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### ► To cite this version:

Harry Zekollari, Lilian Schuster, Fabien Maussion, Regine Hock, Ben Marzeion, et al.. Glacier preservation doubled by limiting warming to 1.5°C versus 2.7°C. *Science*, 2025, 388 (6750), pp.979-983. <10.1126/science.adu4675>. <hal-05108040>

**HAL Id: hal-05108040**

**<https://hal.science/hal-05108040v1>**

Submitted on 11 Jun 2025

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## Glacier preservation doubled by limiting warming to 1.5°C versus 2.7°C

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### Abstract

35 Glaciers adapt slowly to changing climatic conditions, with long-term implications for sea-  
level rise and water supply. Using eight glacier models, we simulate global glacier evolution  
over multi-centennial timescales, allowing glaciers to equilibrate with climate under various  
constant global temperature scenarios. We estimate glaciers globally will lose 39 [15 to 55]%  
40 of their mass, relative to 2020, corresponding to a global mean sea-level rise of 113 [43 to  
204]mm even if temperatures stabilized at present-day conditions. Under the +1.5°C Paris  
Agreement goal, more than twice as much global glacier mass remains at equilibration (53%  
vs. 24%) compared to the warming level resulting from current policies (+2.7°C by 2100 above  
pre-industrial). Our findings stress the need for stringent mitigation policies to ensure the long-  
term preservation of glaciers.

### Main text

Global-scale glacier mass loss profoundly affects our society and the natural environment,  
contributing to sea-level rise (1–3), influencing downstream water resources (4), affecting  
50 biodiversity and ecosystems (5), exacerbating natural hazards (6), and impacting the tourism  
industry (7). Recent projections of all glaciers outside the Antarctic and Greenland ice sheets,  
based on a range of transient climate scenarios, estimate mass losses of roughly 20 – 50%

between 2015 and 2100 depending on emissions scenarios (8–11). However, even if the current climate were to stabilize, glaciers are expected to continue losing mass over extended time periods (12–14). Glaciers may vanish entirely or, if the new climatic conditions permit, retreat until they reach a steady state in which glacier mass and glacier geometry remain approximately stable. This continued loss after climate stabilization is due to the slow adjustment of a glacier's geometry, driven by the gradual flow of ice from high to low elevations (16, 17). Additionally, the lag between the climatic forcing and glacier response is influenced by feedback mechanisms involving elevation and mass balance (18) as well as albedo and mass balance (19).

Observational and modelling studies suggest that the time needed for glaciers to reach a new steady state after a climate perturbation can range from decades to multiple centuries (20–22). However, the mass losses that are committed but not yet realized in response to long-term climate stabilization remains largely unquantified, with insights primarily derived from only two exploratory studies. Mernild et al. (23) used observed ratios of accumulation to total glacier area to estimate present-day committed global mass losses, while Marzeion et al. (13) used a glacier evolution model based on volume-area scaling to project committed losses across various global mean temperature scenarios. Both studies converge on the estimate that approximately 35 to 40% of glacier mass will be lost under early 21<sup>st</sup> century climatic conditions. However, Marzeion et al. (13) did not account for glaciers in the Greenland Periphery and the Subantarctic & Antarctic Islands. Moreover, both studies relied on limited observations to constrain and evaluate their methods, possibly affecting the precision and reliability of their methods and conclusions.

Here, we use eight state-of-the-art glacier evolution models to simulate long-term glacier mass loss of all glaciers outside the ice sheets for 80 constant-climate scenarios. These constant-climate scenarios are derived by repeating eight different 20-year periods between 1850 and 2100 from various climate models forced by Shared Socioeconomic Pathways (Fig. S 1, see Methods). Our diverse scenarios form an ensemble of global and regional climates, each of which is associated with a change in global mean temperature compared to pre-industrial. The glacier models are run for several thousand years to ensure the glaciers have sufficient time to equilibrate with the new climate. These long-term simulations thus enable the quantification of the committed glacier mass loss at regional and global scales under diverse policy-relevant global warming levels.

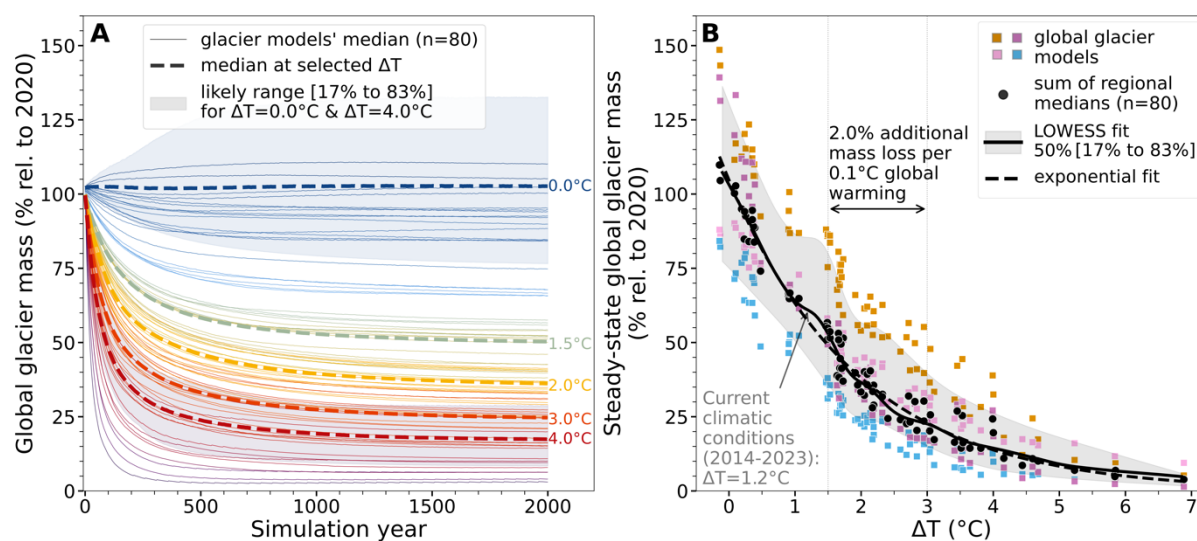
### **Committed glacier mass changes under present-day climate**

Our model simulations project that, if current (2014–2023) climatic conditions (global mean temperature  $\Delta T=1.2^\circ\text{C}$  above pre-industrial (24)) were to persist, glaciers would eventually lose 39 [15 to 55] % of their global glacier mass relative to 2020 ([17<sup>th</sup> to 83<sup>rd</sup>] percentiles are the IPCC (25) 'likely range'; Fig. 1; Table S 1). This already committed, but not yet fully realized, glacier mass loss is projected to contribute 113 [43 to 204] mm to global mean sea-level rise, irrespective of any future warming. This substantial present-day committed mass loss highlights that today's glaciers are strongly out of balance with current climatic conditions due to their long response times. The strong imbalance between glacier geometry and climate is exacerbated by atmospheric warming being particularly pronounced at high elevations (26) and high latitudes (27) where glaciers are predominantly located. In our ensemble of climate models, the median air temperature increase over glacier areas is 80% higher than the global

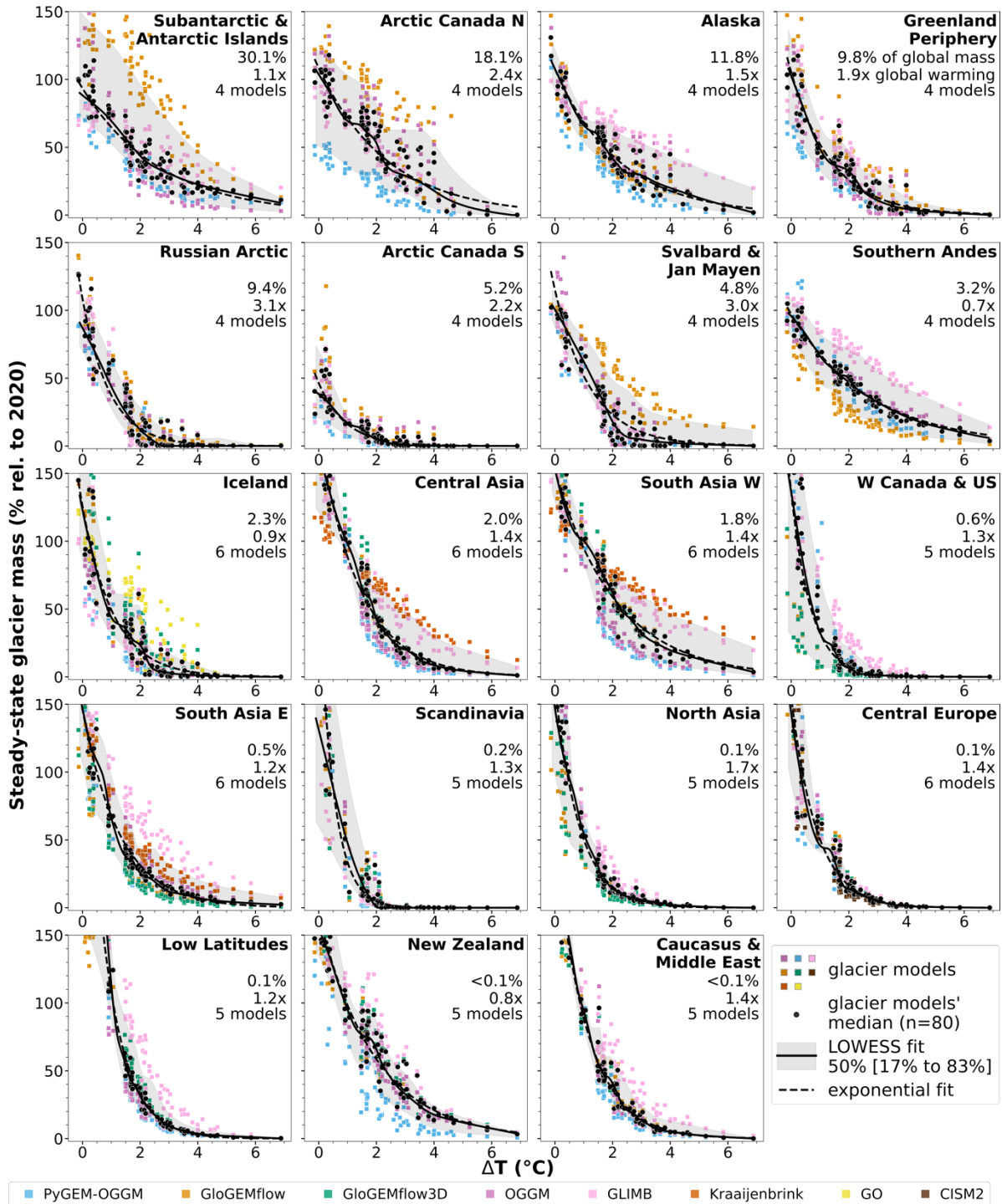
average, a relationship that is consistent regardless of the future global temperature increase (Fig. S 2; see Methods).

The imbalance between current climate and glacier geometry varies greatly among regions, resulting in sharply contrasting regional present-day committed losses (Fig. 2, Fig. 3; Table S 1). Relative losses of some regions are small, such as South Asia West (5 [0 to 30] % under  $\Delta T=1.2^\circ\text{C}$ ), Central Asia (12 [3 to 32] %), and New Zealand (15 [2 to 39] %), while other regions are projected to experience substantial losses regardless of further future warming, such as Arctic Canada South (85 [83 to 94] %), Western Canada and US (74 [43 to 93] %), Scandinavia (66 [24 to 85] %), and Russian Arctic (65 [46 to 80] %).

These regional differences in relative present-day committed losses are correlated with regional glacier elevation range (the highest correlation among the variables considered,  $r = -0.55$ ; Fig. S 3; Fig. 4A). Regions where glaciers span a wide elevation range, typically located at lower latitudes with rugged mountain topography, have a higher potential to adapt to changing climatic conditions, as glaciers can (partly) survive by retreating to higher elevations. Conversely, regions with smaller glacier elevation ranges tend to have higher present-day committed losses. In these regions, glaciers have less potential to retreat to higher elevations, an effect that is particularly pronounced in Arctic Canada South (Fig. 4A). Combined with strong regional warming (2.2 times the global warming, Fig. 2 and Fig. S 4) the glaciers are projected to largely disappear in the coming centuries under present-day climatic conditions. Many of this region's large glaciers are relics of past glaciations (e.g., the 6000 km<sup>2</sup> Barnes ice cap, a remnant of the Laurentide ice sheet (28, 29)) and cannot survive.



**Fig. 1. Projected global glacier mass under constant-climate scenarios.** (A) Evolution of global glacier mass relative to present day (year 2020; 3-year running mean). Solid lines show the results for all 80 constant-climate scenarios (derived from the sum of the regional medians of the glacier model ensemble; colors indicate corresponding global mean warming levels above pre-industrial ( $\Delta T$ , range from  $-0.1^\circ\text{C}$  to  $6.9^\circ\text{C}$ ), dashed lines refer to the median of the solid lines for select warming levels. Shading marks the multi-model ensemble likely range (shown for  $\Delta T=0.0\pm 0.2^\circ\text{C}$  and  $\Delta T=4.0\pm 0.2^\circ\text{C}$ ). (B) Steady-state glacier mass as a function of warming level. Colored dots refer to results for the globally applied glacier models (color-coding per glacier model is in Fig. 2). Black dots are obtained by globally summing regional multi-model medians, through which a LOWESS fit is added.



**Fig. 2. Regional steady-state glacier masses relative to present day (year 2020) as a function of global warming levels above pre-industrial ( $\Delta T$ ).** Dots represent individual simulations forced by 80 constant-climate scenarios per glacier model (4-6 glacier models per region, color-coded). Regions are sorted by descending present-day (2020) glacier mass. For each region, the percentage of global glacier mass in 2020, the warming over the glacierized area relative to the global mean warming (vs. 1986-2005, median value over 80 climate scenarios; see Methods), and the number of glacier models used are given. For fits with respect to (i) warming levels over each region's glacierized area see Fig. S 4, (ii) individual glacier models see Fig. S 5, and (iii) regional masses after 100 years see Fig. S 6.

## Committed glacier mass changes under policy-relevant scenarios

If global temperatures stabilize at the limits targeted in the Paris agreement, glaciers are projected to eventually lose 47 [20 to 64] % of their global mass, relative to 2020, for a +1.5°C scenario and 63 [43 to 76] % for a +2.0°C scenario, contributing 138 [59 to 237] mm and 190 [128 to 279] mm to global mean sea-level rise, respectively (all values at steady state). Under current climate policy pledges, global temperatures are projected to reach 2.7°C above pre-industrial levels by 2100 (30), which would result in eventually losing 76 [54 to 82] % of glacier mass globally, corresponding to 230 [159 to 302] mm of sea-level rise. Thus, more than twice as much global glacier mass is projected to remain long-term under the Paris Agreement +1.5°C goal compared to current climate policies.

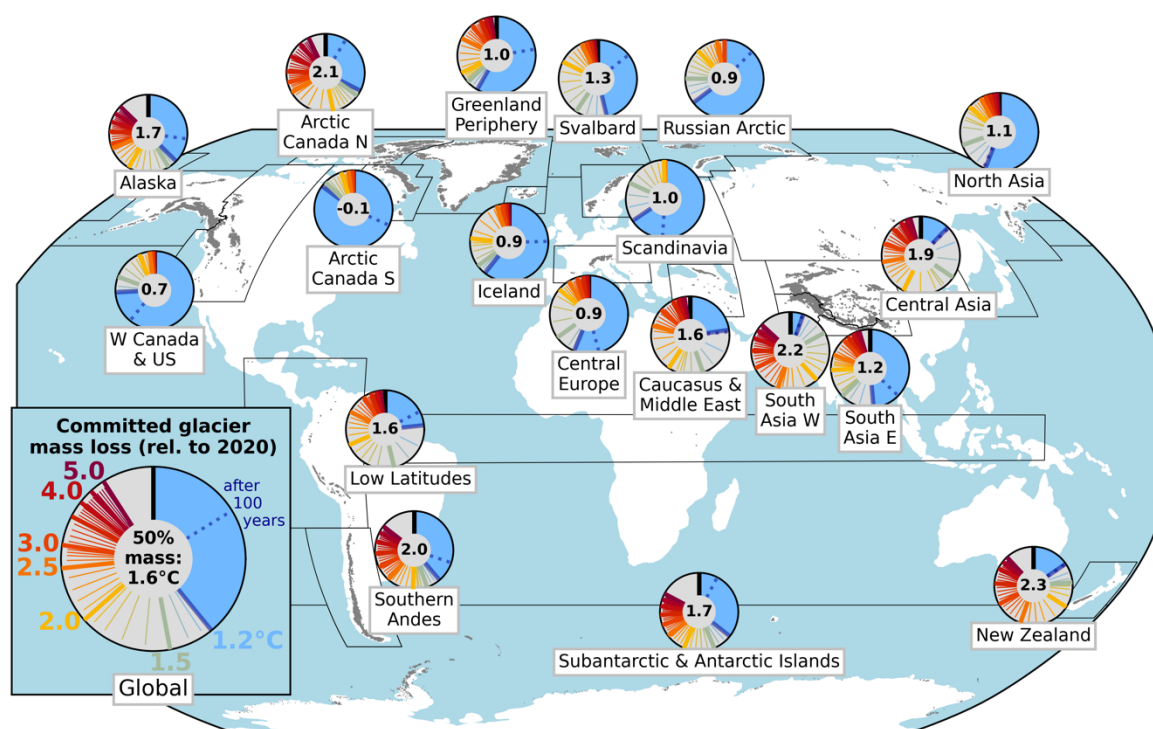
Every additional 0.1°C increase between the +1.5°C and +3.0°C scenario eventually results in an additional 2.0 [1.6 to 2.4] % global glacier mass loss, corresponding to 6.5 [4.6 to 8.9] mm of sea-level rise from glaciers alone (Fig. 1b; Table S 1). Considering the same domain (i.e., without Subantarctic & Antarctic Islands, and the Greenland Periphery) our sensitivity derived from eight glacier models is consistent with that by Marzeion et al. (13), based on a single model (Fig. S 7). For context, recent glacier projections performed with PyGEM-OGGM (10) estimate that a +3.0°C scenario would result in about 8% more global glacier mass loss by 2100 relative to 2015 (34 mm sea-level rise) than the +1.5°C scenario. In their simulations, every 0.1°C increase leads to an additional ~0.6% mass loss and 2.3 mm sea-level rise over the period 2015-2100. The glacier mass loss sensitivity to temperature increase revealed by our experiments based on long-term equilibrated glacier masses is three times larger (2.0% per 0.1°C) when considering all models, or about two times larger (1.4% per 0.1°C) when considering PyGEM-OGGM alone; Fig. S 5), indicating that substantial mass losses resulting from current climate policies will manifest after 2100.

The committed mass loss sensitivity to climate policies varies considerably across regions. Regions currently closest to balance with their climatic conditions, i.e., those with the smallest committed loss under present-day conditions, are the most sensitive to future warming (Fig. 4B; Table S 1). These regions include South Asia West (3.4 [2.0 to 3.6] % per +0.1°C for  $\Delta T=1.5-3.0^\circ\text{C}$ ), Central Asia (3.0 [2.2 to 3.2] % per +0.1°C), the Low Latitudes (3.0 [2.1 to 3.7] % per +0.1°C) and New Zealand (2.9 [2.7 to 2.9] % per +0.1°C). Therefore, while these regions are projected to experience less relative mass loss under present-day climatic conditions than others, they will be the most affected by future warming levels from current climate policies.

At higher warming levels, the relation between committed global glacier losses and warming levels becomes non-linear. At +3.0°C, glaciers are projected to lose 77 [60 to 85] % of their global mass, with all 19 regions losing more than two-thirds of their present-day mass and nine of those regions losing more than 90% (Table S 1). Consequently, in many regions, additional warming above +3.0°C leads to less additional glacier mass loss, because there is little mass left to lose, thereby reducing the sensitivity of global glacier mass loss to temperature change (Fig. 1B). In a 4°C warmer world, glaciers are projected to lose 86 [74 to 93] % of their present-day mass globally, with most mid-latitude regions deglaciating (<5% of mass remaining). In an extreme 5°C warmer world corresponding to the upper range of warming projected by 2100

under SSP5-8.5, 91 [82 to 96] % of global glacier mass is lost in the long term, contributing about 282 [242 to 352] mm to sea-level rise.

Conversely, preserving the present-day global glacier mass would require a return to pre-industrial temperatures (1850-1900;  $\Delta T = +0.0^\circ\text{C}$ , Fig. 1A). Glaciers were substantially larger than today in the second half of the 19<sup>th</sup> century due to colder and/or wetter climatic conditions in the 18<sup>th</sup> and early 19<sup>th</sup> centuries (22, 31–33). The retreat of glaciers in the early 20<sup>th</sup> century was a response to this imbalance, which has more recently been amplified and overtaken by human-induced warming (34, 35). Without anthropogenic warming, present-day temperatures would be close to pre-industrial levels (25) and glaciers would be larger than they are now. In this hypothetical case, global glacier mass would today still be declining towards the present-day observed glacier mass, a multi-centennial process.



**Fig. 3. Committed glacier mass loss at different global warming levels above pre-industrial ( $\Delta T$ ).** In every circle, the colored lines indicate the LOWESS fitted ensemble median estimates of committed mass loss at steady state at different warming levels in the range  $\Delta T = +1.2^\circ\text{C}$  to  $+5.0^\circ\text{C}$  (increasing in clockwise directions in  $0.1^\circ\text{C}$  steps beyond  $1.2^\circ\text{C}$ ; full circle correspond to 100% committed mass loss). The present-day committed mass loss at steady state ( $\Delta T = +1.2^\circ\text{C}$ ) is in light blue, with the loss after 100 simulation years (Fig. S 6) shown as the dotted line. Numbers in the circle centers are the  $\Delta T$  at which 50% of the present (year 2020) regional glacier mass is lost.

### Climate policies and multi-centennial glacier evolution: a tale of contrasting timescales

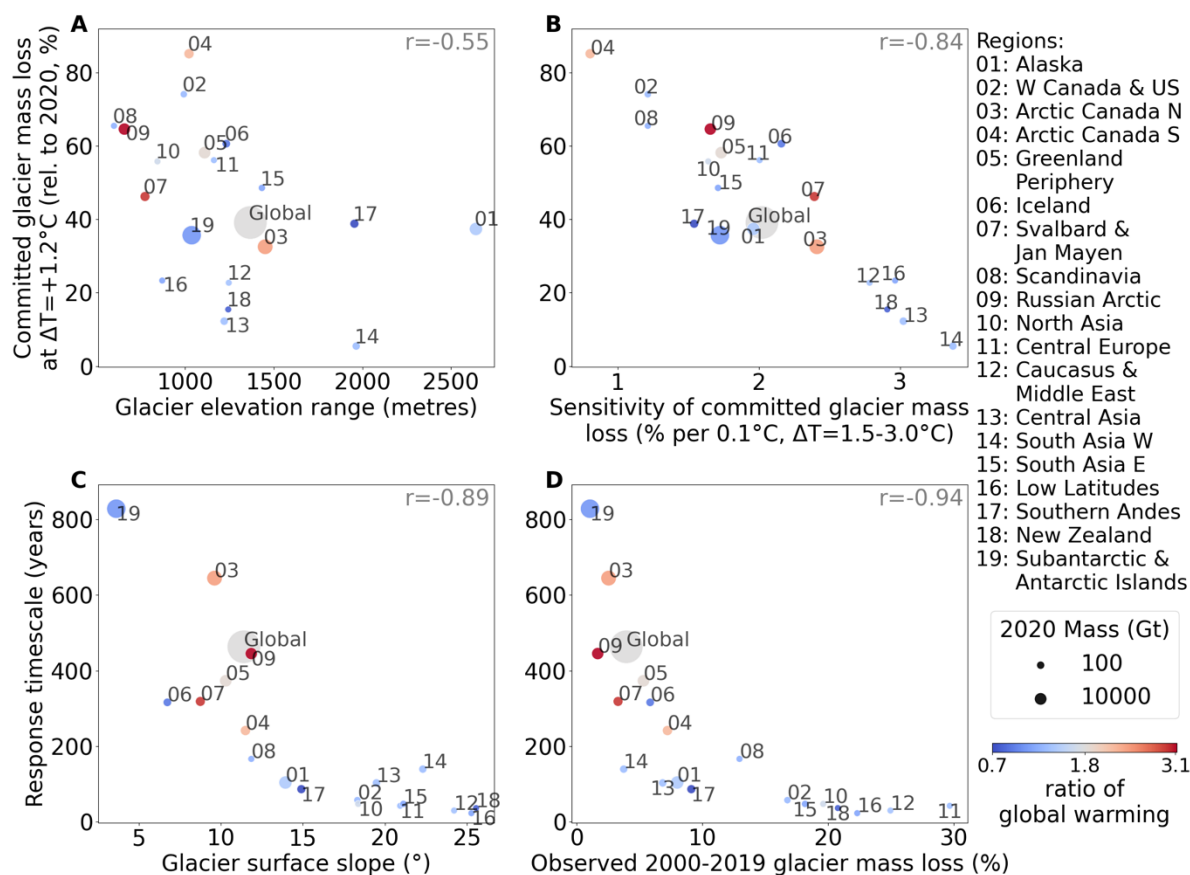
Approximately a millennium is needed for the global glacier mass to fully respond and equilibrate with the most optimistic warming level outlined in the Paris Agreement ( $\Delta T = +1.5^\circ\text{C}$ , Fig. 1A, Fig. S 8). This long response time is largely due to high-latitude regions, which contain by far most of the global glacier mass and require multi-century timescales to respond to changing climatic conditions. Most notably, the Subantarctic & Antarctic Islands

require more than 800 years for 80% of committed mass loss to occur for a +1.5°C scenario (Fig. 4C,D). Other regions like Arctic Canada North, Russian Arctic, Greenland Periphery, Iceland, Svalbard, and Arctic Canada South also respond on long timescales, with 80% changes taking more than 200 years (Table S 1). These slow-responding regions are characterized by gently-sloping glaciers (Fig. 4C, Fig. S 3), contrasting with regions with steeper glaciers where most changes occur within a few decades, such as Low Latitudes (23 [14 to 30] years for 80% change), Caucasus & Middle East (30 [26 to 56] years) and New Zealand (36 [28 to 45] years). Under higher warming levels (above +1.5°C), all regions equilibrate faster as they tend to evolve towards a mostly deglaciated state more rapidly (Fig. S 9B).

The long response timescales result in substantial differences between the glacier states after 100 years and at full equilibration, especially for the slow-responding regions (Fig. 3, Fig. 2 vs. Fig. S 6). The long-term equilibration experiments thus provide a different and complementary perspective on the vulnerability of glaciated regions compared to previous studies that have focused on transient 21<sup>st</sup> century glacier evolution (10, 11). Some regions projected to experience limited mass loss throughout the 21<sup>st</sup> century, such as the Subantarctic & Antarctic Islands (14% mass loss over 2020-2100 for a +2.0°C scenario from an ensemble of three CMIP6-forced glacier evolution models (11)), Russian Arctic (22%), and Arctic Canada South (41%), are expected to lose a large part of their mass in the longer term, with committed losses at +2.0°C reaching 56, 88, and 95%, respectively; Fig. S 10).

Generally, regions modelled to have the longest response timescales are also those with the lowest observed relative mass loss over the past two decades (2000-2019), and vice versa ( $r = 0.94$ , Fig. 4D). For example, the Subantarctic & Antarctic Islands, Arctic Canada North, and Russian Arctic, which each require more than 400 years for 80% of committed changes to occur for a +1.5°C scenario, have lost less than 3% of their mass between 2000 and 2019. In contrast, the fastest responding regions, such as Central Europe, Caucasus & Middle East, Low Latitudes, and New Zealand need less than five decades for 80% changes to occur and each have lost more than 20% of their mass over the first two decades of the 21<sup>st</sup> century.

Our results emphasize that the effectiveness of current and near-term climate policies in mitigating short- to mid-term warming will play a decisive role in shaping the future evolution of glaciers, influencing not only immediate glacier changes but also those that will unfold over multi-centennial timescales. The findings stress the pivotal role of climate policies in preserving our glaciers, which should be a central focus of the United Nations International Year of Glaciers' Preservation in 2025 (36).



**Fig. 4. Present-day committed glacier mass loss and response timescales globally and for 19 glacier regions.** (A-B) Present-day committed mass losses ( $\Delta T = +1.2^\circ\text{C}$ ) as a function of (A) regional mean glacier elevation range, weighted by glacier area and (B) sensitivity of committed glacier mass loss to global mean air temperature change in the range  $\Delta T = +1.5^\circ\text{C}$  to  $+3.0^\circ\text{C}$  (see Methods). (C-D) Response timescale, i.e. the year when 80% of the committed mass loss at  $\Delta T = 1.5^\circ\text{C} \pm 0.2^\circ\text{C}$  has occurred, as a function of (C) glacier-area weighted regional mean surface slope and (D) observed glacier mass change between 2000 and 2019, relative to 2000 (1, 37) (see Methods).  $r$  is the Spearman's rank correlation coefficient for the 19 regions ( $p\text{-value} < 0.02$ ). The coloring of the dots refers to the warming over the glacierized area relative to the global mean warming (vs. 1986-2005, median value over 80 climate scenarios, Fig. 2). The size of the dots scales with the respective 2020 glacier mass. Slope (C) and observed mass loss (D) data are available in Table S3.

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## Acknowledgments

We acknowledge the World Climate Research Programme (WCRP) Climate and Cryosphere Project (CliC) for supporting the Glacier Model Intercomparison Project (GlacierMIP).

- 40 **Funding:** This work was funded by the following: European Union’s Horizon 2020 research and innovation programme – PROTECT, grant agreement number 869304 (to HZ, BM, MH, MJ, NC, TE, and DF); European Research Council (ERC) under the European Union’s Horizon Framework research and innovation programme, grant agreement No 101115565, ICE<sup>3</sup> (to HZ); Research foundation – Flanders (FWO) through an Odysseus Type II project, grant agreement G0DCA23N, GlaciersMD (to HZ and LVT); VUB ZAP Startkrediet, ICEFIELD (to HZ); DOC Fellowship of the Austrian Academy of Sciences at the Department of Atmospheric and Cryospheric Sciences, Universität Innsbruck, No. 25928 (to LS); European Union’s Horizon 2020 research and innovation programme under grant agreement No. 101003687, PROVIDE (to LS and FM); Norwegian Research Council Project 324131 (to RH); ERC-2022-
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ADG No 01096057 GLACMASS (to RH); National Aeronautics and Space Administration grants 80NSSC20K1296 and 80NSSC20K1595 (to RH and DR); Swiss National Science Foundation grant nr. 200021\_184634 (to LC); Dutch Research Council (NWO) Talent Programme Veni, GREENPEAKS, file number VI.Veni.222.019 (to PK); NSF National Center for Atmospheric Research, which is a major facility sponsored by the U.S. National Science Foundation under Cooperative Agreement No. 1852977 (to WL, SM, and GL); Computing and data storage resources for CISM simulations were supported by the Derecho system (doi:10.5065/qx9a-pg09) provided by the NSF National Center for Atmospheric Research (NCAR), sponsored by the National Science Foundation (to WL, SM, and GL); GRICAD infrastructure (to NC); European Research Council (ERC) under the European Union's Horizon Framework research and innovation programme, grant agreement No 101142123, DROP (to WI); World Climate Research Programme (WCRP) Climate and Cryosphere Project (CliC) who funded GlacierMIP workshops.

**Author contributions:** HZ and LS contributed equally to this work and share first authorship. HZ was the main project coordinator of the study, which initiated from original ideas by BM. HZ, LS, FM, RH, and BM designed the GlacierMIP3 experiments, protocol and methods. Funding for data analyses and GlacierMIP3 activities was acquired by FM, RH, BM, HZ. FM did exploratory simulations and analyses to guide the GlacierMIP3 experimental design choices. LS preprocessed the climatic input data for the model experiment in close collaboration with FM. FM, LS, and HZ created test files and example workflows and guided the data submission process. LC, KF, MH, MJ, PK, WL, FM, SM, MO, DR, LS, LVT, and HZ performed the GlacierMIP3 model experiments with contributions in form of supervision and feedback by TE, DF, WI, GL, and AS. LS performed all data analyses, including pre- and postprocessing of the submitted model simulations, and made the figures in close collaboration with HZ and FM, and additional input from RH, BM, and DR. LS did the data curation and validation with input from FM. BM provided resources for computation and data storage. HZ and LS interpreted the results with input from FM, RH, and BM. HZ wrote the original manuscript with major text contributions from RH and LS. FM, DR, and BM provided extensive text reviews and edits, with additional contributions from NC, LC, KF, WI, PK, WL, SM, LVT, and particularly MH and DF.

**Competing interests:** Authors declare that they have no competing interests.

**Data and materials availability:** The submitted data from the glacier model groups and the code to reproduce the figures is available from Schuster, Zekollari et al. (38, 39).

### Supplementary Materials

Methods

40 Figs. S1 to S15

Tables S1 to S3

References (40–66)