Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016

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In recognition of J. Graham Cogley (1948–2018), a pioneer in glacier mass-balance studies

Glaciers distinct from the Greenland and Antarctic Ice Sheets cover an area of approximately 706,000 km^2 globally[1] with an estimated total volume of 170,000 km^3, or 0.4 m of potential sea-level rise equivalent[2]. Retreating and thinning glaciers are icons of climate change[3] and impact regional runoff[4] as well as global sea level[5,6]. For the previous reports of the Intergovernmental Panel on Climate Change (IPCC), mass-change estimates were based on the multiplication of averaged or interpolated results from available observations of a few hundred glaciers with regional glacier areas[7–10]. For data-scarce regions, these results had to be complemented with estimates based on satellite altimetry and gravimetry[11]. These past approaches were challenged by the small number and heterogeneous spatio-temporal distribution of *in situ* measurement series and their often unknown representativeness for the respective mountain range as well as by spatial limitations of current satellite altimetry (only point data) and gravimetry (coarse resolution). Here we use an extrapolation of glaciological and geodetic observations to show that glaciers contributed 27 ± 22 mm to global mean sea-level rise from 1961 to 2016. Regional specific mass-change rates for 2006–2016 range between −0.1 and −1.2 m water equivalent (w.e.) per year, resulting in a global sea-level contribution of 335 ± 144 Gt per year or 0.92 ± 0.39 mm per year. Although statistical uncertainty ranges overlap, our conclusions suggest that glacier mass loss may be larger than previously reported[11]. The current glacier mass loss is thus equivalent to the sea-level contribution of the Greenland Ice Sheet[12], clearly exceeds the loss from the Antarctic Ice Sheet[13], and accounts for 25 to 30% of the total observed sea-level rise[14]. Current mass loss rates indicate that glaciers could virtually disappear in some mountain ranges in this century while heavily glacierised regions will continue contributing to sea-level rise beyond 2100.

Changes in glacier volume and mass are observed by geodetic and glaciological methods[15]. The glaciological method provides glacier-wide surface mass changes based on point measurements from seasonal or annual *in situ* campaigns extrapolated to unmeasured regions of the glacier. The geodetic method determines glacier-wide volume changes by repeated mapping and differencing of glacier surface elevations from *in situ*, air-, and space-borne surveys usually over multi-year to decadal periods.

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In this study, we used glaciological and geodetic data from the World Glacier Monitoring Service (WGMS)[16], complemented by new and yet unpublished geodetic assessments for glaciers in Africa, Alaska, the Caucasus, Central Asia, Greenland periphery, Iceland, New Zealand, Scandinavia, Svalbard, and the Russian Arctic. At present, this dataset includes observations from 450 and 19,130 glaciers for the glaciological and the geodetic samples, respectively, which corresponds to sample sizes of <1% and 9% with respect to the total number of glaciers[1]. We estimated regional mass changes for the 19 first-order regions of the Randolph Glacier Inventory (RGI)[1] (Fig. 1). The observational coverage ranges from <1% to 54% of the total glacier area per region for the glaciological sample and from <1% to 79% for the geodetic sample (Extended Data Fig. 1). In each region, we combined the temporal variability from the glaciological sample, obtained with a spatio-temporal variance decomposition, with the glacier-specific values of the geodetic sample (see Methods). We then extrapolated the calibrated annual time series from the observational to the full glacier sample to assess regional mass changes, taking into account regional area change rates (see Methods). Uncertainties originate from four independent error sources. These relate to the temporal changes assessed from the glaciological sample, to the long-term geodetic values, to the extrapolation to unmeasured glaciers, and to estimates of regional glacier area. For estimating regional mass changes, we spatially interpolated the specific mass changes from the observational sample to all glaciers in the region. The related error was estimated from the deviations of this approach to regional (specific) mass changes calculated as arithmetic averages or as area-weighted averages of the observational sample (see Methods).

Over the full observation period from 1961−2016, global glacier mass changes cumulated to −9,625 ± 7,975 Gt. This corresponds to a contribution of 27 ± 22 mm to global sea level, or a contribution of 0.5 ± 0.4 mm per year when a linear rate is assumed. The total mass change excluding peripheral glaciers in Greenland and Antarctica sums up to −8,305 ± 5,115 Gt, corresponding to a contribution to sea level of 0.4 ± 0.3 mm per year. Cumulative mass changes and corresponding contributions to global sea level were largest from the heavily glacierised regions, with approximately one third originating from Alaska (Fig. 1). Additionally, large contributions originate from regions with less glacierisation but strongly negative specific mass changes such as Western Canada & US (Extended Data Fig. 2). South Asia West was the only region that exhibited mass gain over the full observation period. Cumulative specific mass changes over the full observation period from 1961−2016 were most negative in the Southern Andes, followed by Alaska, the Low Latitudes, Western Canada & US, New Zealand, the Russian Arctic, and Central Europe (Extended Data Fig. 2a). When annual rates are averaged over pentads (i.e., periods of five years, Fig. 2), sea-level contributions ranged between 0.2 ± 0.5 and 0.3 ± 0.4 mm per year until the 1980s and then continuously increased to reach 1.0 ± 0.4 mm in the latest pentad (2011−2016). Over corresponding periods, our estimates show that global glacier mass loss is approximately equivalent to various mass-loss estimates from the Greenland Ice Sheet (with periods between 2003 and 2012)[12], and it exceeds current sea-level rise contributions from the Antarctic Ice Sheet (2012−2017: 219 ± 43 Gt yr^{-1}, including the Antarctic Peninsula)[13] by 62%. Hence, glaciers contributed between 25 and 30% of the observed global mean sea-level rise, which ranged between 2.6 and 2.9 ± 0.4 mm per year over the satellite altimetry era (1993 to mid-2014)[14].

Glacier mass changes were negative in all regions over the latest observational decade from 2006 to 2016 (Table 1), i.e. covering the hydrological years[15] from 2006/07 to 2015/16. Glaciers in South America had the most negative specific mass changes with rates exceeding −1.0 m w.e. per year, followed by glaciers in the Caucasus, Central Europe, Alaska, and Western Canada & US with rates of less than −0.8 m w.e. per year (Fig. 3a). The least negative specific mass changes were found for glaciers in the Antarctic periphery (−0.1 m w.e. yr^{-1}) and in South Asia West, with glaciers close to balanced-

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budget conditions[17,18]. Again, regions with large ice cover and negative specific mass changes showed the largest total losses (Fig. 3b). Record mass losses are thus found in Alaska with rates of −73 Gt per year followed by other heavily glacierised regions (i.e., with glacier areas greater than 29,000 km^2) such as Arctic Canada North (−60 Gt yr^{-1}), the Greenland periphery (−51 Gt yr^{-1}), and the Southern Andes (−34 Gt yr^{-1}, Table 1). Exceptions are Central Asia and South Asia West with limited mass losses (−7 and −1 Gt yr^{-1}) despite their large glacier areas. From the regions with smaller glacierisation, Western Canada & US and Iceland lost most mass at rates of −12 and −8 Gt per year, respectively.

We calculated the relative annual ice loss (Extended Data Fig. 3) by comparing current mass-change rates (2006–2016) to total estimated ice volumes for each region[2]. Nine out of 19 regions lost between 0.5 and 3% of their total ice volume per year. The other regions featured smaller loss rates. Under current ice loss rates, most of today's glacier volume would thus vanish in the Caucasus, Central Europe, the Low Latitudes, Western Canada & US, and New Zealand in the second half of this century. However, the heavily glacierised regions would continue contributing to sea-level rise beyond this century, as glaciers in these regions persist but continue to lose mass. It is worthwhile to note that a substantial part of the future ice loss is already committed due to the imbalance of most glaciers with the current climate[19,20] and that numerical models are required to fully assess future glacier changes in view of climate change scenarios[20,21].

Overall error bars related to regional mass changes (Fig. 3b) consider different sources. In most regions, the geodetic error accounts for the largest contribution, followed by the error related to the temporal changes assessed from the glaciological sample (Extended Data Fig. 4). The extrapolation to unmeasured glaciers contributes significantly to the overall error only in regions with large differences between interpolation methods. The reasons for these differences are region-specific and depend on various factors such as the observational sample, glacier size distribution, or a bias to large tidewater or surge-type glaciers. Uncertainties related to glacier areas and their changes contribute only minimally to the overall error. However, considering area changes is important despite their small contribution to random errors as a constant glacier area over time would result in a systematic error increasing with the length of the time series and the rate of the area change[22,23].

The new approach in combination with the major advance in observational evidence allows for a sound assessment of global glacier mass changes independent from satellite altimetry and gravimetry. This is a basic requirement for the comparison of regional results and the detection of potential biases over the satellite era. Compared to IPCC AR5[11,24], the greatest improvement is in the geodetic sample: it has been boosted from a few hundred glaciers[7] to over 19,000 glaciers globally, with an observational coverage of more than 45% of the glacier area in 11 out of 19 regions (Extended Data Fig. 1). Our new approach, combining the temporal variability from the glaciological sample with large-scale observations from the geodetic sample, facilitates inferring mass changes at annual resolution for all regions and back to the hydrological year 1961/62. This represents a major development as compared to IPCC AR5[11,24] that had to focus on the satellite altimetry and gravimetry era (2003–2009) and relied on estimates modelled using climate data or interpolated values from scarce and mostly uncalibrated observational samples for earlier time periods (see Methods).

Our central estimate for the global rate of glacier mass loss is 47 Gt (or 18%) per year larger than reported in IPCC AR5 (Section 4.3.3.3, Table 4.4)[11,24] over the period from 2003 to 2009 (Extended Data Fig. 5). A direct comparison of our results is possible for the seven regions (all with less than 15,000 km^2 of ice cover) with estimates based on glaciological and geodetic samples in IPCC AR5[11,24]. In these regions, our mass-change estimates are systematically less negative (Extended

Data Fig. 5a). This suggests that our new approach of calibrating regional glaciological mass-change time series with geodetic observations has overcome an earlier reported negative bias in the glaciological sample[11]. Regions with estimates based on satellite altimetry and gravimetry in IPCC AR5[11,24] featured absolute differences in the same order of magnitude but with varying signs. The more negative global mass changes mainly result from heavily glacierised regions where we estimate larger mass losses (e.g., Alaska, peripheral Greenland and Antarctic, Russian Arctic, Arctic Canada North) and are partly offset by smaller mass loss estimates for a few other regions with abundant ice cover (e.g. Arctic Canada South, Iceland, South Asia West, Central Asia; Extended Data Fig. 5b) and by the above-mentioned bias in regions with less glacierisation. Our error bars are considerably larger than and overlap with those reported in IPCC AR5 (Section 4.3.3.3, Table 4.4)[11,24]. However, a direct comparison is challenging since the error bars of the earlier study[11] were based on a combination of regionally different methods and data sources. A detailed comparison will require a regional assessment of glacier changes and related uncertainties including scaling issues from glacier-wide observations (this study) to results from satellite altimetry (regional averages of repeat-path measurements) and gravimetry (coarse resolution of sensor and hydrological models). However, our error estimates are methodologically consistent and consider all known relevant sources of potential errors. We consider the relative differences of our error bars between the regions to be plausible and their absolute values as upper bounds.

Improvements in global glacier mass-change assessments are still possible and necessary. First, the observational database needs to be extended in both space and time. We currently see the most urgent need for closing observational gaps in regions where glaciers dominate runoff during warm/dry seasons, such as in the tropical Andes and in Central Asia[4], and in regions dominating the glacier contribution to future sea-level rise, i.e. Alaska, Arctic Canada, Russian Arctic, and peripheral glaciers in Greenland and Antarctica. Second, a systematic assessment of regional area change rates[25] will improve the estimate of corresponding impacts on regional mass changes. Finally, more research is required to better constrain the observational uncertainties at individual glaciers[26] and for regional mass-change assessments. Despite these remaining challenges, the present assessment of global glacier mass changes provides a new observational baseline for a sound comparison to estimates based on other methods[27] as well as for future modelling studies of glacier contributions to regional runoff and global sea-level rise.

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Author contributions

M.Z. initiated and coordinated the study and wrote the manuscript; the basic concept was jointly developed during a workshop in the Swiss pre-Alps. M.Z., S.N., H.M., I.G., J.H., F.P., L.T., S.K., and G.C. compiled data from the research community and the literature; R.M., J.H., and M.B computed additional geodetic results. M.H., M.B., and F.M. defined clusters and regions used in the analysis. E.T. and N.E. run the variance decomposition model. M.H. performed the calibration of the glaciological signal to geodetic series and the extrapolation to regional changes. M.Z., I.G., S.N., E.T. , and J.H. produced the figures. All authors commented on the manuscript.

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Tables

Table 1 | Annual rates of glacier changes per region from 2006 to 2016

Region (code)	Total area (km^2)	Total volume (km^3)	Specific mass change (m w.e. yr^{-1})	Mass change (Gt yr^{-1})
01 Alaska (ALA)	86,725	18,429	−0.85 ± 0.19	−73 ± 17
02 Western Canada & USA (WNA)	14,524	1,048	−0.83 ± 0.40	−12 ± 6
03 Arctic Canada North (ACN)	105,111	29,721	−0.57 ± 0.80	−60 ± 84
04 Arctic Canada South (ACS)	40,888	8,948	−0.57 ± 0.70	−23 ± 28
05 Greenland (GRL)	89,717	15,780	−0.63 ± 0.21	−51 ± 17
06 Iceland (ISL)	11,060	3,520	−0.71 ± 0.43	−8 ± 5
07 Svalbard and Jan Mayen (SJM)	33,959	8,076	−0.47 ± 0.23	−16 ± 8
08 Scandinavia (SCA)	2,949	306	−0.49 ± 0.27	−1 ± 1
09 Russian Arctic (RUA)	51,592	15,449	−0.47 ± 0.37	−24 ± 19
10 North Asia (ASN)	2,410	146	−0.37 ± 0.31	−1 ± 1
11 Central Europe (CEU)	2,092	116	−0.87 ± 0.07	−2 ± 0
12 Caucasus and Middle East (CAU)	1,307	63	−0.90 ± 0.57	−1 ± 1
13 Central Asia (ASC)	49,303	3,483	−0.15 ± 0.12	−7 ± 6
14 South Asia West (ASW)	33,568	3,092	−0.03 ± 0.12	−1 ± 4
15 South Asia East (ASE)	14,734	906	−0.35 ± 0.12	−5 ± 2
16 Low Latitudes (TRP)	2,341	80	−1.03 ± 0.83	−2 ± 2
17 Southern Andes (SAN)	29,429	5,518	−1.18 ± 0.38	−34 ± 11
18 New Zealand (NZL)	1,162	61	−0.68 ± 1.15	−1 ± 1
19 Antarctic and Subantarctic (ANT)	132,867	46,801	−0.11 ± 0.87	−14 ± 108
Total, excl. GRL and ANT	483,155	98,962	−0.56 ± 0.04	−270 ± 19
Global total	705,739	161,543	−0.48 ± 0.20	−335 ± 144

Current regional and global glacier areas and volumes with specific mass changes (m w.e. yr^{-1}) and mass-change rates from spatial interpolation (Gt yr^{-1}) for the period from 2006 to 2016. Regional glacier areas are from the RGI 6.0 and refer to the first decade of the 21st century[1]. Regional estimates for glacier volumes are based on Huss and Farinotti (2012)[2] updated to the glacier outlines of RGI 6.0. Global totals are calculated as sums of regions for area, volume, and mass change. Global specific mass changes are calculated by dividing the global mass-change rate by global glacier area. Error bars correspond to 95% CIs and originate from independent sources: glaciological sample, geodetic sample, spatial interpolation, and glacier area (see Methods, uncertainty estimates).

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Figures

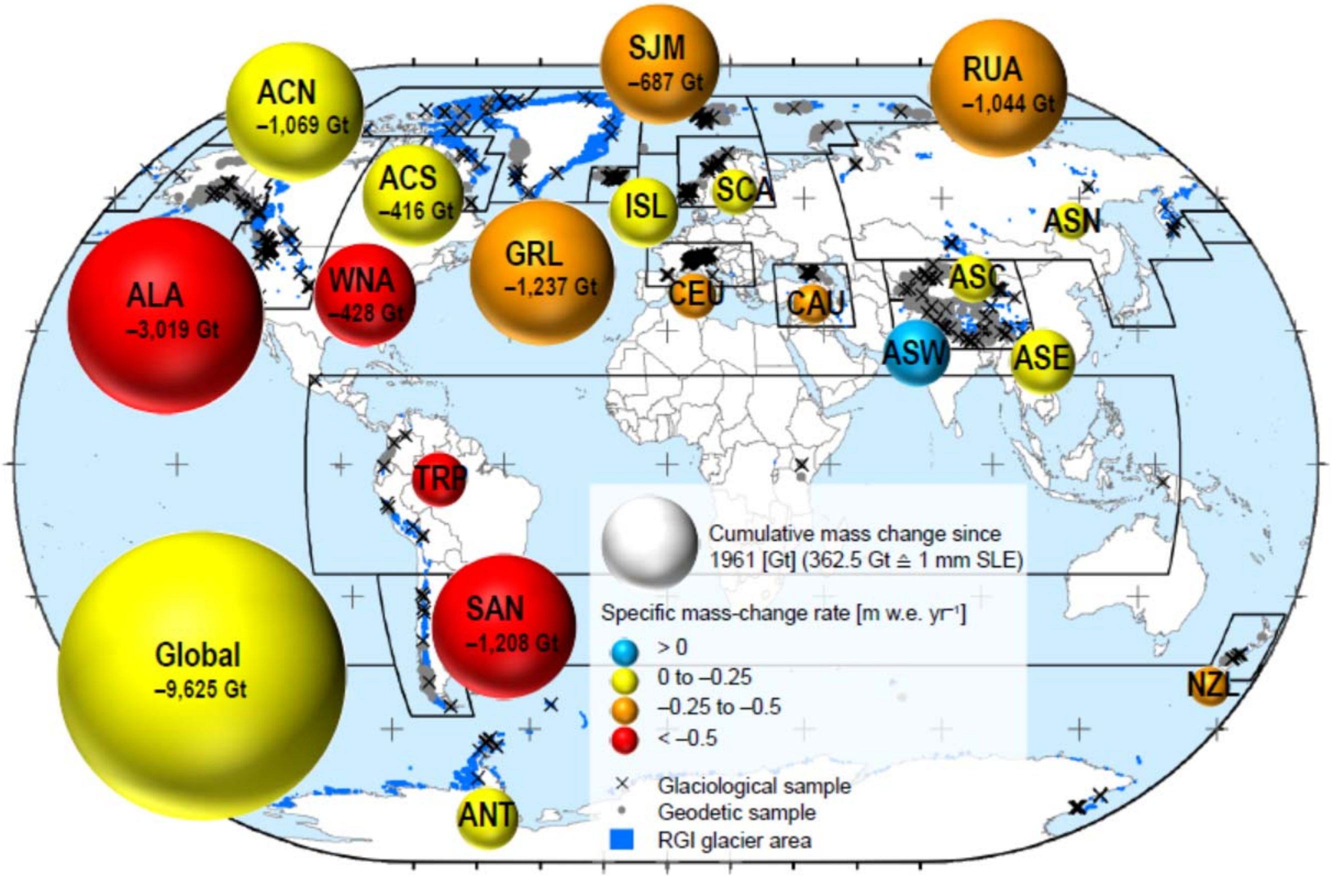

Fig. 1 | Regional glacier contributions to sea-level rise from 1961 to 2016. The cumulative regional and global mass changes (Gt, volume of bubbles) are shown for the 19 first-order regions[1] (bold black lines). Specific mass-change rates (m w.e. yr^{-1}) are indicated by the colour of the bubbles. In the background, the glaciological and geodetic data samples are plotted over the glacier polygons from RGI 6.0. For region codes, see Table 1. Reading example: Glaciers in Alaska (ALA) show the largest contribution to sea-level rise with a total mass change of approximately −3,000 Gt, or 8 mm sea-level equivalent (SLE) from 1961 to 2016, because of a strongly negative specific mass-change rate (−0.6 m w.e. yr^{-1}) combined with a large regional glacier area. Note that South Asia West (ASW, blue bubble) is the only region in which glaciers slightly gained mass.

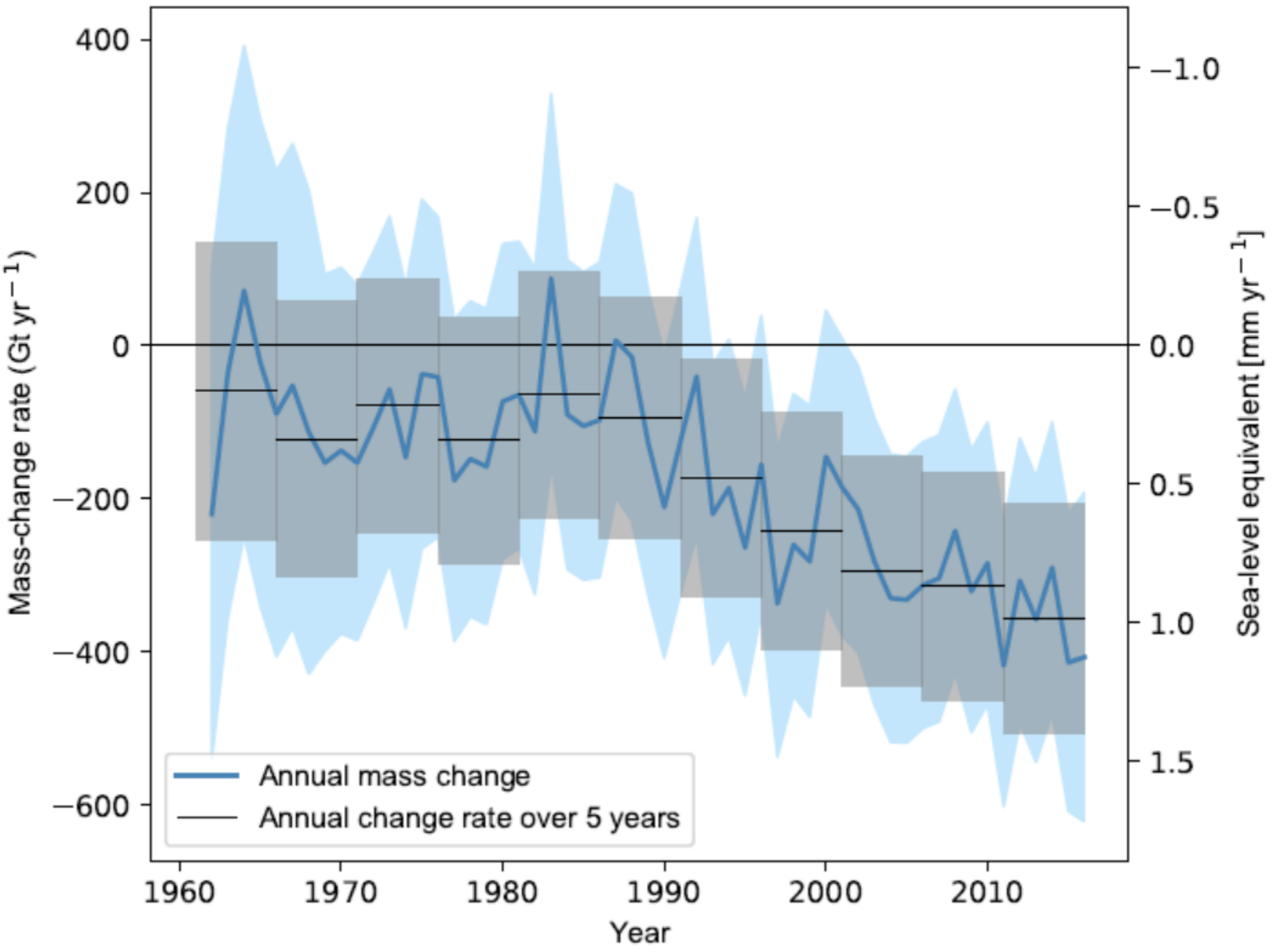

Fig. 2 | Global glacier contributions to sea-level rise from 1961 to 2016. Annual and pentadal mass-change rates (Gt yr^{-1}, left y-axis) and equivalents of mean global sea-level rise (mm yr^{-1}, right y-axis) are shown with related error bars corresponding to 95% CIs. Annual errors originate from independent sources: glaciological sample, geodetic sample, spatial interpolation, and glacier area. Over the five-year periods, the individual error terms are cumulated separately followed by a combination of the multi-year terms according to the law of random error propagations, and a division by the number of years (see Methods).

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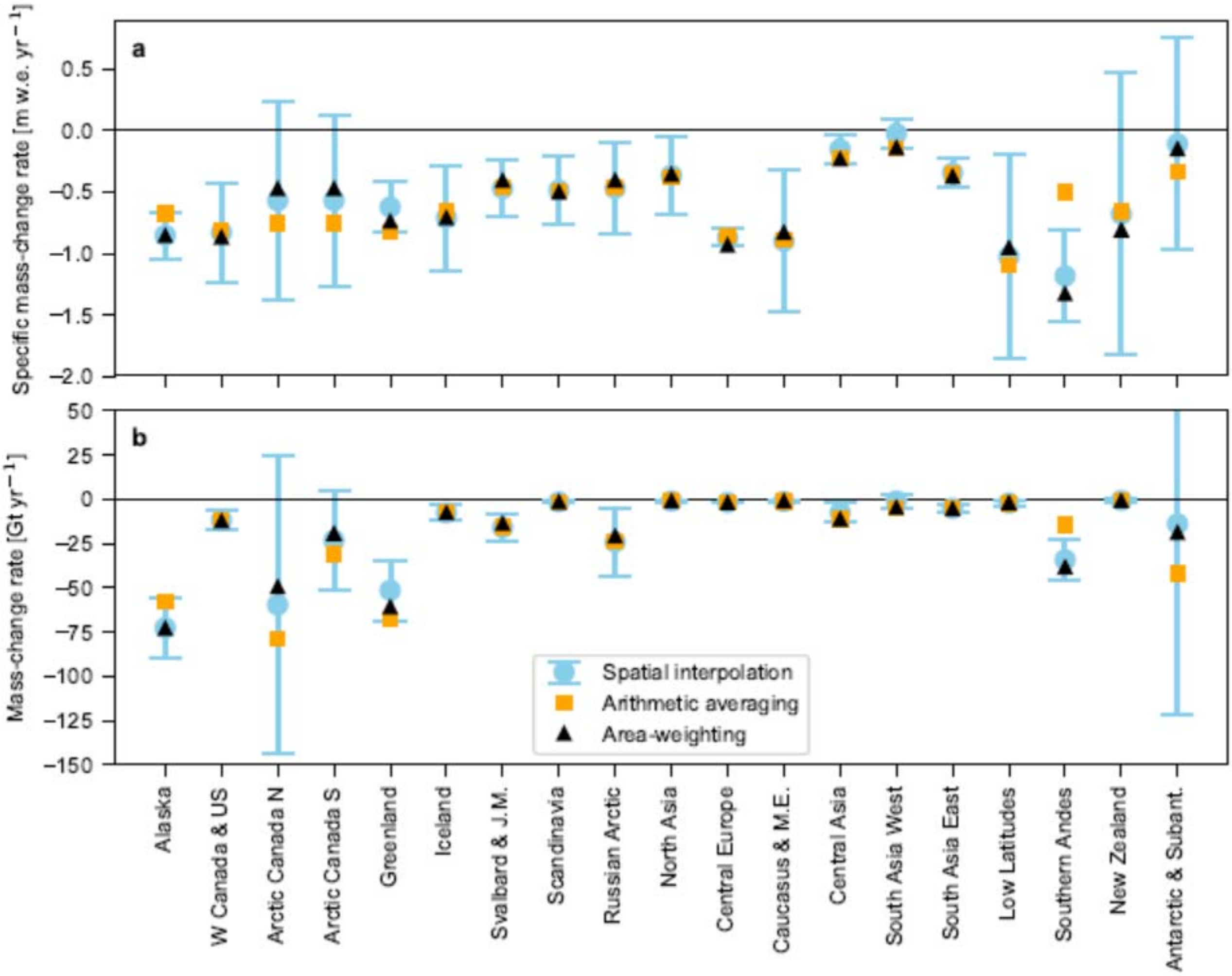

Fig. 3 | Regional estimates of glacier mass change for the period 2006–2016. a–**b**, Annual mass-change rates in m w.e. yr^{-1} (**a**) and in Gt yr^{-1} (**b**) as estimated from spatial interpolation (blue circle), area-weighting (black triangle), and arithmetic averaging (orange square). The spatial interpolation approach (blue) is the reference with results provided in Table 1. Error bars correspond to 95% CIs and consider uncertainties related to the temporal variability of the glaciological sample, the geodetic value, the regional interpolation, the regional glacier area, and a second order crossed term. We estimate the error related to the regional interpolation from the differences between the three interpolation approaches (see Methods, uncertainty estimates).

METHODS

Glaciological and geodetic mass changes. The glaciological method usually provides glacier-wide surface mass balance (B_{sfc}) over an annual period related to the hydrological year. In line with Cogley et al. (2011)[15], we use the unit m w.e. for the specific mass change (1 m w.e. = 1,000 kg m^{-2}) and the unit Gt for the mass change (1 Gt = 10^{12} kg), with mass balance and mass change as synonymous terms. Results are reported as cumulative values over a period of record or as annual change rates (yr^{-1}). The geodetic balance is the result of surface (sfc), internal (int), and basal (bas) mass changes and – in the case of marine-terminating or lacustrine glaciers – of calving (D) in the unit m w.e.:

$$B_{\mathrm{geod}} = \Delta M = B_{\mathrm{sfc}} + B_{\mathrm{int}} + B_{\mathrm{bas}} + D. \tag{1}$$

In practice, the geodetic (specific) mass change is calculated as volume change ΔV over a survey period between t_0 and t_1, from differencing of digital elevation models (DEMs), over the glacier area multiplied by a volume-to-mass conversion factor

$$B_{\mathrm{geod}} = \frac{\Delta V}{\bar{S}} \cdot \frac{1}{(t_1 - t_0)} \cdot \frac{\bar{\rho}}{\rho_{\mathrm{water}}}, \tag{2}$$

where $\bar{S}$ is the average glacier area of the two survey times (t_0, t_1) assuming a linear change through time[26] and $\bar{\rho}$ is the average density of ΔV with a commonly applied value[28] of 850 ±60 kg m^{-3}. The glaciological method is able to satisfactorily capture the temporal variability of the glacier mass change even with only a small observational sample[29,30]. However, its cumulative amount over a given time span is sensitive to systematic errors which accumulate with the number of annual measurements[31,32]. The geodetic method provides mass changes covering the entire glacier area and large glacier samples. However, the method requires a density conversion and surveys are typically carried out at multi-annual to decadal intervals only. For both measurements, we use the latest version (wgms-fog-2018-06) of the Fluctuations of Glaciers (FoG) database from the WGMS[16]. The glaciological sample was recently updated with observations from latest years, consolidated by adding results from approximately 100 additional glaciers[7], and by replacing entire mass-balance series after reanalysis[33–37]. The geodetic sample was increased recently by the inclusion of large-scale assessments from several mountain regions[17,38–42].

For the present study, we complemented the dataset from the WGMS with an additional 70,873 geodetic volume change observations computed for 6,551 glaciers in Africa, Alaska, the Caucasus, Central Asia, Greenland's periphery, Iceland, New Zealand, the Russian Arctic, Scandinavia, and Svalbard (Extended Data Table 1). This was achieved by calculating geodetic mass changes from ASTER DEMs processed using MMASTER[43] which were co-registered using off-glacier elevations from ICESat as common frame following Nuth and Kääb (2011)[44]. Where available, ArcticDEM 2 m strips, SPOT5-based DEMs from IPY-SPIRIT, or the High Mountain Asia 8 m DEMs[45] were used to increase spatial and temporal coverage, after re-sampling to 30 m resolution to match the resolution of the ASTER DEMs. Pairs of DEMs (e.g., ASTER/ASTER or ASTER/ArcticDEM) were automatically chosen based on at least 40% overlap and a time separation of at least eight years. This time separation together with the selection of DEMs towards the end of the ablation period (Extended Data Table 1) aims at reducing the effect of seasonal variations in the surface elevation and minimizes differences to glaciological survey dates. Based on the selected DEM pairs, glacier elevation changes were computed for various time periods ranging between 2000 and 2018. The local hypsometric method[46] was used to fill voids in the DEMs. For each

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glacier outline with an area of at least 0.6 km^2 from the RGI 6.0, the glacier hypsometry was calculated using 100 m elevation bins. For each DEM pair, the mean elevation difference per elevation bin was calculated, and multiplied by the glacier hypsometry to obtain a volume change. The longest available differences with at least 70% data coverage were then used for each glacier to obtain geodetic mass change. For the peripheral glaciers in Western Greenland, geodetic mass changes were calculated using the Aero DEM[47] from 1985 and a pre-release of the 2010–14 TanDEM-X Global DEM. Before differencing, all DEMs were co-registered to each other[44]. The glacier volume change was estimated using the local hypsometric method[46], using elevations derived from TanDEM-X and the RGI 6.0 outlines. Again, only glaciers with at least 70% data coverage were used. Uncertainties in geodetic mass changes were estimated based on differences between the two DEMs after co-registration following the approach by Brun et al. (2017)[17].

Glacier inventory. The global distribution of glaciers was derived from the RGI[1,48] which is a snapshot glacier inventory derived from the Global Land Ice Measurements from Space (GLIMS) database[49] and a large compilation of national and regional sources compiled by the RGI consortium[1]. We used glacier area and its distribution with elevation (i.e. glacier hypsometry) for the 215,547 glaciers in the RGI 6.0 covering a total area of 705,739 km^2 that mainly refer to survey years between 2000 and 2010. Improvements with respect to earlier RGI versions as used in IPCC AR5[11,24] (168,331 glaciers, 726,258 km^2) include the separation of glacier complexes (e.g., ice fields or ice caps) into individual glaciers, replacement of nominal glaciers (i.e. size-equivalent circles) by real glacier outlines, assignment of glacier-specific survey dates, and the introduction of glacier-specific hypsometries (Extended Data Fig. 1). The latter comes as a list of elevation-band areas (at a resolution of 50 m in height) in the form of integer thousands of the glacier's total area[1]. Note that currently the RGI includes peripheral glaciers surrounding the Greenland Ice Sheet[50] but not the peripheral glaciers on the Antarctic Peninsula[51] and in the McMurdo Dry Valleys[52]. For future versions of the RGI, the inclusion of these peripheral glaciers in Antarctica should be considered to reach global completeness and consistency with the classification of peripheral glaciers in Greenland[50].

Changes in glacier area. For hydrological and sea-level applications, it is the conventional mass balance that is relevant, i.e. the mass change calculated over a constantly changing area and hypsometry of a glacier[15]. While the changes in hypsometry are implicitly captured, the changes in glacier area need to be explicitly accounted for by both the glaciological and the geodetic methods[26]. In contrast to earlier approaches, we considered the impact of changes in glacier area over time on regional mass-change estimates. Therefore, we used a collection of relative area changes from IPCC AR5 (Chapter 4, Fig. 4.10, Table 4.SM.1)[24] extended with additional literature[53–55] to obtain area change rates for all first-order glacier regions.

Glacier volume estimates. Regional estimates for glacier volumes were based on Huss and Farinotti (2012)[2] updated to the glacier outlines of RGI 6.0.

Spatial regionalization. For regional analysis it is convenient to group glaciers by proximity. This was achieved by using the latest version of glacier regions as available from the Global Terrestrial Network for Glaciers[56]. These 19 first-order and more than 90 second-order regions derive ultimately from glacier regions proposed by the GLIMS project around the year 2000 and from studies dealing with global glacier distribution[57,58] and are implemented in both the RGI and in the FoG databases. For mass-balance studies, the 19 first-order regions seem to be appropriate because of their manageable number and their geographical extent, which is close to the spatial correlation distance of glacier mass-balance variability (i.e.

several hundred kilometres)[59,60]. We further divided these regions for areas that are known to feature large diversities in mass-balance gradients and where sufficient data coverage allowed (Extended Data Table 2).

Extraction of temporal variability from the glaciological sample. In a first step, we subdivided the sample of glaciological series into spatial clusters. We started from the smallest possible units (second-order glacier regions) and then extended them until the number and completeness of the time series was acceptable to ensure a proper variance decomposition based on visual and quantitative criteria, such as a common mass-balance temporal variability (i.e., a high correlation between annual mass-balance series) and spatial consistency (i.e., a cluster cannot be geographically too wide). The resulting 20 regional clusters correspond to first- and second-order glacier regions or a combination thereof (Extended Data Table 2). For half of these clusters the available mass-balance series cover the full survey period with only minor data gaps of a few years. For the other half of the clusters, we complemented the glaciological sample with a few long-term series from neighbouring regions that feature a similar mass-balance variability (Extended Data Table 2). For the few clusters without glaciological data before the mid-1970s, we use the mean value of the geodetic sample (i.e. neglecting inter-annual variability) for these years and set the related uncertainty to twice the average value of the first decade with glaciological observations.

Second, the temporal mass-balance variability was extracted for each cluster using a variance decomposition model[61] which is a further development of the approach by Lliboutry (1974)[30] based on Bayesian techniques[62,63] and applied to a regional sample of glacier-wide mass balances instead of to a series of point measurements. For this model, we defined the specific mass change for a given glacier i and year t as

$$B_{\mathrm{glac},i,t} = \alpha_0 + \alpha_i + g(t) + z(t) + \varepsilon_{i,t}, \qquad (3)$$

where α_0 is the cluster's annual average and α_i is the glacier-specific site deviation of the (specific) mass change from the cluster's average. The variables $g(t)$ and $z(t)$ are the long-term trend and annual fluctuations, respectively, of the time deviation from the average, and $\varepsilon_{i,t}$ are residuals. The variable $g(t)$ was taken as a smooth non-parametric trend and $z(t)$ as a white noise term. Their sum is the annual deviation of the glaciological sample from the average α_0, which is further used in the analysis:

$$B_{\mathrm{glac,cluster}} = g(t) + z(t) \qquad (4)$$

Model inference was performed using Bayesian simulation techniques giving access, for any parameter or combination of parameters, to a point estimate and to a credibility interval quantifying the related uncertainty. This especially applies to cumulated temporal deviations $\sum_{t=t1}^{t2}(g(t)+z(t))$ over any time interval $[t_1,t_2]$ such as the full period from 1961 to 2016 (Extended Data Fig. 6)

Calibration to mass-change values from the geodetic sample. For each cluster (Extended Data Table 2), the temporal mass-balance variability as derived from the glaciological sample $B_{\mathrm{glac,cluster}}$ was calibrated to the values from the geodetic methods[26]. Due to the differences in the length of the geodetic survey periods, the calibration was carried out individually for all glaciers with available geodetic balances. If more than one geodetic survey was available per glacier, those with the longest survey periods were combined by arithmetic averaging of annual change rates. For each glacier i, we calculated the mean annual deviation $\overline{\beta_t}$ between the glaciological balance of the cluster $B_{\text{glac.cluster}}$ and the glacier-specific geodetic balance $B_{\text{geod},i}$ over a common time period of N years between t_0 and t_1:

$$\overline{\beta_t} = \frac{B_{\text{geod},i} - \sum_{t_0}^{t_1} B_{\text{glac,cluster}}}{N}. \tag{5}$$

The annual calibrated specific mass change for every glacier i and year t was then calculated as:

$$\Delta M_{\text{cal},i,t} = B_{\text{glac,cluster},t} + \overline{\beta_t}. \tag{6}$$

As a result, for each glacier with available geodetic data we obtained a calibrated specific mass-change series that features the temporal variability of the glaciological cluster but is adjusted to the glacier-specific geodetic value (Extended Data Fig. 7).

Calculation of regional mass changes and contributions to sea-level. To estimate the total mass change, the results from the sample with available (geodetic) data need to be scaled to all glaciers of a region (from RGI 6.0). We followed three different approaches to calculate the regional specific mass change ΔM_{region} (in the unit m w.e. yr^{-1}): arithmetic averaging $\Delta M_{\text{region,AVG}}$, area-weighting $\Delta M_{\text{region,AW}}$, and spatial interpolation $\Delta M_{\text{region,INT}}$. For the approaches $\Delta M_{\text{region,AVG}}$ and $\Delta M_{\text{region,AW}}$, the arithmetic and glacier area-weighted average, respectively, of the annual specific mass change of the observational sample was assigned to all unobserved glaciers in the region. For our reference approach $\Delta M_{\text{region,INT}}$, the individual specific mass-changes were spatially interpolated to all glacier locations in the region using an inverse distance weighting function. For all approaches, we calculated the regional mass change ΔM_{region} (in unit Gt yr^{-1}) as the product of the specific mass change multiplied with the regional glacier area from RGI 6.0 and applying the relative area change rates of the corresponding region. Global mass changes ΔM_{global} were calculated as the sum of all regional mass changes. For conversion to sea-level equivalent, a total area of the ocean of 362.5 x 10^6 km^2 was assumed[64].

Uncertainty estimates. The random error of the regional mass change σ_{regional} is composed of the errors related to (i) the temporal changes in the regional glaciological sample σ_{glac}, (ii) the geodetic values of the individual glaciers σ_{geod}, (iii) the extrapolation from the observational to the full sample $\sigma_{\text{extrapolation}}$, (iv) the glacierised area σ_{area} of the region, and (v) a second-order crossed term related to the calculation of the regional mass change (as the product of specific mass change multiplied by the glacierised area):

$$\sigma_{\text{regional}} = \sqrt{{\sigma_{\text{glac}}}^2 + {\sigma_{\text{geod}}}^2 + {\sigma_{\text{extrapolation}}}^2 + {\sigma_{\text{area}}}^2 + {\sigma_{\text{crossed}}}^2}. \tag{7}$$

The variable σ_{glac} can be rigorously estimated from the variance decomposition (Extended Data Fig. 6). However, we used a less computationally intensive approach to estimate it for any sub-period (pentad, decade) from the full study period. Specifically, the annual standard deviations of the temporal deviation ($g(t) + z(t)$) as obtained from the variance decomposition model were summed up according to the law of random error propagation. Hence, the standard deviation of any sub-period was evaluated as if annual deviations would be independent. The variable σ_{glac} implicitly accounts for errors related to differences in the glaciological survey period since the sample contains results from various time systems (e.g., fixed-date, floating-date, stratigraphic)[15].

The variable σ_{geod} is the uncertainty from the geodetic method. We calculated the annual values as rates, i.e. dividing the reported (multi-year) uncertainties by the number of years between the two surveys. It includes the observation uncertainty $\sigma_{\mathrm{geod.observation}}$ as reported with the geodetic results. In addition, we considered the uncertainty introduced by calibrating annual mass-balance variability with geodetic values $\sigma_{\mathrm{calibration}}$ (Eq. 6), which was inferred for each glacier individually based on randomly superimposing σ_{glac} and extracting the standard deviation of average balances over the reference period. The uncertainties related to density conversion factor $\sigma_{\mathrm{density}}$ were set to ± 60 kg m^{-3} based on Huss (2013)[28]. The overall geodetic uncertainty was calculated from these terms, assuming them to be uncorrelated, and was divided by the square root of the number of independent items n of information in the sample:

$$\sigma_{\mathrm{geod}} = \sqrt{\frac{\sigma_{\mathrm{geod.observation}}{}^2+\sigma_{\mathrm{calibration}}{}^2+\sigma_{\mathrm{density}}{}^2}{n}}. \tag{8}$$

In the ideal case, n would be equal to the number of geodetic series in the regional sample. For space-borne surveys, however, the geodetic uncertainty is usually derived from the stable terrain in between a group of glaciers. We thus assumed geodetic uncertainties uncorrelated for samples larger than 50 glaciers and estimated n by dividing the regional geodetic sample size by 50. Note that for the geodetic sample, we do not explicitly formulate uncertainties related to differences in the survey date. For individual glaciers, a corresponding rigorous estimate would be possible using seasonal mass-balance information, meteorological data, and numerical modelling[7,26,33]. These studies show that the corresponding uncertainties can be relevant for individual years but tend towards zero for longer period of records and larger samples.

To estimate $\sigma_{\mathrm{extrapolation}}$, we used the regional mass change from spatial interpolation ($\Delta M_{\mathrm{regoin,INT}}$) as best guess and calculated the extrapolation uncertainty as 1.96 standard deviations of the results from the three approaches ($\Delta M_{\mathrm{region,INT}}$, $\Delta M_{\mathrm{region,AVG}}$, $\Delta M_{\mathrm{region,AW}}$). As for σ_{glac}, $\sigma_{\mathrm{extrapolation}}$ was evaluated over any sub-period by the square root of the number of survey years assuming that annual values are uncorrelated.

For the regional glacier area, we assumed a general uncertainty of ± 5% for the total area derived from the RGI 6.0 based on an earlier single-glacier and basin-scale uncertainty estimates[48] and in line with the latest GCOS product requirements (Table 25, Terrestrial ECV product requirements)[65]. This was combined with an error related to the regional area changes $\sigma_{\mathrm{area.change}}$, which was estimated as 1.96 standard deviations of different ways to calculate regional change rates. For a given region, the first approach, used as reference, weights multiple published change rates by the total ice cover of the corresponding glacier samples. The second approach weights multiple results by the length of the survey periods. The uncertainties related to the total area and to area changes were assumed to be uncorrelated and, hence, cumulated according the law of random error propagation.

Over multi-year periods, contrary to σ_{glac}, $\sigma_{\mathrm{extrapolation}}$, and $\sigma_{\mathrm{crossed}}$, the error related to the geodetic values and glacier areas (σ_{geod} and σ_{area}) cumulate linearly. Consequently, the individual terms need to be cumulated separately followed by a combination of the multi-year terms according to the law of random error propagation (cf. Equation 7). For global sums, the overall error was calculated by cumulating the regional errors according to the law of random error propagation.

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Code availability. The analytical scripts are available from the authors on request.

Data availability. The temporal variabilities for the glaciological clusters as well as the regional and global mass change results have been deposited in the zenodo repository (http://doi.org/10.5281/zenodo.1492141). The full sample of glaciological and geodetic observations for individual glaciers are publicly available from the WGMS (http://doi.org/10.5904/wgms-fog-2018-11).

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Extended Data Tables

Region	DEMs used	SP	N	SDdoy	RDdoy	Glaciers	Observations
Alaska	ASTER, ArcticDEM, IPY-Spirit	2000–17	11 ± 2	159 ± 49	168 ± 44	122	485
Greenland	TanDEM-X, AeroDEM	1985–12	27 ± 2	183 ± 183	200 ± 15	1,202	1,202
Iceland	ASTER, ArcticDEM, IPY-Spirit	2000–17	10 ± 2	209 ± 67	160 ± 81	254	2,463
Svalbard	ASTER, ArcticDEM, IPY-Spirit	2000–17	12 ± 2	191 ± 45	181 ± 34	1,072	8,334
Scandinavia	ASTER, ArcticDEM	2000–17	11 ± 2	221 ± 49	178 ± 73	1,036	11,925
Russian Arctic	ASTER, ArcticDEM, IPY-Spirit	2000–17	11 ± 2	176 ± 46	178 ± 32	372	3,679
Caucasus	ASTER	2000–17	11 ± 2	217 ± 32	201 ± 82	360	3,576
Africa	ASTER	2000–17	11 ± 2	184 ± 92	95 ± 70	11	182
Central Asia	ASTER, HMA DEMs	2000–17	11 ± 2	253 ± 24	227 ± 38	1,683	7,174
New Zealand	ASTER	2000–18	12 ± 2	104 ± 70	135 ± 125	439	31,853
Total						6,551	70,873

Extended Data Table 1 | Overview on new geodetic volume changes

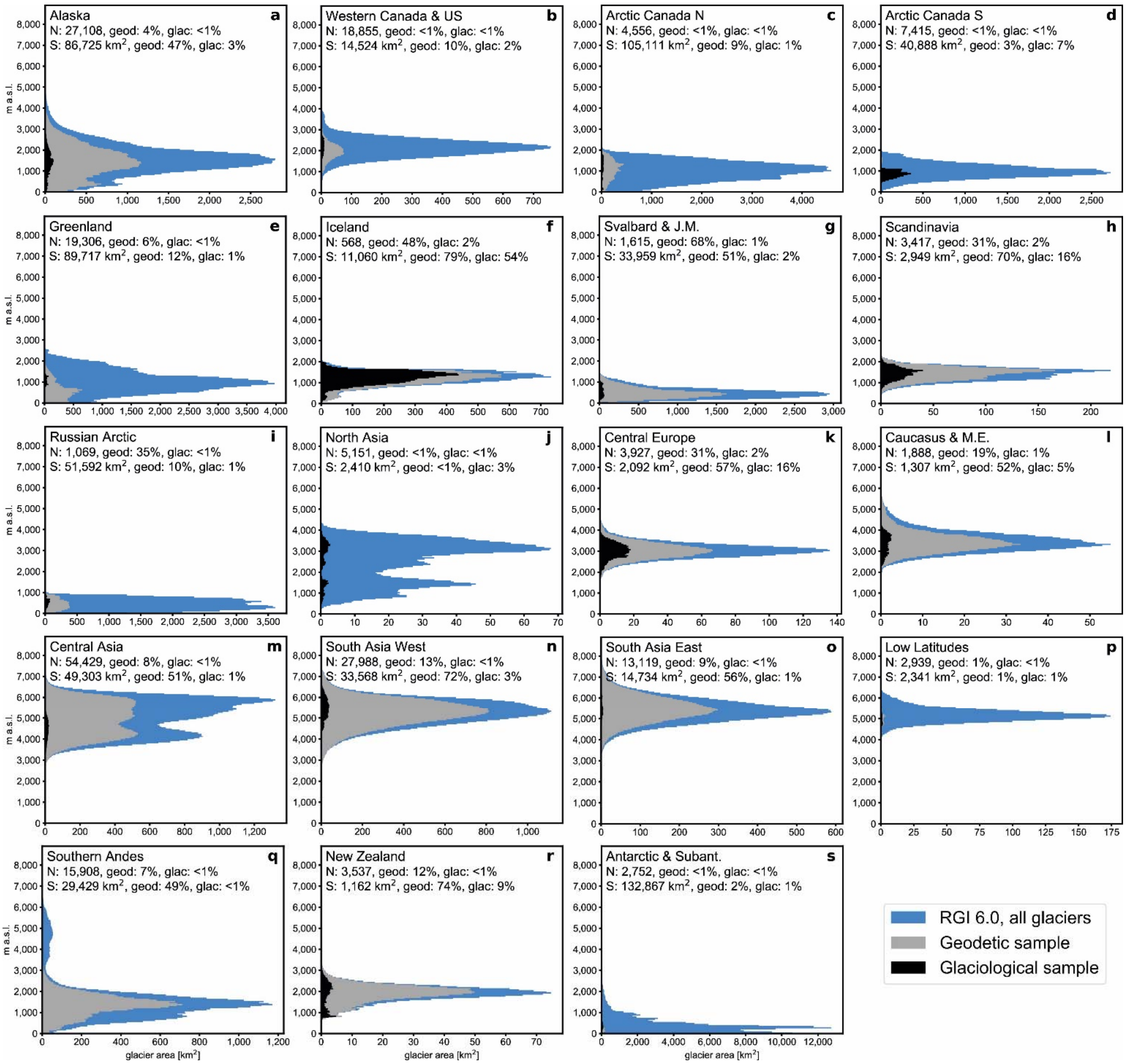
For each first-order region[56] with new geodetic surveys, the number of glaciers and observations are given together with DEMs used, the range of survey periods (SP), the average length of the survey period (N) as well as the day of the year (doy) of the average survey date (SD) and of the average reference date (RD). The averages of N, SDdoy, and RDdoy are given together with the corresponding standard deviations. The TanDEM-X as used for Greenland is a merged product from surveys between 2010 and 2014 from any month of the year.

Cluster	1^{st} and 2^{nd} order regions	N	Complementary mass-balance series
C01: Alaska & British Columbia	ALA, WNA-02	19	none
C02: Western Canada	WNA-01, WNA-03	3	South Cascade (WNA-05), Lemon Creek (ALA-06)
C03: Western USA	WNA-04, WNA-05	24	none
C04: Canadian Arctic	ACN, ACS	10	none
C05: Greenland	GRL	8	Storglaciären (SCA-01), Storbreen (SCA-03), White (ACN-02)
C06: Iceland	ISL	14	Storglaciären (SCA-01), Storbreen (SCA-03)
C07: Svalbard & Russian Arctic	SJM, RUA	17	none
C08: Scandinavia North	SCA-01	17	none
C09: Scandinavia South-West	SCA-02	17	none
C10: Scandinavia South-East	SCA-03	6	none
C11: Northern Asia	ASN-01-03,-05-06	10	Maliy Aktru, Leviy Aktru, Vodopadniy (ASN-04), Urumqi No 1 (ASC-04)
C12: Russian Altay	ASN-04	4	Urumqi No 1 (ASC-04)
C13: Central Europe	CEU	59	none
C14: Caucasus	CAU	11	none
C15: Central Asia South-West	ASW, ASC-01-03,-05	25	Urumqi No. 1 (ASC-04)
C16: Central Asia South-East	ASE, ASC-04,-06-09	22	Ts. Tuyuksu (ASC-03)
C17: Low Latitudes	TRP-01	11	Lewis (TRP-03)
C18: Southern Andes	SAN	12	none
C19: New Zealand	NZL	6	Lewis (TRP-03), Echaurren Norte (SAN-02), Piloto Este (SAN-02)
C20: Antarctic & Subantarctic	ANT	10	Echaurren Norte (SAN-02), Piloto Este (SAN-02)

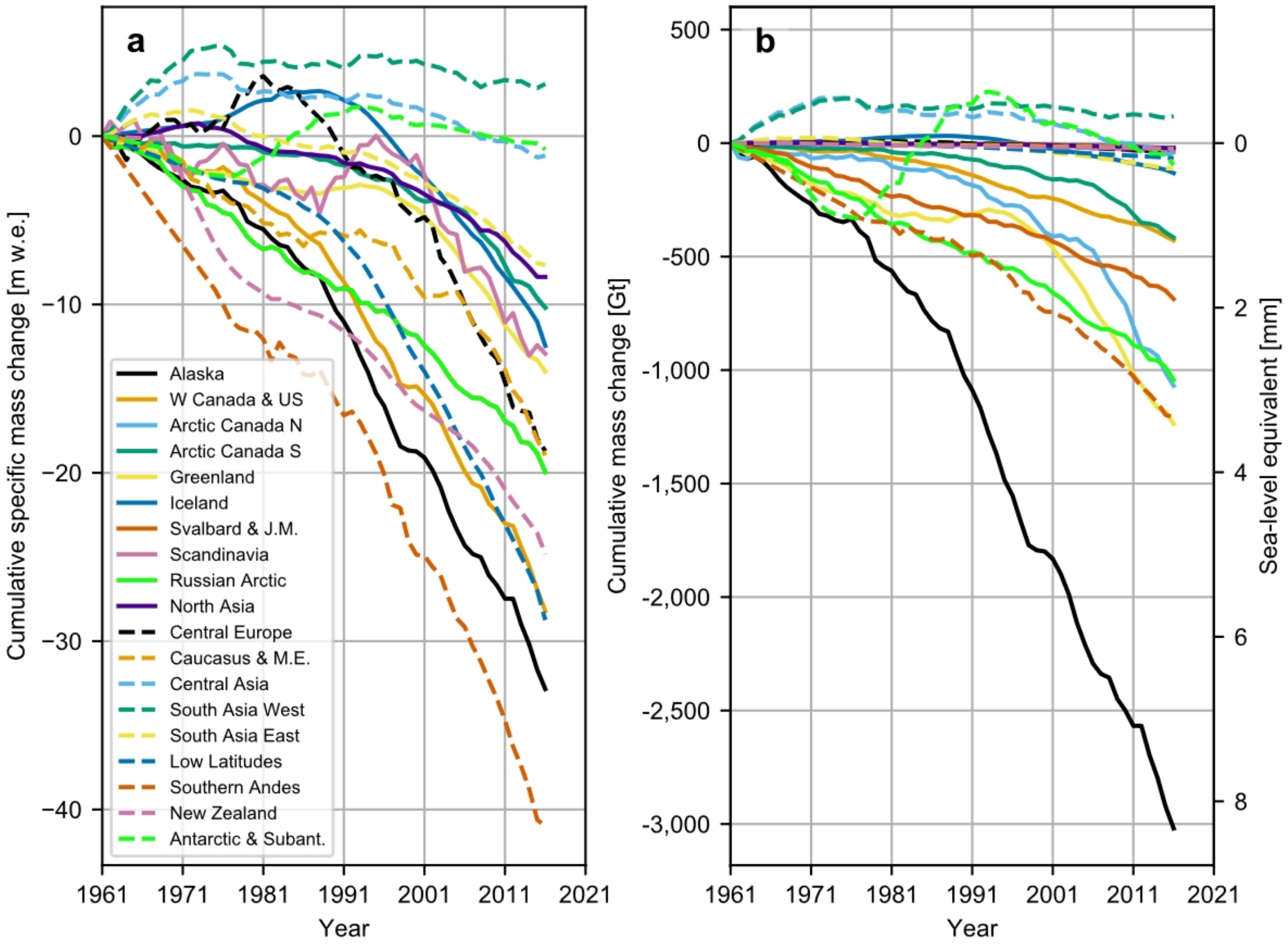
Extended Data Table 2 | Spatial clusters used for analysis of the temporal variability from glaciological samples

Spatial clusters and corresponding 1^{st} and 2^{nd} order regions[56] as used for extracting the temporal variability of the glaciological sample. N indicates the number of available glaciological time series per cluster. We complemented clusters with limited time coverage with long-term mass-balance series from neighbouring regions. For regions codes, see Table 1.

Extended Data Figures



Extended Data Fig. 1 | Regional glacier hypsometry and observational coverage. a–s, For each of the 19 first-order regions, glacier hypsometry from the RGI 6.0 (blue) is overlaid by glacier hypsometry of both the geodetic (grey) and the glaciological (black) samples used in the present study. Values of the total number (N) and total area (S) of glaciers are given for each region together with the relative coverage of both the glaciological and the geodetic samples. Plots are ordered according to the region numbers in RGI 6.0 (see Table 1).



Extended Data Fig. 2 | Cumulative regional glacier changes since the 1960s. a–**b**, Cumulative mass changes in m w.e. (**a**) and in Gt (**b**) are shown for the 19 regions. Specific mass changes (**a**) indicate the observed glacier thickness changes. Total glacier mass changes (**b**, left y-axis) correspond to the regional contributions to global mean sea-level rise (**b**, right y-axis). Reading example: Cumulative specific mass changes were most negative in the Southern Andes with an average regional glacier thickness change of approximately −40 m w.e. (a) resulting in a cumulative mass change of −1,200 Gt (**b**). Glaciers in Alaska experience less negative specific mass changes (**a**) but contribute much more to global sea-level rise (**b**) because of the larger regional glacier area.

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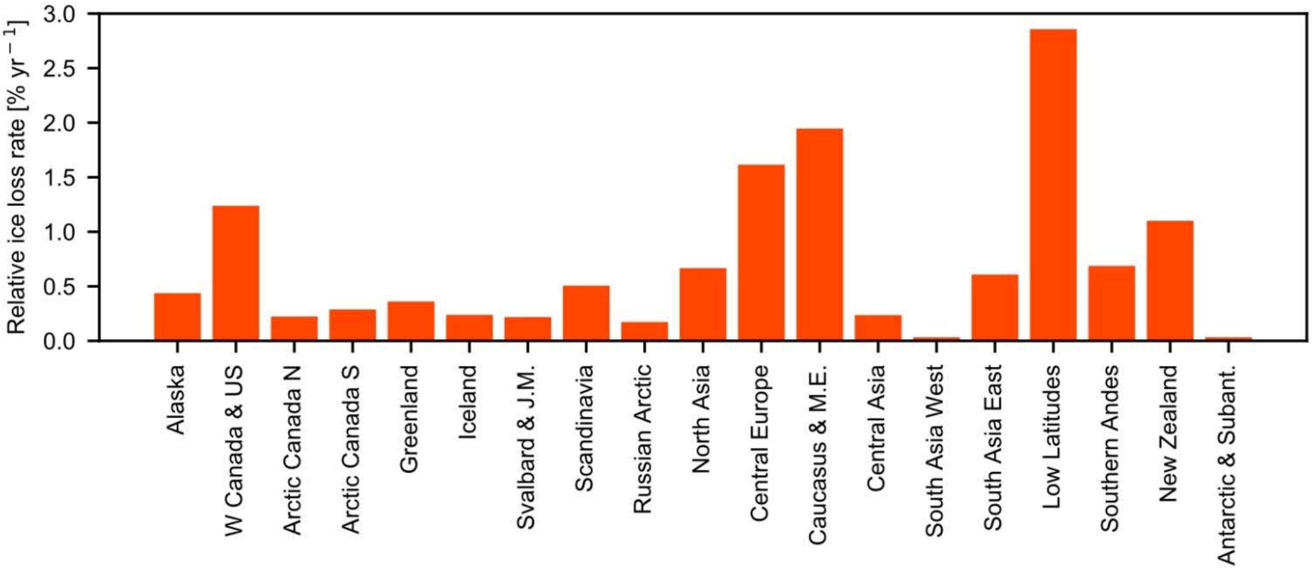
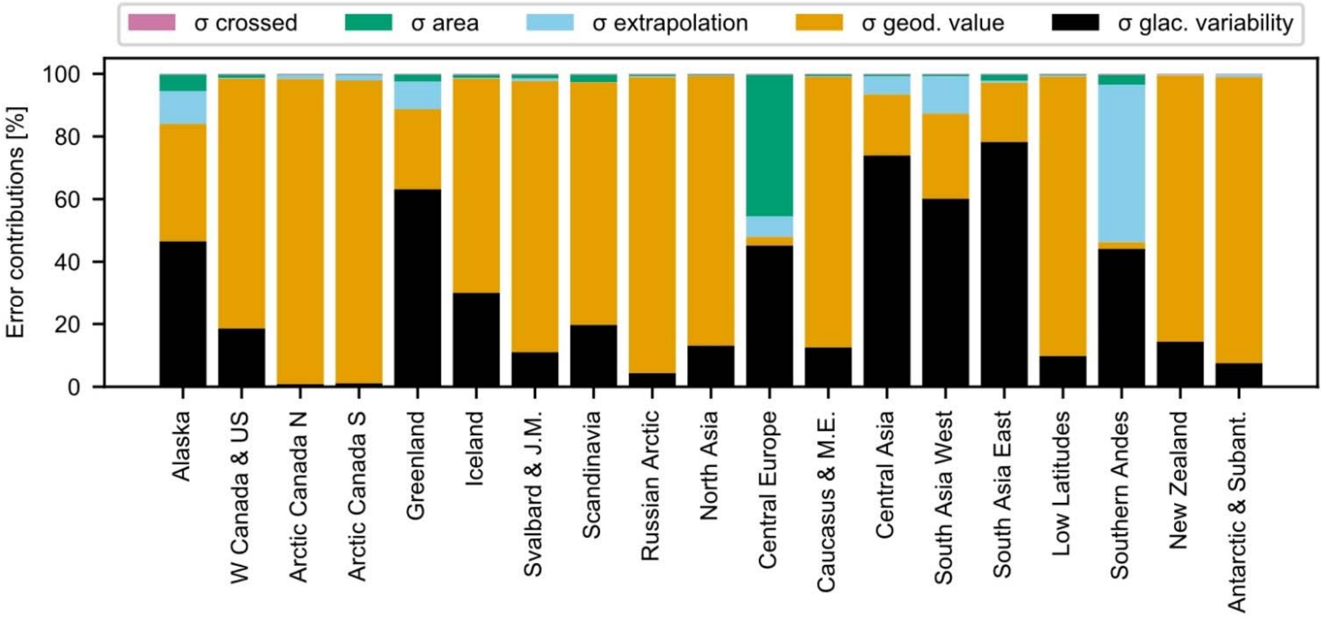


Extended Data Fig. 3 | Relative annual ice loss for the period from 2006 to 2016. Annual mass change rates (see Fig. 3b) relative to estimated total ice volumes[2] are plotted as vertical bars (% yr^{-1}).



Extended Data Fig. 4 | Relative error contributions for the period 2006–2016. Relative contributions (%) of the different sources to the overall regional error bars as shown in Fig. 3b. Reading example for Alaska: The overall error estimate is dominated by the glaciological and the geodetic errors with contributions of 47% and 37%, respectively, whereas the errors for extrapolation (10%), glacier area (5%), and second-order crossed uncertainties (<1%) are of less importance. A special case is Central Europe: the large number of high-quality observations from air-borne surveys comes with reported geodetic uncertainties that are one order of magnitude smaller than the space-borne estimates in other regions. As a result, the overall error bars are much smaller (Fig. 3) and the relative contributions from other error sources become larger. In the Southern Andes, the relative contribution of the geodetic error is reduced by the large sample size while glaciological and interpolation errors feature large absolute values.

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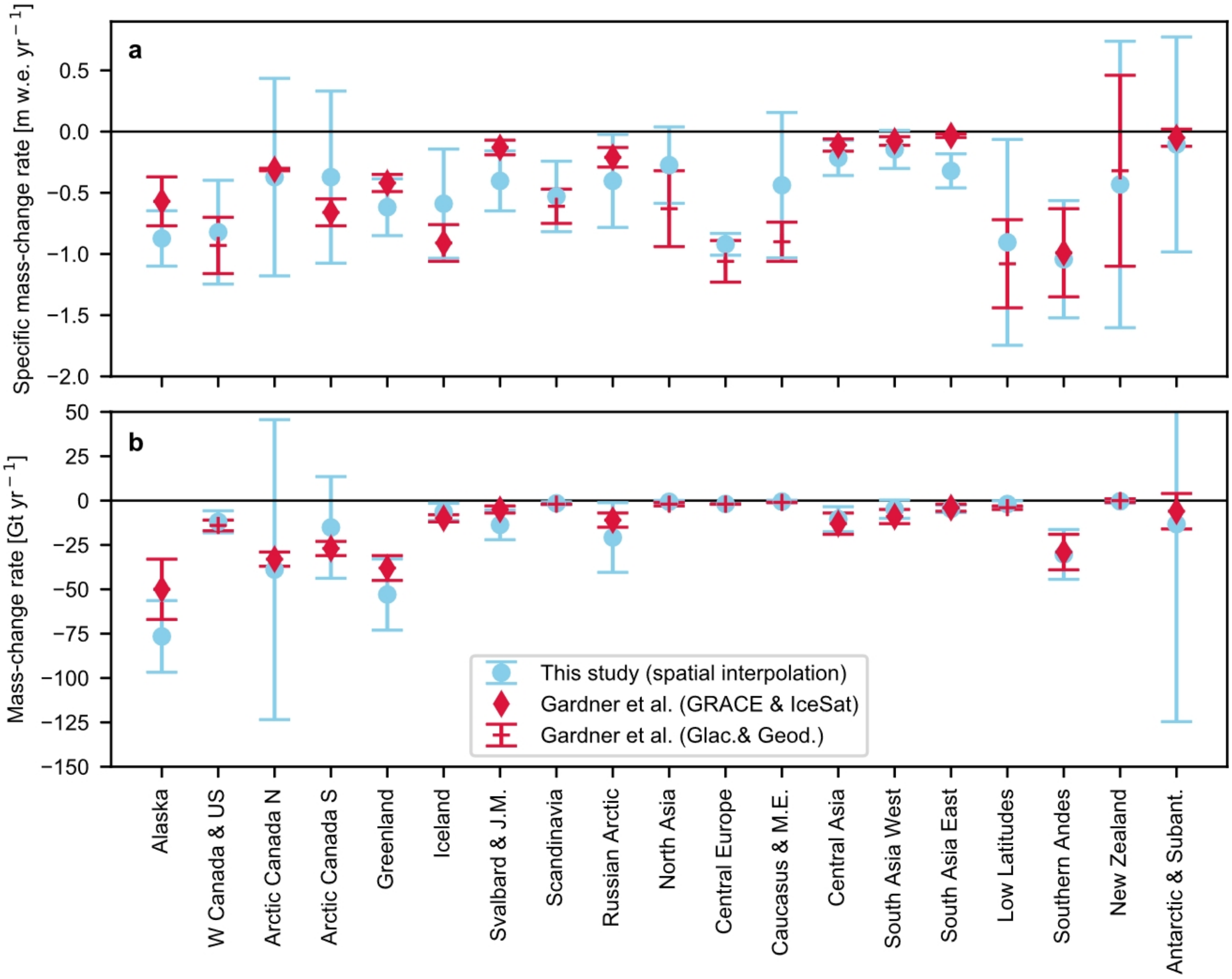
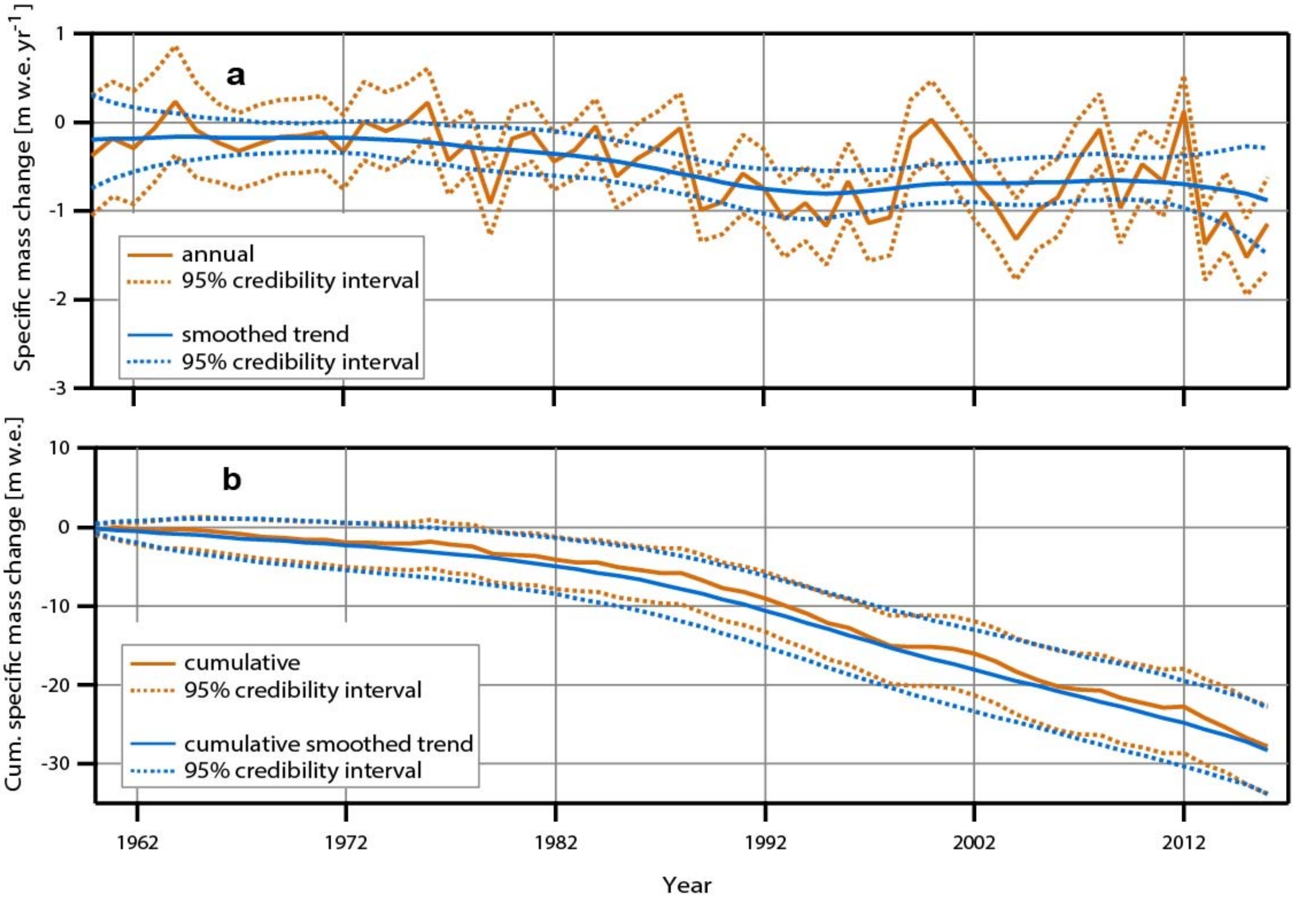


Extended Data Fig. 5 | Comparison of regional mass changes to results from IPCC AR5. a–**b**, Annual specific mass-change rates in m w.e. yr^{-1} (**a**) and in Gt yr^{-1} (**b**) as shown in Fig. 3 but for the period 2003−2009. The estimates and related error bars (corresponding to 95% CIs) for this study are shown in blue. The results from IPCC AR5[11,24] are shown in red differentiating between those based on glaciological and geodetic observations (crosses) and those based on ICESat and/or GRACE (diamonds). Global mass change rates are −260 ± 28 Gt per year and −307 ± 148 Gt per year as estimated by IPCC AR5[11,24] and this study, respectively



Extended Data Fig. 6 | Temporal variability of the glaciological mass balance for Alaska & British Columbia 1961-2016. a–b, Annual (**a**, m w.e. yr^{-1}) and cumulative (**b**, m w.e.) values for the cluster's smooth trend ($g(t)$, blue lines) and annual deviations ($g(t)$+$z(t)$, orange lines) as reconstructed from the variance decomposition (see Methods, Eqs. 3 and 4) based on glaciological measurements from 19 glaciers (Extended Data Table 2, Cluster 01).

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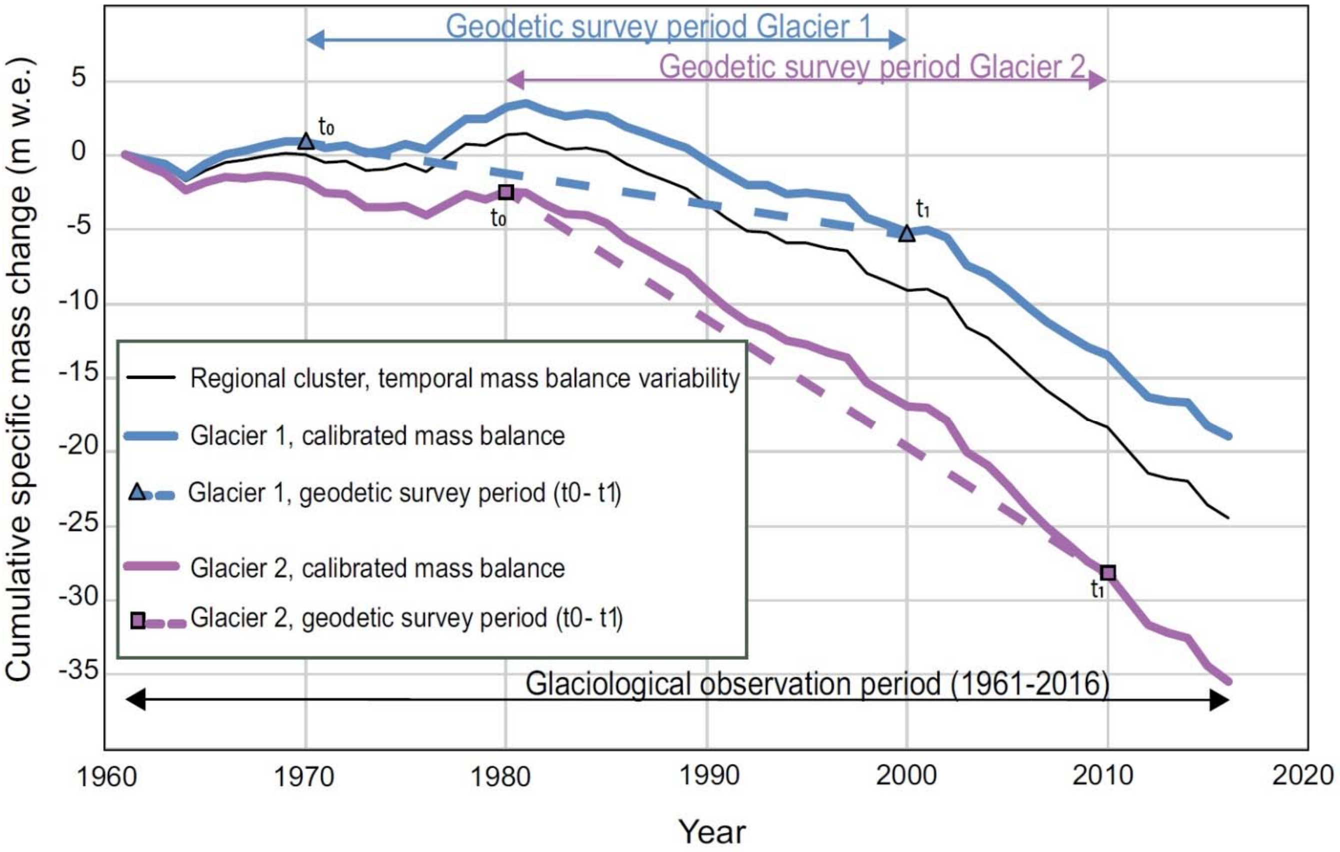

Extended Data Fig. 7 | Calibration of temporal variability from glaciological sample to geodetic values of individual glaciers. Schematic representation of the approach to calibrate the cumulative temporal variability (black line, m w.e.), as derived from the variance decomposition (see Extended Data Fig. 6), to geodetic values of individual glaciers (blue and purple lines, m w.e.). For Glacier 1 and Glacier 2, the mean annual deviations between the glaciological balance of the cluster and the glacier-individual geodetic balances were 0.1 and −0.2 m w.e. per year, respectively, over corresponding survey periods between t_0 and t_1 (see Methods, Eq. 5).