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# Global glacier retreat: a revised assessment of committed mass losses and sampling uncertainties

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## Abstract

Most glaciers and ice caps (GIC) are out of balance with the current climate. To return to equilibrium, GIC must thin and retreat, losing additional mass and raising sea level. Because glacier observations are sparse and geographically biased, there is an undersampling problem common to all global assessments. Here, we further develop an assessment approach based on accumulation-area ratios (AAR) to estimate committed mass losses and analyze the undersampling problem. We compiled all available AAR observations for 144 GIC from 1971–2010 and found that most glaciers and ice caps are farther from balance than previously believed. Accounting for regional and global undersampling errors, our model suggests that GIC are committed to additional losses of 30 ± 11 % of their area and 38 ± 17 % of their volume if the future climate resembles the climate of the past decade. These losses imply global mean sea-level rise of 163 ± 73 mm, assuming total glacier volume of 430 mm sea-level equivalent. To reduce the large uncertainties in these projections, more long-term glacier measurements are needed in poorly sampled regions.

## 1 Introduction

Averaged over a typical year, glaciers accumulate snow at upper elevations and ablate snow and ice at lower elevations. When the total accumulation is equal, on average, to the total ablation, a glacier is in balance with its local climate. If accumulation exceeds ablation over a period of years to decades, glaciers must thicken and advance; if ablation exceeds accumulation, glaciers must thin and retreat. Most of the Earth's glaciers are retreating (e.g., Meier et al., 2007; Bahr et al., 2009; WGMS, 2012).

Glacier annual mass balance has been measured by direct field methods for about 340 glaciers and ice caps, of which about 70 have uninterrupted records of 20 yr or more (Dyurgerov, 2010; WGMS, 2012). This is a small fraction of the Earth's estimated 200 000 or more GIC (Arendt et al., 2012; Huss and Farinotti, 2012). Globally integrated

GIC mass changes therefore cannot be measured directly, but must be estimated by upscaling observations from a small number of glaciers and ice caps. Several analyses (Dyurgerov and Meier, 2005; Kaser et al., 2006; Meier et al., 2007; Cogley, 2009a, 2012) based on direct and geodetic measurements suggest that GIC mass loss is raising sea level by about 1 mm $yr^{-1}$. This is about one-third of the total rate of sea-level rise inferred from satellite altimetry, with ocean thermal expansion and ice-sheet mass loss accounting for most of the remainder (Cazenave and Llovel, 2010). GRACE gravity measurements from 2003–2010 suggest a smaller GIC sea-level contribution of about 0.4 mm $yr^{-1}$, excluding GIC peripheral to the Greenland and Antarctic ice sheets (Jacob et al., 2012). These GRACE estimates, however, have large regional uncertainties, rely on the performance of global hydrologic models, and cover less than a decade.

Several modeling studies have projected global-scale transient glacier mass changes in response to forcing from climate models (e.g., Raper and Braithwaite, 2006; Radić and Hock, 2011; Marzeion et al., 2012; Slangen et al., 2012). Based on output from ten global climate models prepared for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4), sea level is projected to rise by 124 ± 37 mm during the 21st century from GIC mass loss, with the largest contributions from Arctic Canada, Alaska, and Antarctica (Radić and Hock, 2011). Another study (Marzeion et al., 2012) used 15 global climate models prepared for the IPCC Fifth Assessment Report (AR5) and projected that GIC mass loss by 2100 will range from 148 ± 35 mm to 217 ± 47 mm, depending on the emission scenario. For model calibration and validation, these studies used direct and geodetic mass balance observations available for fewer than 1 % of the Earth's glaciers. Undersampling is a significant problem for these studies and for all methods that project global sea-level rise from GIC.

Bahr et al. (2009; henceforth BDM) developed an alternative approach for projecting global glacier volume changes. This approach is based on the accumulation-area ratio (AAR), the fractional glacier area where accumulation exceeds ablation. For a glacier in balance with the climate, the AAR is equal to its equilibrium value, $AAR_0$. Glaciers with $AAR < AAR_0$ will retreat from lower elevations, typically over several decades or longer, until the AAR returns to the equilibrium value. From the ratio $\alpha = \mathrm{AAR}/\mathrm{AAR}_0$, BDM derived $p_\mathrm{A}$ and $p_\mathrm{V}$, the fractional changes in area $A$ and volume $V$ required to reach equilibrium with a given climate. They showed that for a given glacier or ice cap, $p_\mathrm{A} = \alpha - 1$ and $p_\mathrm{V} = \alpha^\gamma - 1$, where $\gamma$ is the exponent in the glacier volume–area scaling relationship, $V \propto A^\gamma$ (Bahr et al., 1997). Data and theory suggest $\gamma = 1.25$ for ice caps and $\gamma = 1.36$ for glaciers. Using AAR observations of ~ 80 GIC during 1997–2006 (Dyurgerov et al., 2009), BDM computed a mean AAR of 44 ± 2 %, with $\mathrm{AAR} < \mathrm{AAR}_0$ for most GIC. They estimated that even without additional warming, the volume of glaciers must shrink by 27 ± 5 %, and that of ice caps by 26 ± 8 %, to return to equilibrium.

The AAR method provides physics-based estimates of committed GIC area and volume changes and complements techniques such as mass balance extrapolation (Meier et al., 2007) and numerical modeling (Oerlemans et al., 1998; Raper and Braithwaite, 2006). Compared to direct mass balance measurements, AARs are relatively easy and inexpensive to estimate with well-timed aerial and satellite images, which could potentially solve the undersampling problem. Here we adopt the BDM approach and develop it further. Instead of assuming that a sample of fewer than 100 observed GIC, mostly in Europe and western North America, is representative for the global mean, we test the foundations of this assumption and quantify its uncertainties. We aim not only to provide a revised estimate of committed global-scale glacier mass losses, but also to assess the sampling errors associated with the limited number of available AAR observations.

## 2 Data and methods

We compiled a data set of AAR and mass balance for 144 GIC (125 glaciers and 19 ice caps) from 1971–2010, mainly from the World Glacier Monitoring Service (WGMS, 2012) but with additional data from various sources (see Supplement). Thus we expanded and updated the data set used by BDM. Figure 1 shows the locations of GIC in the updated data set, and Fig. 2 shows the number of GIC with AAR observations in each year. These data were distilled from a larger data set that included several dozen additional glaciers in the WGMS database. For each glacier or ice cap we computed $AAR_0$ by linear regression of the AAR with mass balance (Fig. S1 in Supplement). We retained only those GIC for which the linear relationship is statistically significant ($p < 0.10$), in order to remove GIC with short time series and those for which AAR methods are not applicable.

We then computed annual, pentadal, and decadal averages of AAR and $\alpha$ for selected regions (Fig. 1) and for the full data set, along with the fractional change in area and volume required for GIC to reach equilibrium with a given climate. The arithmetic mean AAR and $\alpha$ have fallen during each decade since the 1970s (Fig. 3). We found a decadal-average $\alpha < 1$, implying future retreat if recent climate conditions continue, for 93 out of 96 GIC with observations during the 2000s. The mean AAR for 2001–2010 is $34 \pm 3\,\%$. (Here and below, error ranges computed from our data set correspond to a 95 % confidence interval.) This is well below BDM's estimate of $44 \pm 2\,\%$, implying that the observed GIC are farther from balance than previously reported.

GIC observations, however, are sparse and geographically biased, thus complicating any extrapolation of global glacier mass loss from the available data. Direct AAR and mass-balance measurements have focused on small to mid-size glaciers in accessible regions such as the Alps, Scandinavia, and the western US and Canada (Fig. 1). Area is not correlated significantly ($p > 0.10$) with AAR or $\alpha$ for observed GIC spanning a range of $\sim 0.1\,\mathrm{km}^2$ to $1000\,\mathrm{km}^2$ (Fig. S2 in Supplement), suggesting that glacier size is not a large source of bias. Geographic bias, on the other hand, could be important. Much of the Earth's glacier mass is located in regions with poorly observed in-situ mass changes, including Antarctica, Greenland, Alaska, Arctic Canada, the Russian Arctic, Central Asia, and the Southern Andes (Dyurgerov, 2010). In our data set, these seven regions have only 17 GIC with observed AAR during 2001–2010.

Table 1 shows the decadal mean $\alpha$ for each of 14 regions with one or more GIC in the 2001–2010 data set. Among regions with at least three observed GIC, the highest values are in Alaska ($\alpha = 0.89 \pm 0.28$) and Antarctica ($\alpha = 0.89 \pm 0.28$), with the lowest

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values in Svalbard ($\alpha = 0.49 \pm 0.15$) and Central Europe ($\alpha = 0.47 \pm 0.06$). Three regions with low glacier mass (Central Europe, Scandinavia, and W. Canada/US) contain more than half the GIC in the data set and have relatively low $\alpha$. These regional differences suggest that the full data set may not be spatially representative and that projections based on the arithmetic mean $\alpha$ could overestimate committed GIC losses.

To show how geographical bias and undersampling can affect estimates of global glacier mass balance and AAR, we applied three different averaging methods: (1) the arithmetic mean for the full data set; (2) the arithmetic mean for 38 GIC in eight high-mass regions (Arctic Canada, Antarctica, Alaska, Greenland, the Russian Arctic, Central Asia, Svalbard, and the Southern Andes; see Fig. 1) that collectively contain about 97 % of the Earth's glacier mass outside ice sheets (Radić and Hock, 2010); and (3) a mean obtained by upscaling the regional mean values, with each value weighted by the region's GIC area or volume. Because method 3 assumes GIC to be representative only of their regions and not of the entire Earth, it is the least likely to be geographically biased. This method, however, is limited to the past decade, because several high-mass regions had no observations in earlier decades.

The method 3 errors are dominated by errors in a few large undersampled regions, including Arctic Canada, Antarctica, Greenland, and Alaska. We estimated regional errors by subsampling GIC in two well-represented regions, Central Europe and W. Canada/US, and computed the difference between the mean $\alpha$ of each subsample and of the full sample. The spread of differences as a function of subsample size (Fig. S3 in Supplement) gives an estimate of the error $\delta\alpha$ in poorly sampled regions with small area (e.g., Iceland, New Zealand, Caucasus, and Svalbard). For poorly sampled regions with large area (e.g., Greenland, Arctic Canada, the Russian Arctic, and Antarctica, whose glaciers experience different climate regimes within the region) we carried out the same analysis but using two combined regions: (1) Central Europe and Scandinavia, and (2) W. Canada/US and Alaska. All errors are derived as root-mean-square-errors, RMSE, at 95 % confidence interval. See the Supplement for more details.

Figure 4 shows pentadal average global glacier mass balance for 1971–2010 as estimated by each method, along with the estimates of Kaser et al. (2006) and Cogley (2012). (No published benchmarks exist for global average $\alpha$. However, $\alpha$ and mass balance are closely correlated, as shown in Fig. S4 in Supplement, suggesting that a method which is representative for mass balance is also representative for $\alpha$.) The estimates of Cogley (2012) are based on both geodetic and direct measurements and are more negative by 100–200 $\mathrm{kg\,m^{-2}\,yr^{-1}}$ than the direct-only estimates from Kaser et al. (2006), probably because the direct measurements exclude rapidly thinning calving glaciers (Cogley, 2009a).

The multi-decade time series in Fig. 4 show significant trends toward more negative mass balance. Method 1 (the mean of all observed GIC) gives a post-2000 mass balance more negative than the published estimates, suggesting a bias due to high melt rates in over-represented low-mass regions. Method 2 (the mean from high-mass regions) agrees closely with the direct-based estimates and, as expected, gives a less negative mass balance than the direct-plus-geodetic estimates. Method 3 (based on regional upscaling) agrees closely with method 2 in 2001–2005 and 2006–2010, but with large uncertainty ranges due to propagation of errors from undersampled high-mass regions.

This comparison suggests that to a good approximation, methods 2 and 3 are globally representative for glacier mass balance (and hence $\alpha$), with two caveats. First, the direct-plus-geodetic results imply that the exclusion of calving glaciers could result in a positive bias of 100–200 $\mathrm{kg\,m^{-2}\,yr^{-1}}$. Second, GRACE measurements (Jacob et al., 2012) during 2003–2010 suggest an average mass balance (excluding GIC peripheral to the two ice sheets) of $-290 \pm 58\,\mathrm{kg\,m^{-2}\,yr^{-1}}$, compared to $-400$ to $-500\,\mathrm{kg\,m^{-2}\,yr^{-1}}$ for our data set. These two potential biases are of similar magnitude but opposite sign. A mass-balance bias of 100 $\mathrm{kg\,m^{-2}\,yr^{-1}}$ would be associated with biases of about 0.06 in $p_\mathrm{A}$ and 0.08 in $p_\mathrm{V}$.

# 3 Results and discussion

To estimate committed GIC area and volume losses based on present-day climate, we applied method 3 to observations of $\alpha$ from 2001–2010. A window of about a decade is optimal because it is long enough to average over interannual variability but short compared to glacier dynamic time scales. We adjusted for geographic bias by weighting each regional mean value by the region's total GIC area (for computing $p_A$) or volume (for computing $p_V$) (Radić and Hock, 2010). Errors were estimated based on the number of observed GIC per region and are dominated by a few under-represented regions, We found $\alpha = 0.70 \pm 0.11$ for 2001–2010, implying committed area losses of 30 ± 11 % and volume losses of 38 ± 17 % if climate conditions of 2001–2010 continue in the future. The resulting sea-level rise scales linearly with the initial glacier volume. Assuming a total GIC volume of 430 mm sea-level equivalent (SLE) (Huss and Farinotti, 2012), these committed glacier losses would raise global mean sea level by 163±73 mm. Using a larger value of 600 mm SLE (Radić and Hock, 2010), global mean sea level would rise by 228 ± 102 mm.

Method 2 yields similar estimates. The mean $\alpha$ during 2001–2010 for GIC in high-mass regions is $0.70 \pm 0.10$, implying committed area losses of 30 ± 10 % and volume losses of 37 ± 12 % (where the error estimates are based on the assumption that these GIC are globally representative). The close agreement with method 3 suggests that method 2 does not have a large geographic bias with respect to $\alpha$.

The Earth is expected to warm further (Meehl et al., 2007), making it likely that long-term GIC area and volume losses will exceed estimates based on the climate of the past decade. From method 2, there is a significant trend ($p < 0.01$) in average annual $\alpha$ of $-0.0052 \pm 0.0033\,\mathrm{yr}^{-1}$ from 1971–2010 (Fig. 3). The trend is nearly identical for the subset of GIC with observations in all four decades, implying that the changing composition of the data set does not substantially bias the trend. The trend in $\alpha$ has been much steeper since 1990; there is a significant trend ($p < 0.01$) of $-0.0078 \pm 0.0080\,\%\,\mathrm{yr}^{-1}$ for 1991–2010, whereas the 1971–1990 trend is not significant ($p > 0.10$). By extrapolating these trends, we can estimate the losses required to equilibrate with the climate of future decades. Taking $\alpha = 0.70 \pm 0.10$ as the 2005 value and extending the 40 yr trend, the average would fall by $0.18 \pm 0.12$ over 35 yr, reaching $0.52 \pm 0.16$ by 2040. The Earth's GIC would then be committed to losing 58 ± 17 % of their volume. Relative to present-day GIC volume, which is decreasing by about 2 % per decade, the losses would be somewhat greater. These error ranges may understate the true uncertainties, because of natural interdecadal variability and because the method 2 data set may not be globally representative.

Glacier area and volume losses will occur on decade-to-century time scales. The AAR method does not directly predict rates of retreat and thinning, but theory (Jóhannesson et al., 1989) predicts that the volume response time for a typical glacier with a mean thickness of 100–500 m is on the order of 100 yr. Scaling analysis (Bahr and Radić, 2012) implies that glaciers thinner than 500 m contain a majority of the Earth's total glacier volume (see Supplement), suggesting that a large fraction of committed glacier volume losses will occur within a century. However, larger GIC with longer response times will continue to lose mass and raise sea level after 2100.

This analysis has focused on global ice losses and sea-level rise, but glacier retreat and thinning will also have regional impacts associated with changes in seasonal runoff (Immerzeel et al., 2010; Kaser et al., 2010) and glacier hazards (Kääb et al., 2005). In some regions, fractional area and volume ice losses will exceed the global average. Assuming that the observed GIC are regionally representative, GIC in Central Europe will lose 64 ± 7 % of their volume if future climate resembles the climate of the past decade (which included several record heat waves). We also project substantial volume losses in Scandinavia (56 ± 7 %), W. Canada/US (53 ± 7 %) and Iceland (35 ± 11 %). Projections elsewhere are less certain because of the smaller sample sizes.

## 4 Conclusions

AARs are declining faster than most glaciers and ice caps can respond dynamically. As a result, committed area and volume losses far exceed the losses observed to date. Based on regional upscaling of AAR observations from 2001–2010, we conclude that the Earth's glaciers and ice caps will ultimately lose 30 ± 11 % of their area and 38 ± 17 % of their volume if the future climate resembles the climate of the past decade. Committed losses could increase substantially during the next few decades if the climate continues to warm. These relative losses are larger than those estimated by BDM, reflecting the lower AARs in data that have become available since the earlier study. Our projections, however, have large uncertainties (40 % relative error in the projected mass loss) that are dominated by under-represented high-mass regions, including Arctic Canada, Antarctica, Greenland, and Alaska.

To reduce the uncertainties, more observations are needed in poorly sampled regions. Direct mass-balance and AAR measurements are inherently labor-intensive and limited in coverage. AARs can be estimated, however, from aerial and satellite observations of the end-of-summer snowline (Fig. 5). Deriving $\mathrm{AAR}_0$ from observations requires mass-balance measurements for about a decade, but BDM found that the global mean $\mathrm{AAR}_0$ can be used for most GIC with only moderate loss of precision. Huss et al. (2013) recently showed that simple mass balance modeling, combined with terrestrial and airborne/spaceborne AAR observations, can be used to determine glacier mass changes. Also, AAR methods could be extended to tidewater glaciers, incorporating calving as well as surface processes.

**Supplementary material related to this article is available online at: http://www.the-cryosphere-discuss.net/7/1987/2013/tcd-7-1987-2013-supplement.zip.**

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## References

Arendt, A. A., Bolch, T., Cogley, J. G., Gardner, A., Hagen, J.-O., Hock, R., Kaser, G., Pfeffer, W. T., Moholdt, G., Paul, F., Radić, V., Andreassen, L., Bajracharya, S., Beedle, M., Berthier, E., Bhambri, R., Bliss, A., Brown, I., Burgess, E., Burgess, D., Cawkwell, F., Chinn, T., Copland, L., Davies, B., de Angelis, H., Dolgova, E., Filbert, K., Forester, R., Fountain, A., Frey, H., Giffen, B., Glasser, N., Gurney, S., Hagg, W., Hall, D., Haritashya, U. K., Hartmann, G., Helm, C., Herreid, S., Howat, I., Kapustin, G., Khromova, T., Kienholz, C., Koenig, M., Kohler, J., Kriegel, D., Kutuzov, S., Lavrentiev, I., LeBris, R., Lund, J., Manley, W., Mayer, C., Miles, E., Li, X., Menounos, B., Mercer, A., Moelg, N., Mool, P., Nosenko, G., Negrete, A., Nuth, C., Pettersson, R., Racoviteanu, A., Ranzi, R., Rastner, P., Rau, F., Rich, J., Rott, H., Schneider, C., Seliverstov, Y., Sharp, M., Sigurosson, O., Stokes, C., Wheate, R., Winsvold, S., Wolken, G., Wyatt, F., and Zheltyhina, N: Randolph Glacier Inventory [v2.0]: a Dataset of Global Glacier Outlines, digital media, available at: http://www.glims.org/RGI/RGI_Tech_Report_V2.0.pdf, Global Land Ice Measurements from Space, Boulder, Colorado, 2012.

Bahr, D. B. and Radić V.: Significant contribution to total mass from very small glaciers, The Cryosphere, 6, 763–770, doi:10.5194/tc-6-763-2012, 2012.

Bahr, D. B., Meier, M. F., and Peckham, S. D.: The physical basis of glacier volume-area scaling, J. Geophys. Res., 102, 20355–20362, 1997.

Bahr, D. B., Dyurgerov, M., and Meier, M. F.: Sea-level rise from glaciers and ice caps: a lower bound, Geophys. Res. Lett., 36, L03501, doi:10.1029/2008GL036309, 2009.

Cazenave. A. and Llovel, W.: Contemporary sea level rise, Annu. Rev. Mar. Sci., 2, 145–173, 2010.

Cogley, J. G.: Geodetic and direct mass-balance measurements: comparison and joint analysis, Ann. Glaciol., 50, 96–100, 2009a.

Cogley, J. G.: A more complete version of the world glacier inventory, Ann. Glaciol., 50, 32–38, 2009b.

Cogley, J. G.: The future of the world's glaciers, in: The Future of the World's Climate, edited by: Henderson-Sellers, A. and McGuffie, K., Elsevier, Amsterdam, 197–222, 2012.

Dyurgerov, M. B.: Data of Glaciological Studies – Reanalysis of Glacier Changes: From the IGY to the IPY, 1960–2008, Publication No. 108, Institute of Arctic and Alpine Research, Boulder, Colorado, 2010.

Dyurgerov, M. B. and Meier, M. F.: Glaciers and the Changing Earth System: a 2004 Snapshot, Occas. Paper 58, Institute of Arctic and Alpine Research, Boulder, Colorado, 117 pp., 2005.

Dyurgerov, M. B., Meier, M. F., and Bahr, D. B.: A new index of glacier area change: a tool for glacier monitoring, J. Glaciol., 55, 710–716, 2009.

Huss, M. and Farinotti, D.: Distributed ice thickness and volume of all glaciers around the world, J. Geophys. Res., 117, F04010, doi:10.1029/2012JF002523, 2012.

Huss, M., Sold, L., Hoelzle, M., Stokvis, M., Salzmann, N., Farinotti, D., and Zemp, M.: Towards remote monitoring of sub-seasonal glacier mass balance, Ann. Glaciol., 54, 85–93, doi:10.3189/2013AoG63A427, 2013.

Immerzeel, W. W., van Beek, L. P. H., and Bierkens, M. F. P.: Climate change will affect the Asian water towers, Science, 328, 1382–1385, 2010.

Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S.: Recent contributions of glaciers and ice caps to sea level rise, Nature, 482, 514–518, 2012.

Jóhannesson, T., Raymond, C., and Waddington, E.: Time-scale for adjustment of glaciers to changes in mass balance, J. Glaciol., 35, 355–369, 1989.

Kääb, A., Reynolds, J. M., and Haeberli, W.: Glacier and permafrost hazards in high mountains, in: Global Change and Mountain Regions: An Overview of Current Knowledge, edited by: Huber, U. M., Bugmann, H. K. M., and Reasoner, M. A., Springer, Dordrecht, the Netherlands, 225–234, 2005.

Kaser, G., Cogley, J. G., Dyurgerov, M. B., Meier, M. F., and Ohmura, A.: Mass balance of glaciers and ice caps: consensus estimates for 1961–2004, Geophys. Res. Lett., 33, L19501, doi:10.1029/2006GL027511, 2006.

Kaser, G., Großhauser, M., and Marzeion, B.: Contribution potential of glaciers to water availability in different climate regimes, P. Natl. Acad. Sci. USA, 107, 20223–20227, 2010.

Marzeion, B., Jarosch, A. H., and Hofer, M.: Past and future sea-level change from the surface mass balance of glaciers, The Cryosphere, 6, 1295–1322, doi:10.5194/tc-6-1295-2012, 2012.

Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D. J., Held, H., Kriegler, E., Mach, K. J., Matschoss, P. R., Plattner, G.-K., Yohe, G. W., and Zwiers, F. W.: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties (Intergovernmental Panel on Climate Change), available at: http://www.ipcc.ch, 2010.

Meehl, G. A. and Stocker, T. F.: Global climate projections, in: Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M. M. B., Miller Jr., H. L., and Chen, Z., Cambridge University Press, Cambridge, 2007.

Meier, M. F., Dyurgerov, M. B., Rick, U. K., O'Neel, S., Pfeffer, W. T., Anderson, R. S., Anderson, S. P., and Glazovsky, A. F.: Glaciers dominate eustatic sea-level rise in the 21st century, Science, 317, 1064–1067, 2007.

Oerlemans, J., Anderson, B., Hubbard, A., Hybrechts, P., Jóhannesson, T., Knap, W. H., Schmeits, M., Stroeven, A. P., van de Wal, R. S. W., Wallinga, J., and Zuo, Z.: Modelling the response of glaciers to climate warming, Clim. Dynam., 14, 267–274, 1998.

Radić, V. and Hock, R.: Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data, J. Geophys. Res., 115, F01010, doi:10.1029/2009JF001373, 2010.

Radić, V. and Hock, R.: Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise, Nat. Geosci., 4, 91–94, 2011.

Raper, S. C. B. and Braithwaite, R. J.: Low sea level rise projections from mountain glaciers and icecaps under global warming, Nature, 439, 311–313, 2006.

Slangen, A. B. A., Katsman, C. A., van de Wal, R. S. W., Vermeersen, L. L. A., and Riva, R. E. M.: Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios, Clim. Dynam., 38, 1191–1209, 2012.

World Glacier Monitoring Service (WGMS): Fluctuations of Glaciers 2005–2010 (Vol. X), edited by M. Zemp et al., ICSU (WDS)/IUGG (IACS)/UNEP/UNESCO/WMO, Zurich, Switzerland, Publication based on database version: doi:10.5904/wgms-fog-2012-11, 336 pp., 2012.

**Table 1.** Regional mean values of $\alpha = \mathrm{AAR}/\mathrm{AAR}_0$ for 2001–2010[a].

| Region | Mean $\alpha$ |
|---|---|
| Alaska (3) | $0.89 \pm 0.28$ |
| W. Canada/US (19) | $0.57 \pm 0.06$ |
| Arctic Canada (2) | $0.60 \pm 0.35$ |
| Greenland (1) | $0.34 \pm 0.51$ |
| Iceland (10) | $0.72 \pm 0.09$ |
| Svalbard (6) | $0.49 \pm 0.15$ |
| Scandinavia (18) | $0.53 \pm 0.06$ |
| Central Europe (19) | $0.47 \pm 0.06$ |
| Caucasus (2) | $0.81 \pm 0.32$ |
| Central Asia (7) | $0.80 \pm 0.16$ |
| Northern Andes (4) | $0.71 \pm 0.21$ |
| Southern Andes (1) | $0.71 \pm 0.51$ |
| New Zealand (1) | $0.92 \pm 0.47$ |
| Antarctic (3) | $0.89 \pm 0.28$ |
| Global (96) | $0.70 \pm 0.11$ |

[a] Error ranges give 95 % confidence interval. The number of observed GIC per region is shown in parentheses. The global mean is obtained by method 3.

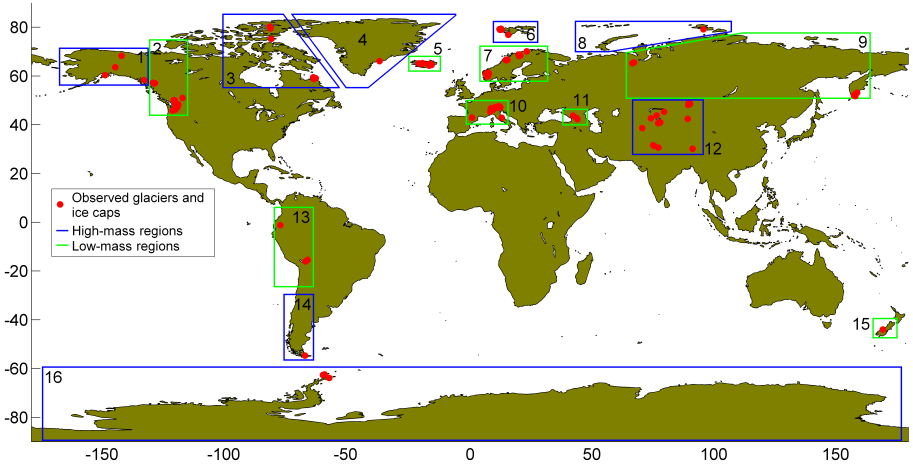

**Fig. 1.** Locations of the 144 glaciers and ice caps (GIC) in the updated data set. The data are divided into 16 regions: (1) Alaska, (2) W. Canada/US, (3) Arctic Canada, (4) Greenland, (5) Iceland, (6) Svalbard, (7) Scandinavia, (8) Russian Arctic, (9) North Asia, (10) Central Europe, (11) Caucasus, (12) Central Asia, (13) Northern Andes, (14) Southern Andes, (15) New Zealand, and (16) Antarctica. The data set contains 38 GIC in high-mass regions (ice volume $V > 5000\,\mathrm{km}^3$; outlined in blue) and 106 GIC in low-mass regions ($V < 5000\,\mathrm{km}^3$; outlined in green). Volume estimates are from Radić and Hock (2010).

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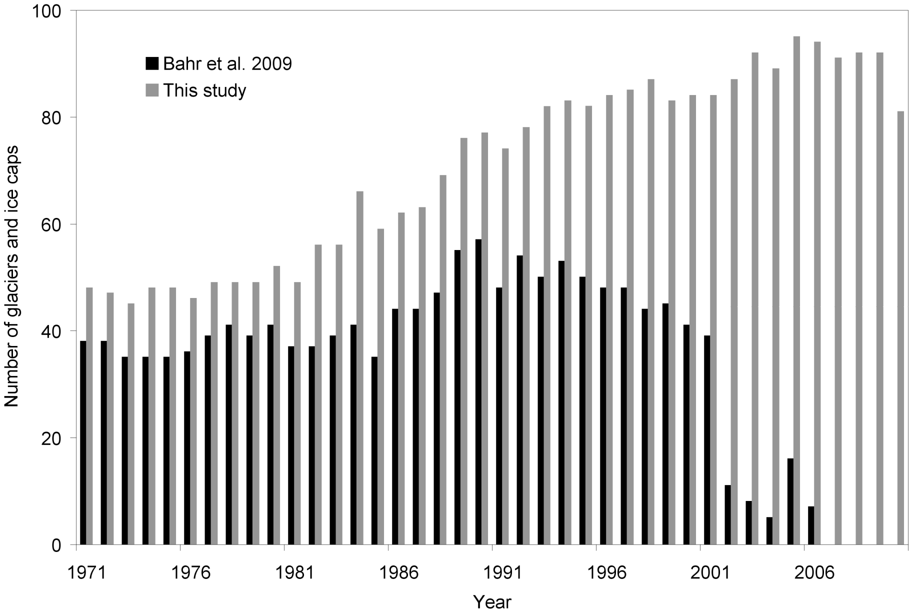

**Fig. 2.** Number of glaciers and ice caps with AAR observations per year in the Bahr et al. (2009) data set (black) and in the updated data set used in this study (grey).

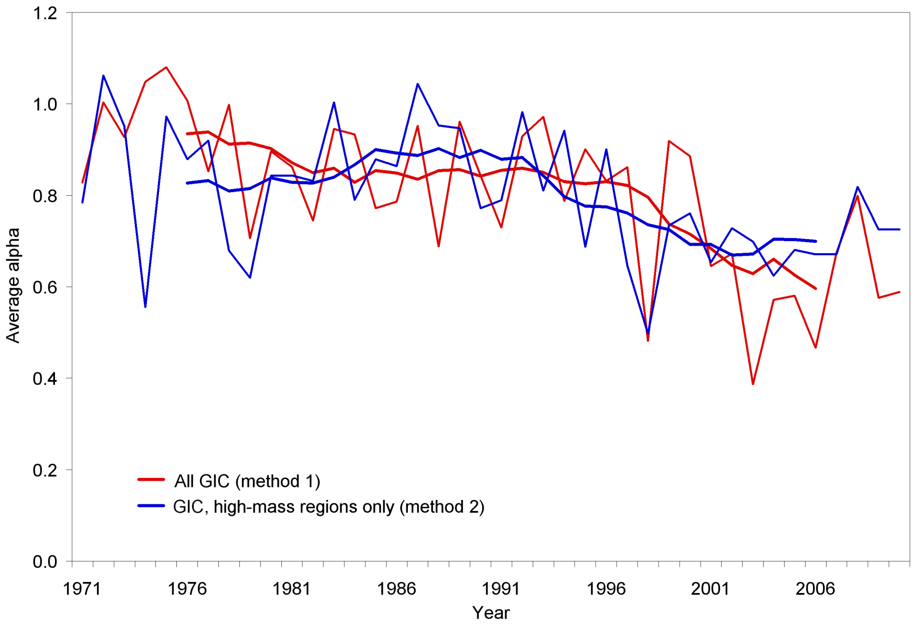

**Fig. 3.** Annual average $\alpha = \mathrm{AAR}/\mathrm{AAR}_0$ for the full data set (thin red line) and for the GIC in high-mass regions only (thin blue line), 1971–2010. The thick red and blue lines are 10 yr running means. Both the full data set and the high-mass-only data sets have significant ($p < 0.01$) negative trends during 1971–2010 and 1991–2010. The 1971–1990 trends are not significant ($p > 0.10$).

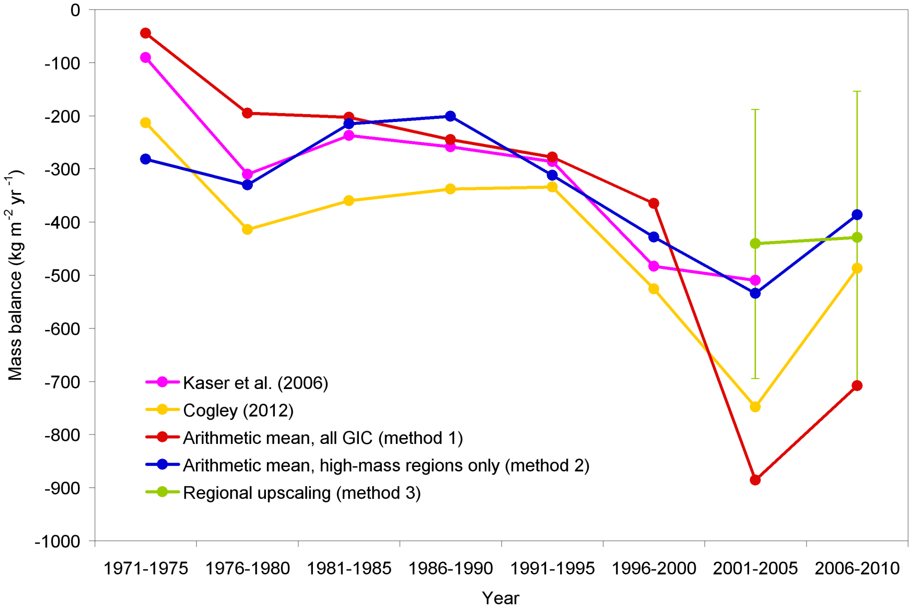

**Fig. 4.** Pentadal average mass balance, 1971–2010. Estimated global average GIC mass balance (kg m$^{-2}$ yr$^{-1}$) at 5 yr intervals from published estimates and from this dataset: (1) Kaser et al. (2006), based on direct glacier measurements (purple); (2) Cogley (2012), based on direct plus geodetic measurements (yellow); (3) arithmetic mean of all GIC in the 1971–2010 data set (method 1; red); (4) arithmetic mean of GIC in the eight high-mass regions of Fig. 1 (method 2; blue); (5) average based on area-weighted upscaling of regional means (method 3; green) including error bars at 95 % confidence interval.

**Fig. 5.** Brewster Glacier, New Zealand, at the end of the 2008 ablation season. The glacier area is 2.5 km$^2$. The 2008 glacier mass balance is $-1653\,\mathrm{kg\,m{-}2\,yr^{-1}}$, and the AAR is 10 %. Grey firn areas generally lie in the ablation zone. The photo illustrates the difficulty of determining a specific elevation at which a glacier is in equilibrium. Photo taken by A. Willsman (Glacier Snowline Survey, National Institute of Water and Atmospheric Research Ltd. (NIWA), New Zealand), 14 March 2008.