2024-supplement

The Cryosphere
Open Access

Supplement of

Twenty-first century global glacier evolution under CMIP6 scenarios and the role of glacier-specific observations

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Supplementary material

Text S1 – calculating the multi-model median values

All reported multi-(climate)model median values (most of which are over the 2015-2100 period) are obtained by first calculating the median over the climate models for every individual year and subsequently calculating the difference. This approach ensures a consistency between the displayed and the reported values (e.g., in Figure 2, Figure 4, Figure 7, Figure 8, Table 1). An alternative approach, consisting of first calculating the 2015-2100 differences for every individual climate model and then taking the multi-model median, results in identical values when the initial volume (2015) is the same, and very slight differences when the initial volume depends on the climate model. Values in Table 1 in some cases very slightly differ from those in Table S5 in Rounce et al. (2023), since in Rounce et al. (2023) the initial volume slightly varies, and first the 2015-2100 differences are calculated for every climate model and then the median is calculated. The 95% confidence interval is defined as the range of ± *1.96* standard deviations of individual model estimates (in line with Rounce et al., 2023).

	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
BCC-CSM2-MR		x	x	x	x
CESM2-WACCM		x	x	x	x
CESM2		x	x	x	x
EC-Earth3-Veg	x	x	x	x	x
EC-Earth3		x	x	x	x
FGOALS-f3-L		x	x	x	x
GFDL-ESM4	x	x	x	x	x
INM-CM4-8		x	x	x	x
INM-CM5-0		x	x	x	x
MPI-ESM1-2-HR		x	x	x	x
MRI-ESM2-0	x	x	x	x	x
NorESM2-MM		x	x	x	x

Table S 1: Future climate scenarios, consisting of 51 combinations of 12 climate models (rows) and 5 SSPs (columns). For SSP1-1.9, given the very lower number of members (n=3), the results are not deemed representative for this emission scenario, and are therefore not discussed in this study (the glacier projections under SSP1-1.9 can however be accessed; see ‘Data availability’ section).

<table>
<tr><th></th><th>Surface mass balance (SMB)</th><th>Geometry evolution</th><th>Original reference / study</th><th>Notes</th></tr>
<tr><td>GloGEM</td><td rowspan="3">Melt calculated from temperature-index / degree-day model. Surface-type distinction used in GloGEM and PyGEM. For the SMB, PyGEM was originally inspired on the GloGEM architecture, with other alterations, including a Bayesian framework to determine the SMB parameters. OGGM v1.6.1 uses a new SMB calibration approach with a dynamical approach.

More details on the mass balance model are provided in the main text and studies where models were introduced (Huss and Hock, 2015; Maussion et al., 2019; Rounce et al., 2020a, b, 2023).</td><td>Based on retreat parameterization (Huss et al., 2010), i.e. not with ice-dynamical processes as in GloGEMflow (Zekollari et al., 2019)</td><td>Huss and Hock (2015)</td><td>The model was run with CMIP6 climate forcing. The current version of the model was not run with CMIP5 forcing. CMIP5 simulations exist as included in GlacierMIP2 (with previous model version; see Marzeion et al. (2020), Figure 9)</td></tr>
<tr><td>OGGM</td><td rowspan="2">Based on conservation of mass (continuity equation), accounting for ice-dynamical processes (ice flow simulated by the shallow ice approximation along elevation-band flowlines). For the geometry evolution, PyGEM simulations rely on the OGGM framework.</td><td>Maussion et al. (2019)</td><td>Results presented in this study are based on OGGM v1.6.1, with glaciers binned along elevation bands (i.e., not with individual glacier branches) and a dynamical spin-up. The exact same model version was used for the CMIP5 and CMIP6 simulations.</td></tr>
<tr><td>PyGEM</td><td>Rounce et al. (2020a, b, 2023)</td><td>In this study, we compare new GloGEM and OGGM simulations with the PyGEM results as presented in Rounce et al. (2023).</td></tr>
</table>

Table S 2: Brief overview of the glacier evolution models used in this study (GloGEM and OGGM) and the glacier evolution model to which our simulations are compared (PyGEM).

RGI region	c_{prec} initial value	c_{prec} lower boundary	c_{prec} higher boundary
01- Alaska	1.5	1.0	2.0
02 - Western Canada and US	1.6	1.1	2.1
03 - Arctic Canada North	1.6	1.1	2.1
04 - Arctic Canada South	1.8	1.3	2.2
05 – Greenland periphery	1.6	1.1	2.1
06 - Iceland	1.8	1.4	2.2
07 - Svalbard	1.5	1.0	2.0
08 - Scandinavia	1.8	1.2	2.2
09 - Russian Arctic	1.5	1.0	2.0
10 - North Asia	2.0	1.7	2.8
11 - Central Europe	1.7	1.3	2.3
12 – Caucasus and Middle East	2.0	1.6	2.6
13 - Central Asia	1.5	1.0	2.0
14 - South Asia West	1.7	1.2	2.2
15 - South Asia East	1.5	1.0	2.0
16 - Low Latitudes	1.0	0.5	1.5
17 - Southern Andes	1.7	1.2	2.2
18 - New Zealand	1.8	1.4	2.4
19 – Antarctic and subantarctic	1.2	0.8	1.8

Table S 3: Initial values and boundaries between which the multiplicative precipitation parameter (c_{prec}) is allowed to vary for individual glaciers during the calibration procedure of GloGEM. These region-specific boundaries are chosen in order to draw results towards observed accumulation rates from in-situ measurements.

	2015-2050			**2015-2100**		
	SSP1-2.6	SSP2-4.5	SSP5-8.5	SSP1-2.6	SSP2-4.5	SSP5-8.5
01- Alaska	41.3%	41.2%	39.6%	27.3%	14.3%	4.3%
02 - Western Canada and US	34.7%	35.3%	30.2%	19.7%	7.8%	0.5%
03 - Arctic Canada North	20.3%	21.0%	20.2%	41.0%	41.0%	36.2%
04 - Arctic Canada South	22.4%	23.3%	23.1%	29.4%	22.1%	11.5%
05 – Greenland periphery	33.8%	34.4%	34.3%	48.2%	39.8%	21.1%
06 - Iceland	29.4%	30.1%	28.2%	36.2%	30.1%	9.8%
07 - Svalbard	35.3%	35.7%	35.2%	46.1%	36.5%	18.9%
08 - Scandinavia	19.8%	18.4%	17.3%	25.7%	16.2%	5.6%
09 - Russian Arctic	27.5%	28.2%	28.0%	47.2%	40.7%	22.7%
10 - North Asia	30.2%	26.1%	25.1%	14.1%	5.0%	0.0%
11 - Central Europe	25.3%	22.5%	17.2%	16.1%	4.6%	1.1%
12 – Caucasus and Middle East	18.5%	13.0%	8.7%	4.4%	4.3%	0.0%
13 - Central Asia	55.1%	55.0%	54.0%	50.7%	33.4%	8.6%
14 - South Asia West	49.2%	48.8%	49.3%	62.9%	47.2%	10.3%
15 - South Asia East	40.4%	37.6%	35.3%	19.2%	8.9%	1.1%
16 - Low Latitudes	7.7%	6.4%	2.6%	5.6%	0.9%	0.0%
17 - Southern Andes	37.0%	36.6%	31.1%	28.6%	16.0%	5.3%
18 - New Zealand	12.5%	9.0%	13.8%	4.7%	1.5%	3.1%
19 – Antarctic and subantarctic	33.7%	33.4%	32.4%	42.4%	41.0%	37.2%

Table S 4: Fraction of glaciers (>0.1 km^3) for which difference in projected volume changes arising from calibration approach (i.e. calibration to glacier-specific mass balance vs. regional mass balance) exceeds 10%.

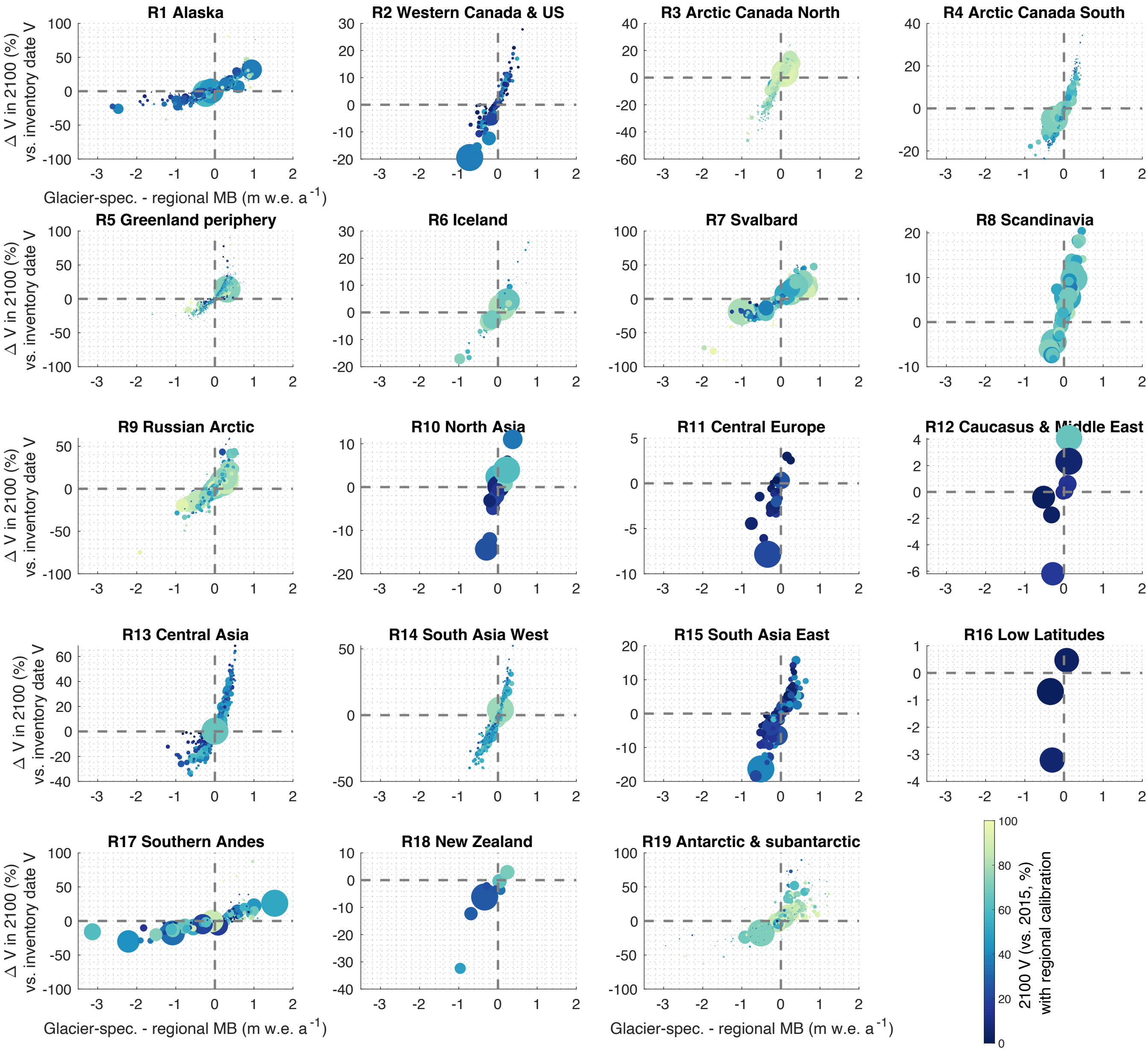

Figure S 1: Difference in the projected volume change (between inventory date and 2100 under SSP2-4.5) for the glacier-specific vs. regional mass balance calibration under SSP2-4.5 (multi-climate model median shown here). Every panel corresponds to an individual region from the RGI, in which every dot represents an individual glacier with a volume >1km^3, where the size of the dot directly relates to the glacier size, while the colour represents the 2100 glacier volume (vs. 2015) for the projections with the regional calibration (i.e., same MB forcing for every glacier). Note that the y-axis scale differs among the panels.

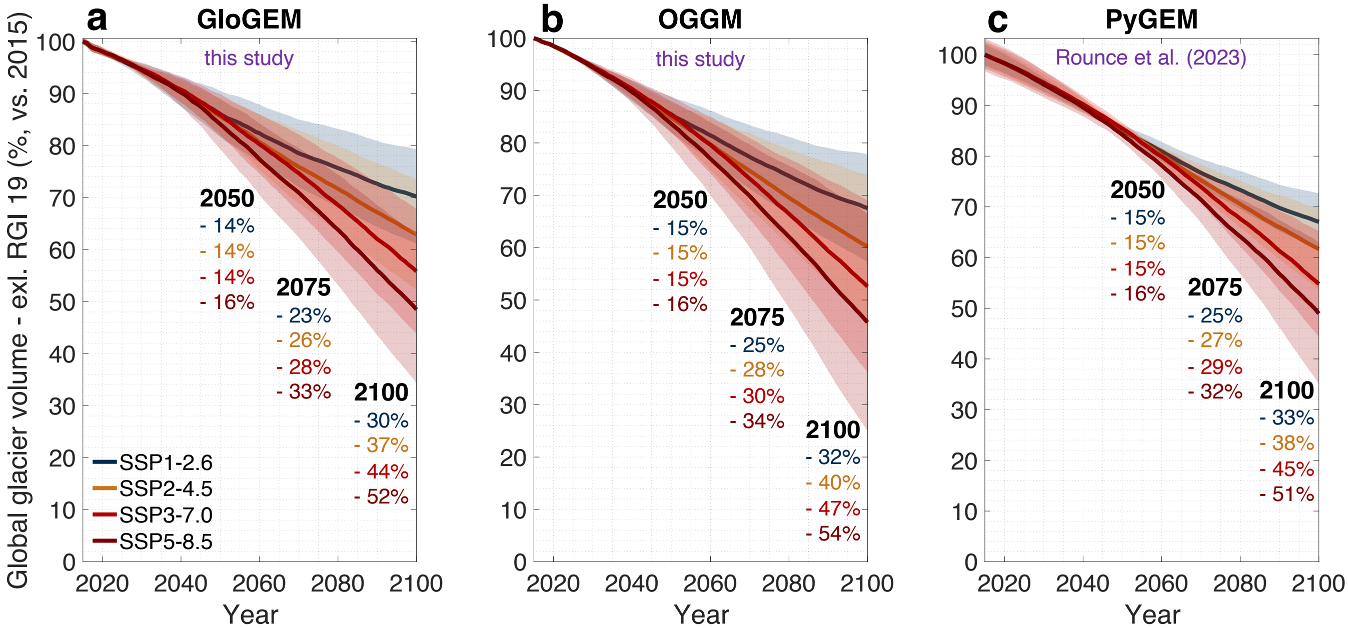

Figure S 2: Same as Figure 7 in main text, but excluding RGI Region 19 'Antarctic and Subantarctic': Evolution of 21st century global (except for 'Antarctic and Subantarctic') glacier volume compared to 2015 as modelled with (a) GloGEM (this study), (b) OGGM (this study), and (c) PyGEM (Rounce et al., 2023) under various future climate projections (multi climate-model median shown for every SSP). Shading indicates ±1 standard deviation of climate model ensemble. As opposed to GloGEM and OGGM, for PyGEM (Rounce et al., 2023) the initial volume is dependent on the climate scenario, hence the spread in projected global glacier volume from 2015 onwards.

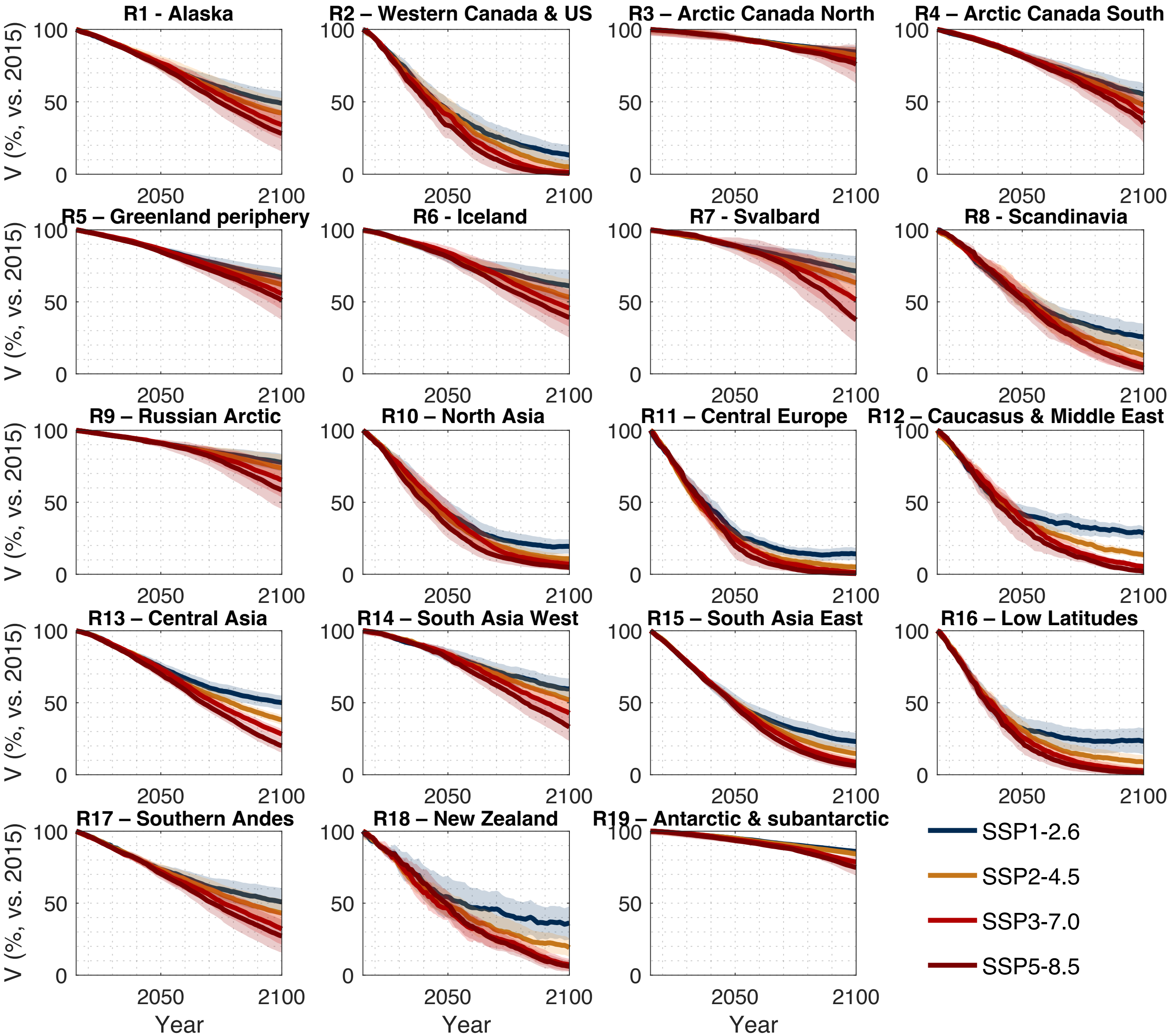

Figure S 3: Same as Figure 8 in main text, but here for PyGEM (Rounce et al., 2023): Evolution of 21st century glacier volume compared to 2015 as modelled with PyGEM (Rounce et al., 2023) for every region of the Randolph Glacier Inventory (RGI v6.0) under various future climate projections (multi climate-model median shown for every SSP). Shading indicates ±1 standard deviation of climate model ensemble. In these simulations, the mass balance forcing component is calibrated for every glacier to match the glacier-specific geodetic mass balance observations by Hugonnet et al. (2021).