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Title:

A Consensus Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009

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One Sentence Summary:
Large differences in previous estimates of recent glacier mass change are reconciled and gaps in knowledge of glacier changes in High Mountain Asia, Antarctica and Greenland are filled using multiple satellites (GRACE and ICESat) and in-situ observations.

Glaciers distinct from the ice sheets are losing large amounts of water to the world's ocean. However, estimates of their contribution to sea-level rise disagree. We provide a consensus estimate by standardizing existing, and creating new, mass-budget estimates from satellite gravimetry and altimetry and from local glaciological records. In many regions, local measurements are more negative than satellite-based estimates. Glaciers around the Greenland Ice Sheet are losing mass rapidly while those in Antarctica are contributing little to sea-level rise. All regions have lost mass during 2003–2009, with the largest losses from Arctic Canada, Alaska, coastal Greenland, the southern Andes and High-Mountain Asia. Over this period the global mass budget was -259±28 Gt yr^{-1}, equivalent to the combined loss from both ice sheets and accounting for 29±13% of the observed sea-level rise.

Global estimates of glacier mass changes have traditionally been based on extrapolation of local geodetic and glaciological measurements. These records indicate increasing mass loss in recent decades (*1-3*). However, a recent study (*4*) using Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry from 2003 to 2010 suggests that global glacier mass wastage is much less than previously thought (*1, 5*). To investigate this discrepancy, we recalculated existing results from glaciological extrapolation and the Gravity Recovery and Climate Experiment (GRACE) to a common spatial and temporal reference that we compare with independent altimetric estimates from the Ice, Cloud, and land Elevation Satellite (ICESat). We provide new estimates of regional mass budgets for glaciers peripheral to the Greenland and Antarctic Ice Sheets and for the glaciers of High Mountain Asia based on elevation changes from ICESat.

For regional glacier analyses we rely on the Randolph Glacier Inventory (RGIv3 (*6*)), a globally complete digital database of glacier coverage. It defines 19 glacier regions that contain a total glacierized area of ~729,400 km^2 (circa 2000: Fig. 1 and Table 1). Deriving regional and global mass budgets from glaciological and local geodetic measurements is complicated because the set of measured glaciers is sparse for many regions and can be biased towards smaller land-terminating glaciers (*7*). Monitoring of glacier mass change on a global scale using satellite gravimetry or altimetry has only become possible with the launch of the GRACE and ICESat satellites in early 2002 and 2003, respectively. The ICESat mission ended in October 2009, giving a 6-year overlap with GRACE from October 2003 to October 2009 during which we are able to compare results from all three methods. Unless otherwise stated, all the mass budgets on which we rely (*8-10*) have been updated to cover this common time span over the RGI regions, with no changes to the original methods. All reported estimates are accompanied by 95% confidence intervals.

We recalculate recent GRACE glacier mass change estimates (*4, 11*) with updated mascons (Table S1). We also make alternative GRACE estimates of glacier mass changes by expanding the methods of Wouters et al. (*12*), which were originally developed to retrieve mass changes for the Greenland Ice Sheet and Arctic glaciers (*12-14*), to all glacierized regions (Table S2). Both analyses use monthly time-variable GRACE gravity field solutions produced by the University of Texas Center for Space Research: the Wouters et al. approach uses product Release 5 and the updated Jacob et al. estimates (*4*) use product Release 4. The two analyses give a total mass budget for all glaciers outside Greenland and Antarctica of -170 ± 32 Gt yr^{-1} and -166 ± 37 Gt yr^{-1}, respectively. The two GRACE estimates also agree well on a regional scale (*11*) so for the remaining analysis we average them and refer to the combined result as JW12. The averaged gravimetric estimate is half as negative as a more conventional estimate (*2*) based on spatial interpolation of glaciological and local geodetic measurements (hereafter referred to as glaciological records). This method yields a mass budget of –329 ± 121 Gt yr^{-1} (we refer to these results as C09). If we include glaciers peripheral to the Greenland and Antarctic Ice Sheets, C09 gives a total estimate for all glaciers of -491 ± 200 Gt yr^{-1} which is comparable to an earlier estimate (–402 ± 95 Gt yr^{-1}) of glacier mass loss for 2006 also determined from extrapolation of local glaciological records (*1*). In the following, we address the large discrepancies between gravimetric and glaciological estimates region-by-region and compare them with estimates from ICESat laser altimetry where available.

Peripheral glaciers in Antarctica (*15*) and Greenland (*16*) account for about 30% of the global glacier area, but until recently there have been no published region-wide estimates for our study period. We present an analysis of elevation changes along ICESat near-repeat tracks using a plane-fitting technique that accounts for the local surface slope (*8*). We use surface elevations from the GLA12 and GLA06 altimetry products Release 533, with standard saturation correction applied and no correction for potential inter-campaign biases (*11*). In Antarctica we correct elevation changes for variations due to change in the firn density using a firn pack model with a horizontal grid resolution of ~27 km (*17, 18*). We attribute residual volume changes after these firn corrections to changes in glacier ice and convert them to mass changes using a density of 900 ± 17 kg m^{-3}. The Antarctic peripheral glaciers (133,200 km^2) have not changed much in total mass (-6 ± 10 Gt yr^{-1}), which is in contrast to earlier modeling estimates for 1961-2004 (*19*). There are, however, sub-regional examples of both loss (Antarctic Peninsula Islands, -7 ± 4 Gt yr^{-1}) and gain (Ellsworth Land Islands, 3 ± 4 Gt yr^{-2}). For Greenland we lack firn pack model simulations and instead rely on estimates of the firn area and the bulk density of the firn volume change (*11*). We estimate a total mass budget of -38 ± 7 Gt yr^{-1} for the Greenland peripheral glaciers (89,700 km^2). All sub-regions experienced significant thinning [Fig. 2, (*11*)] except for the Flade Isblink Ice Cap, Greenland's largest ice cap (*20*). Our estimate is consistent with a recently published estimate of -28 ± 11 Gt yr^{-1} for the period 2003-2008 that was determined from ICESat data using methods comparable to ours but assuming a larger firn area and lower bulk density for the firn volume change (*21*). We do not include this estimate in our analysis as it does not cover the full 2003-2009 period. ICESat-based estimates are less negative than

C09 in both Greenland and Antarctica (Fig. 3), but only significantly different in Antarctica, where the C09 estimate is 100 Gt yr^{-1} more negative. The cause of the disagreement is discussed following our assessment of regional mass changes.

Outside of Greenland and Antarctica, there are four high latitude regions with published glacier mass budgets from ICESat (2003-2009) that we can compare with the C09 and JW12 estimates: Arctic Canada North (*13*) (-37 ± 7 Gt yr^{-1}); Arctic Canada South (*13*) (-24 ± 6 Gt yr^{-1}); Svalbard(*8*) (-5 ± 1 Gt yr^{-1}); and the Russian Arctic (*14*) (–10 ± 4 Gt yr^{-1}). Summing mass budgets for these 4 regions gives an ICESat estimate of -75 ± 10 Gt yr^{-1}, a JW12 estimate of -78 ± 12 Gt yr^{--1} and a C09 estimate of -116 ± 52 Gt yr^{-1}. Regional errors are considered uncorrelated for ICESat and JW12, but fully correlated for C09. ICESat and GRACE agree well in all regions, whereas C09 is considerably more negative although error bounds usually overlap [Fig. 3, (*11*)].

The two remaining large (>5000 km^2) high-latitude regions, Alaska and Iceland, have no published mass budgets from ICESat. Alaska mass-budget estimates from C09 and JW12 are -72 ± 22 Gt yr^{-1} and -42 ± 11 Gt yr^{-1}, and two other GRACE estimates give mass budgets of -54 ± 26 Gt yr^{-}1 and -61 ± 22 Gt yr^{-1} (*9, 10*). Although estimates have overlapping error bounds, there is still considerable spread in the mean values. For Iceland, the C09 and JW12 estimates of glacier mass change of -9 ± 2 Gt yr^{-1} and -11 ± 3 Gt yr^{-1} agree well.

The largest glacierized region outside the Arctic and Antarctic is High Mountain Asia (HMA). Glacier changes in this region are spatially heterogeneous and not well known (*22*). Himalayan and Hindu Kush glaciers have recently been found to be losing mass (*23*) while the glaciers in the Karakoram are in near balance (*24*). For complete comparison with JW12 and C09, we analyze ICESat altimetry for the entire HMA using two approaches: a modification of the method of Moholdt and others (*8*); and methods similar to those of Kääb and others (*23*) , whose analysis was restricted to about half of the glacierized area in HMA (*11*). Both approaches use an elevation model from the Shuttle Radar Topography Mission to correct for topographic differences between ICESat points. The results confirm a heterogeneous pattern of elevation change (Fig. 4, (*11*)) with most rapid thinning (< -0.4 m yr^{-1}) in the south (Himalaya) and north (Tien Shan), moderate rates of thinning (~-0.3 m yr^{-1}) in Eastern and Southern Tibet, and near balance (-0.12 to +0.16 m yr^{-1}) in the western and central portions of the region (Pamir, Karakoram, and Western Kunlun). We convert volume changes to mass changes using a density of 900 kg m^{-3} and sum the sub-regional estimates (Table S5) to obtain a total HMA mass budget of –29 ± 13 Gt yr^{-1}. This estimate shows significant mass loss and is within the error bounds of JW12 (-19 ± 20 Gt yr^{-1}). Both satellite-based estimates are significantly less negative than C09 (-86 ± 26 Gt yr^{-1}).

The two remaining large (>5000 km^2) glacierized regions are the southern Andes (including Patagonia) and Western Canada / United States. For the southern Andes the mass budget estimates of JW12 (-29 ± 10 Gt yr^{-1}) and C09 (-23 ± 12 Gt yr^{-1}) agree relatively well, with another GRACE estimate (-21 ± 11 Gt yr^{-1}: 2003 - 2009)(*25*) and with estimates for a longer time period from analysis of multi-temporal digital elevation models for the three major icefields in the region (-28 ± 3 Gt yr^{-1}: 2000 - 2011/12)(*26-28*). The comparison is more troublesome in Western Canada / US where C09 gives a net loss of -14 ± 3 Gt yr^{-1} and JW12 gives a net gain of +7 ± 10 Gt yr^{-1}. The only previous estimate (*29*) of glacier mass change for this region, based on differencing of digital elevation models, yielded mass loss at -8 ± 4 Gt yr^{-1} during 1985-2000 (excluding those sub-regions that are part of the Alaska region as defined by RGI). The C09 estimate for the same period (-9 ± 2 Gt yr^{-1}) agrees well with Schiefer and others (*29*) and glaciological records indicate that the most recent decade has seen accelerated glacier loss. This suggests that C09 performs satisfactorily in this region and that JW12 may not adequately separate the glacier mass signal from other mass changes in the region.

The remaining six small regions (glacier area <5000 km^2 each) contain only 2% of Earth's glaciers by area (Table 1). The JW12 gravimetric estimates of glacier mass change for these regions have larger uncertainties than the glaciological estimates (Fig. 3), and there are no concurrent regional-scale measurements of elevation changes since ICESat track coverage is insufficient for reliable estimation. These sparsely glacierized regions all have a relatively high density of glaciological records (Table S3), and we therefore expect C09 to perform satisfactorily here. Summing all six regions gives a C09 estimate of -12 ± 4 Gt yr^{-1} and a JW12 estimate of +4 ± 16 Gt yr^{-1}.

Our assessment shows that ICESat and GRACE estimates of mass change for large glacierized regions agree well, and that estimates derived from the interpolation of glaciological records can be substantially more negative (Fig. 3). This suggests that the database of glaciological records is negatively biased. To investigate this bias we extract subsamples of ICESat elevation change data within 100 km of the C09 glaciological measurements in the five regions where both data sets are available. These ICESat subsamples reveal that the neighborhoods of the glaciological measurements are typically thinning more rapidly than the regional mean (Fig. 5). 41 of the 49 glacier neighborhoods had rates of thinning higher than their respective regional averages (Fig. S9). Across the five regions, which account for 75% of the global glacierized area, the area-weighted difference between the regional mean and the elevation changes in the C09 neighborhoods, is -0.43 m yr^{-1}, which would translate to a large global mass-budget bias of -201 Gt yr^{-1} for 2003–2009. Thus, glaciers with glaciological measurements tend to be located in sub-regions where mass loss is greater than in their region as a whole, and this sampling bias is likely the major source of the discrepancy between C09 and the satellite-based estimates.

For our consensus estimate of global glacier mass wastage, GRACE and ICESat estimates are favored for all regions that have glacierized area greater than 5000 km^2, except Western Canada / United States. In the latter region, and in six smaller regions where the density of in-situ measurements is relatively high and the GRACE uncertainty exceeds ±1000 kg m^{-2} yr^{-1}, we take C09 as the best estimate of mass change. C09 also has a relatively high measurement density for Iceland so we include it in the method-averaged estimate for Iceland. On the basis of this synthesis we estimate that Earth's glaciers had a mass budget for 2003-09 of -215 ± 26 Gt yr^{-1} when peripheral glaciers in Greenland and Antarctica are excluded, and -259 ± 28 Gt yr^{-1} when peripheral glaciers are included (Table 1).

Compared to longer-term global estimates from 1960/61 to 2004/05, our consensus mass budget is slightly less negative than three of four previous studies (*2, 19, 30*) but more negative than the fourth (*3*). This could imply that there has been no increase in glacier mass loss in the most recent decade, but this conflicts with the glaciological records themselves (Fig. 6) and with repeat geodetic measurements (*13, 25, 31-33*). We instead suggest that most previous assessments have overestimated global mass losses due to interpolation of sparse glaciological measurements that are not representative for the largest glacierized regions. We can only demonstrate this negative bias for the 2003-09 period, but it has been long suspected also for earlier periods (*34, 35*). This calls for a re-examination of previous global estimates based on interpolation of glaciological records, which will probably lead to a downward revision of the estimated total contribution of glaciers to sea level rise over the past century.

Our consensus estimate of glacier mass wastage between 2003 and 2009 implies a sea-level contribution of 0.71 ± 0.08 mm sea level equivalent yr^{-1}, accounting for 29 ± 13 % of the observed sea level rise (2.50 ± 0.54 mm yr^{-1}) for the same period (*11*). The total glacier mass loss is comparable to a recent estimate for the whole of Greenland and Antarctica (*36*) (peripheral glaciers + ice sheets) for the period 2003 to 2008. To avoid double-counting, we subtract our estimates for peripheral glacier mass loss from this total to obtain a total ice-sheet mass budget of -290 ± 50 Gt yr^{-1} (*11*) and a total land ice (all glaciers + ice sheets) mass budget of -549 ± 57 Gt yr^{-1}, amounting to a sea-level rise of 1.51 ± 0.16 mm SLE yr^{-1} which is 61 ± 19 % of the total global sea level rise (*11*).

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Figures:

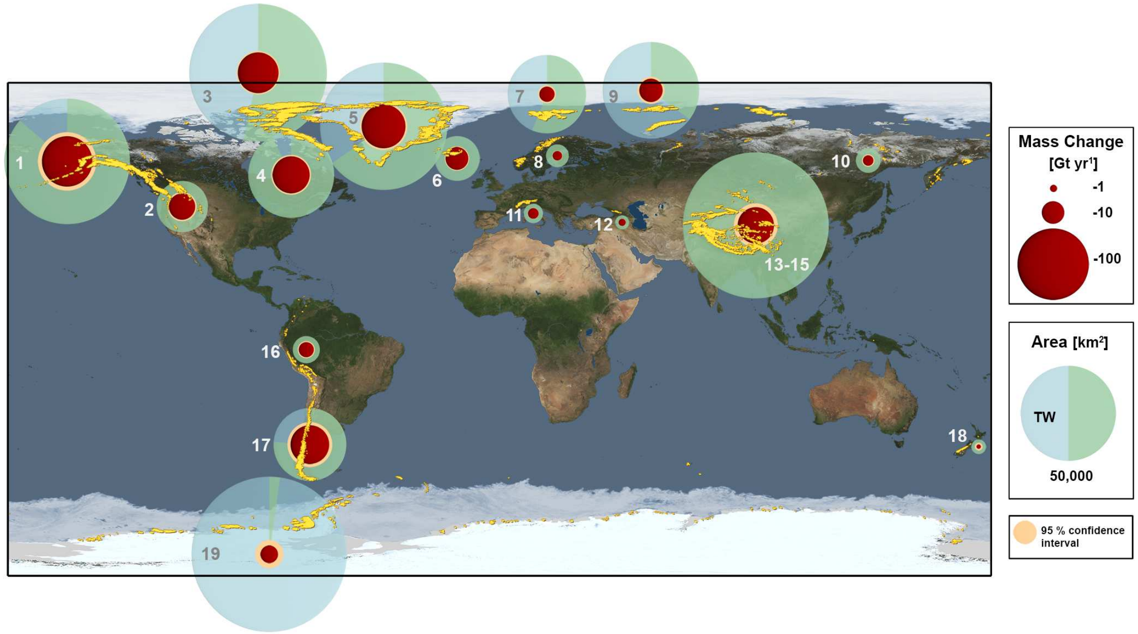

Fig. 1: Red circles show 2003-09 regional glacier mass budgets, while pale blue/green circles show regional glacier areas with tidewater basin fractions [TW; extent of ice flowing to termini in the ocean] in blue shading (Table 1). Peach colored halos surrounding red circles show 95% confidence interval in mass change estimates, but can only be seen in regions that have large uncertainties.

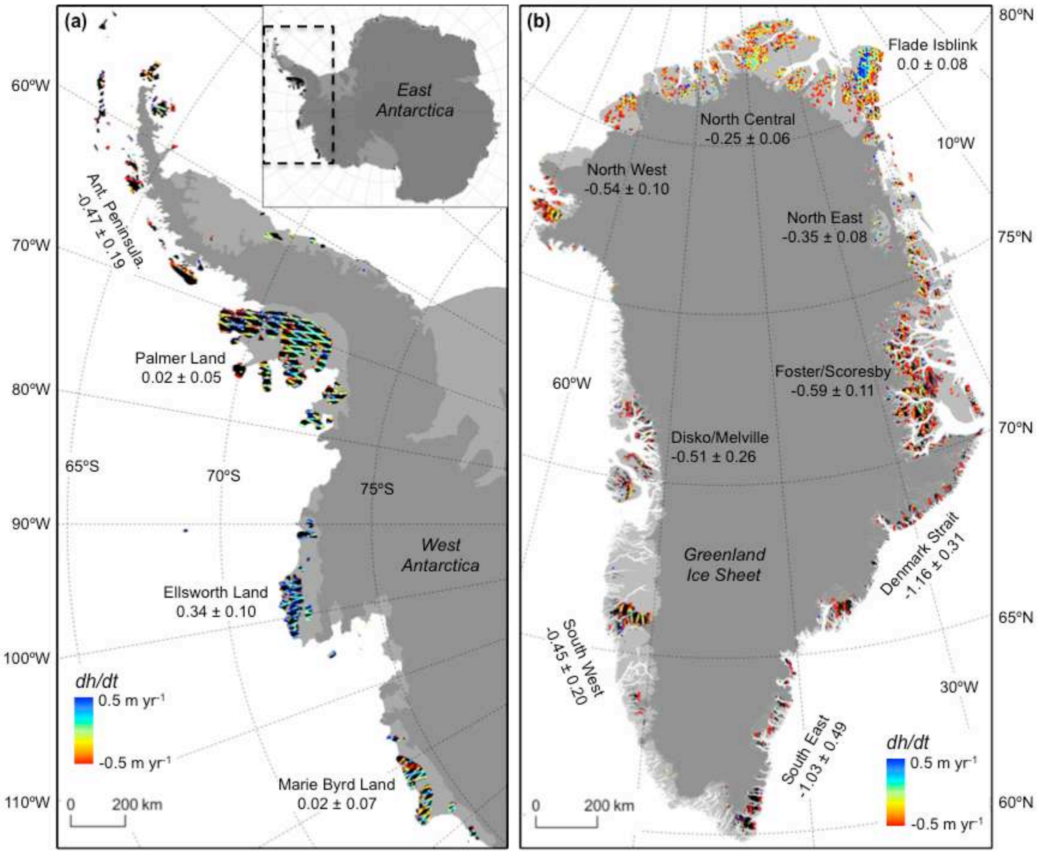

Fig. 2: Elevation change rates (*dh/dt*) between Oct. 2003 and Oct. 2009 for peripheral glaciers in (a) West Antarctica and (b) Greenland. Grey shadings from black to white show glaciers, ice sheets, ice shelves, land surfaces and ocean, respectively. West Antarctica contains 85% of the peripheral glacier cover in Antarctica. Remaining glaciers are found on scattered islands around East Antarctica (11%, inset map) and on remote Sub-Antarctic islands (4%, not shown). Text labels define a set of sub-regions with accompanying average elevation change rates in m yr^{-1} (Table S4). Uncertainties give the 95% confidence interval.

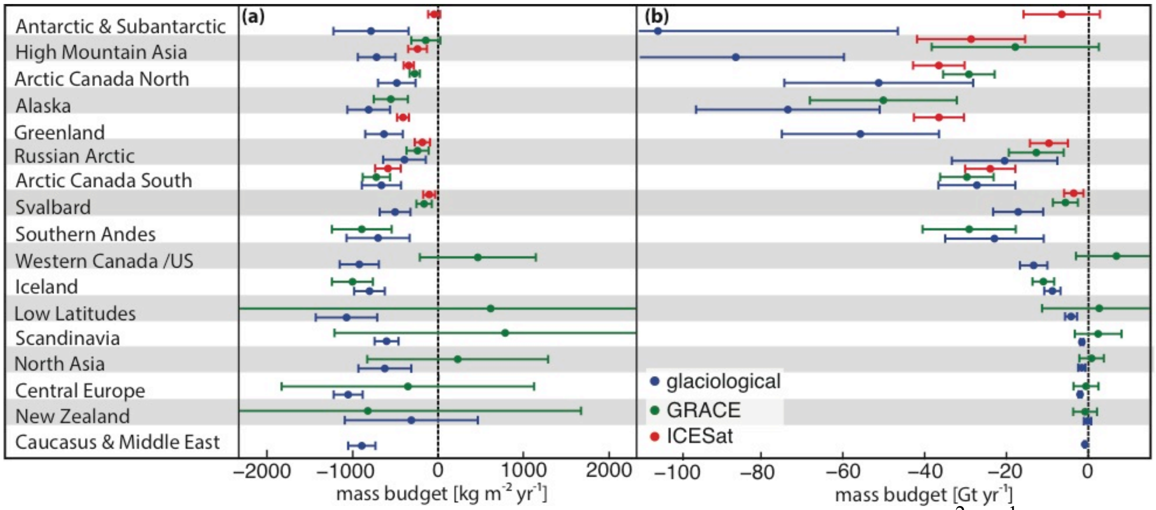

Fig. 3. Regional estimates of glacier mass change for 2003-09 in (a) kg m^{-2} yr^{-1} and (b) Gt yr^{-1}. Estimates are as assessed using ICESat (*8, 13, 14*) and GRACE [JW12, (*9, 10*)], and from interpolation of glaciological records (*2*) with an updated measurement dataset for 2003-09 [glaciological]. Regions are arranged top to bottom by total glacierized area. Uncertainties give the 95% confidence interval.

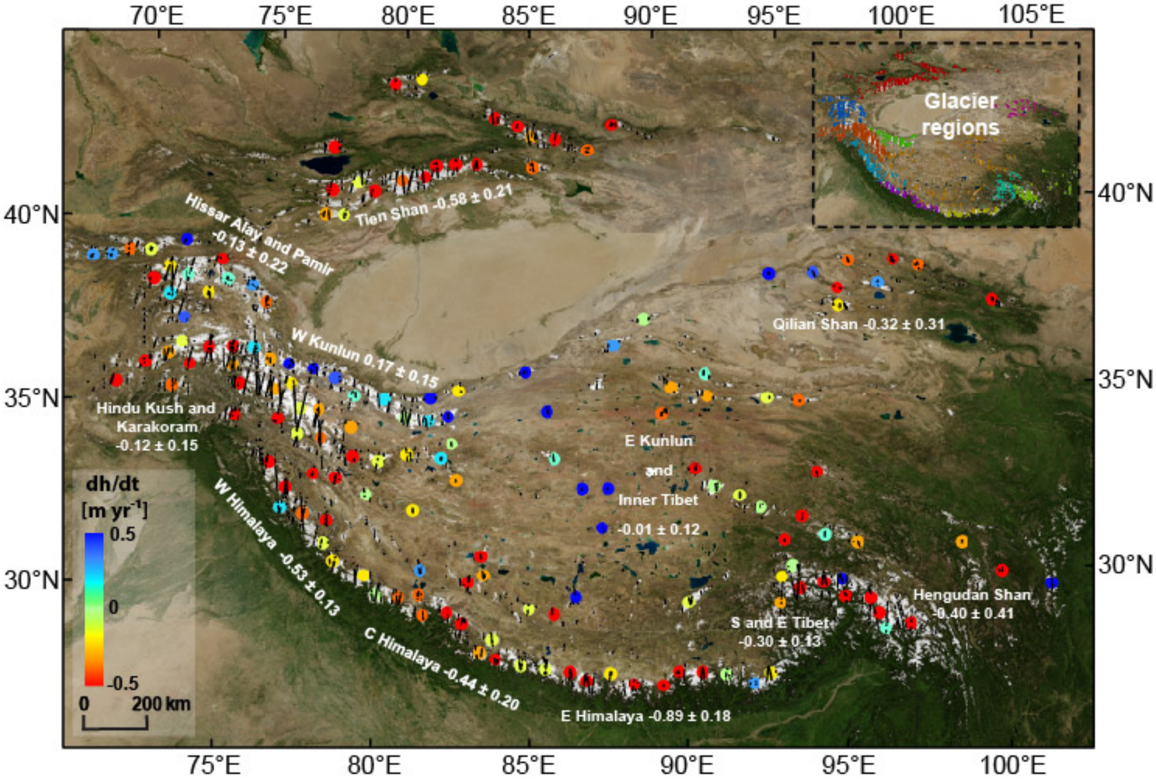

Fig. 4. Averaged elevation change rates (*dh/dt*) between Oct. 2003 and Oct. 2009 for High Mountain Asia. Each colored dot represents an independent spatial average of a minimum of 50 *dh/dt* observations within a radius of 50 km. ICESat ground tracks over glaciers are shown with thin black lines. The inset image and text labels define a set of

sub-regions for which we have estimated area-averaged elevation changes (shown here in m yr^{-1} together with their uncertainties) and mass budgets (Table S5). Uncertainties give the 95% confidence interval.

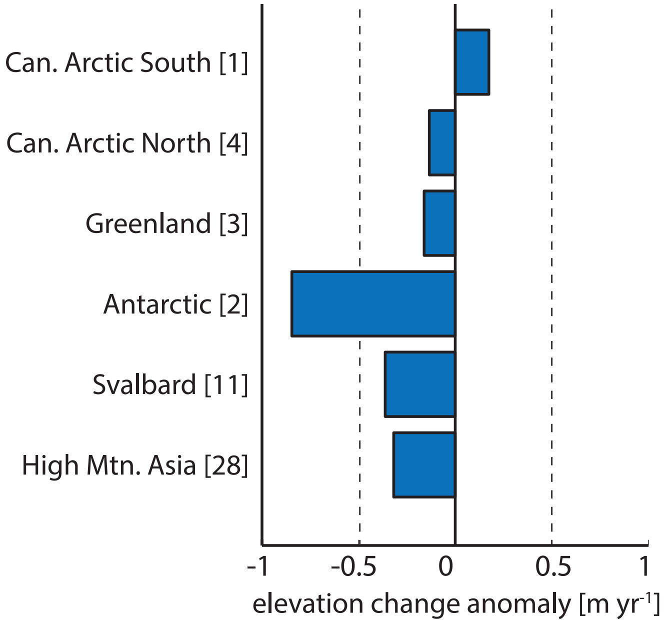

Fig. 5. ICESat-derived elevation change anomalies between neighborhoods of glaciological and local geodetic measurements and averages over their RGI regions. Each neighborhood is centered on a measured glacier and has a radius of 100 km. Each region name is followed by its number of measured glaciers during the 2003-2009 period. Negative values indicate that neighborhoods of glaciological records experienced thinning at higher rates than the regional average.

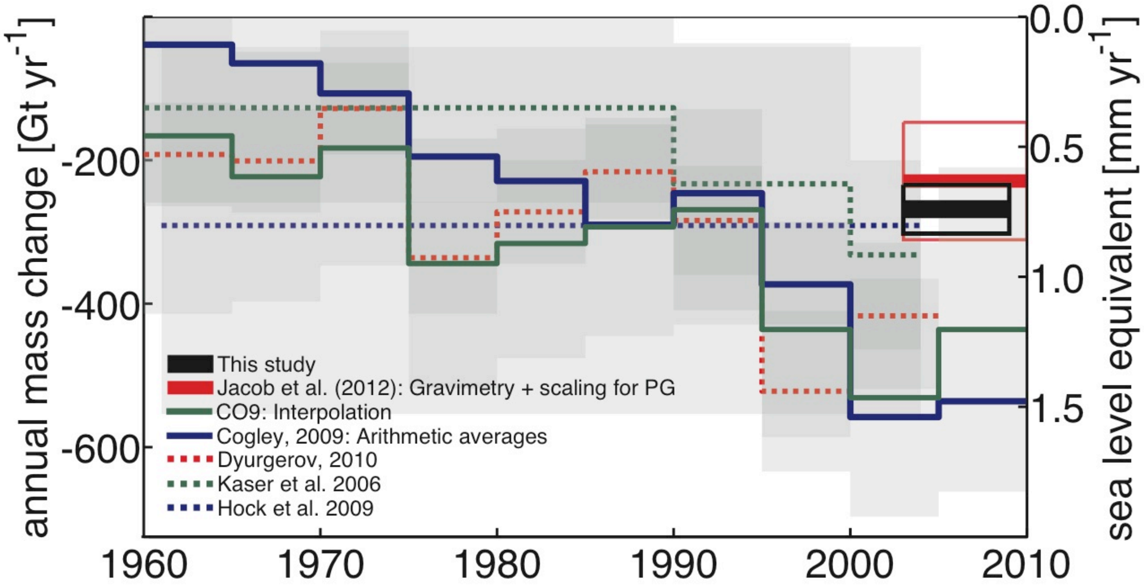

Fig. 6: Global estimates of glacier mass change. All estimates have been multiplied by the ratio of the total glacier area used in this study, 729,400 km^2, to that used in each source. 95% confidence intervals are shown for all estimates except the arithmetic averages of C09 (*2*), which have formal errors in the range 410-1520 Gt yr^{-1}. The two C09 estimates are determined from an updated set of glaciological records using the methods of Cogley (*2*).

Tables:

Table 1: Regional breakdown of total and tidewater glacier basin area, best estimate of mass budget for 2003-09 with 95% confidence interval, and methods selected as most suitable for estimating glacier mass change [G = GRACE, I = ICESat, gl = glaciological].

	region	total area [km^2]	tidewater area [km^2]	mass budget [kg m^{-2} yr^{-1}]	mass budget [Gt yr^{-1}]	method	ref.
1	Alaska	87100	11900	-560 ± 200	-50 ± 17	G	new, (*4, 9, 10*)
2	Western Canada/US	14600	0	-930 ± 230	-14 ± 3	gl	(*2*)
3	Arctic Canada North	104900	48800	-310 ± 40	-33 ± 4	I, G	new, (*4, 13*)
4	Arctic Canada South	40900	3000	-660 ± 110	-27 ± 4	I, G	new, (*4, 13*)
5	Greenland	89700	31300	-420 ± 70	-38 ± 7	I	new
6	Iceland	11100	0	-910 ± 150	-10 ± 2	G, gl	new, (*2, 4*)
7	Svalbard	34000	14900	-130 ± 60	-5 ± 2	I, G	new, (*4, 8*)
8	Scandinavia	2900	0	-610 ± 140	-2 ± 0	gl	(*2*)
9	Russian Arctic	51600	33400	-210 ± 80	-11 ± 4	I, G	new, (*4, 14*)
10	North Asia	3400	0	-630 ± 310	-2 ± 1	gl	(*2*)
11	Central Europe	2100	0	-1060 ± 170	-2 ± 0	gl	(*2*)
12	Caucasus & Middle East	1100	0	-900 ± 160	-1 ± 0	gl	(*2*)
13-15	High Mountain Asia	118200	0	-210 ± 100	-26 ± 12	I, G	new, (*4*)
16	Low Latitudes	4100	0	-1080 ± 360	-4 ± 1	gl	(*2*)
17	Southern Andes	29400	7000	-930 ± 330	-29 ± 10	G	new, (*4, 25*)
18	New Zealand	1200	0	-320 ± 780	0 ± 1	gl	(*2*)
19	Antarctic & Subantarctic	133200	130200	-50 ± 70	-6 ± 10	I	new
Total excluding Greenland & Antarctic		506600	119000	-420 ± 50	-215 ± 26		
Global total		**729400**	**280500**	**-350 ± 40**	**-259 ± 28**		