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# Brief communication: *Ad hoc* estimation of glacier contributions to sea-level rise from latest glaciological observations

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**Abstract**

Comprehensive assessments of global glacier mass changes based on a variety of observations and prevailing methodologies have been published at multi-annual intervals. For the years in between, the glaciological method provides annual observations of specific mass changes but is suspected to not be representative at the regional to global scales due to uneven glacier distribution with respect to the full sample. Here, we present a simple approach to estimate and correct for this bias in the glaciological sample and, hence, to provide an *ad hoc* estimate of global glacier mass changes and corresponding sea-level equivalents for the latest years, i.e. 2016/17 and 2017/18.

## 1 Introduction

Globally, more than 215,000 glaciers – distinct from the Greenland and Antarctic ice sheets – cover an area of about 700,000 km$^2$ (RGI, 2017) with a recently re-estimated total volume of about 160,000 km$^3$ (Farinotti et al., 2019). Glaciers react sensitively to changes in climate (Bojinski et al., 2014) and substantially contribute to regional runoff (e.g., Huss and Hock, 2018; Kaser et al., 2010) and global sea-level change (e.g., Hock et al., 2019; Marzeion et al., 2018). In the context of the Intergovernmental Panel on Climate Change (IPCC) assessment reports, the glaciological community has periodically published observational estimates of glacier contributions to sea-level rise based on coordinated efforts making use of all available data at that time: IPCC TAR (2001): Meier (1984), Trupin et al. (1992); IPCC AR4 (2007): Kaser et al. (2006) based on Cogley (2005), Dyurgerov and Meier (2005), and Ohmura (2004) ; IPCC AR5 (2013): Gardner et al. (2013) mainly based on Cogley (2009). These approaches were challenged by small observational samples covering not more than a few hundred glaciers, with an uneven spatial and temporal distribution (Zemp et al., 2015) and were complemented for IPCC AR 5 with estimates from spaceborne altimetry and gravimetry (Gardner et al., 2013). In view of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019), Zemp et al. (2019) increased the observational sample to more than 19,000 glaciers by combining the results from glaciological and geodetic (from DEM differencing) methods to assess annual

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019

The Cryosphere Discussions

mass changes and corresponding sea-level equivalents from 1961 to 2016. All of these major assessments provided new observational baselines for the comparison with estimates based on other methods (e.g. spaceborne gravimetry or altimetry), as well as for modelling studies of future glacier contribution to regional runoff and global sea-level change. In view of the *global stocktake* to assess the collective progress towards achieving the Paris Agreement (cf. UNFCCC, 2016, Article 14)), there is an increased demand for regular updates on the state of the climate. However, the approaches underlying these results are unsuitable for providing annual updates on the basis of new glaciological observations acquired each year due to the extensive analysis efforts required and due to generic lack of updates from multi-annual geodetic surveys (from DEM differencing). Here, we present a computational framework to produce *ad hoc* estimates of global-scale glacier contributions to sea-level rise from annual updates of glaciological observations. For this purpose, we combine the annual anomaly provided by the glaciological sample (relative to a decadal mean) with the (mean) absolute mass-change rate of a reference dataset (i.e., Zemp et al., 2019) over a common calibration period (from 2006/07 to 2015/16). As a result, we here provide preliminary estimates of regional and global glacier mass changes and related uncertainties for the hydrological years 2016/17 and 2017/18. We also discuss the regional biases of the glaciological sample and conclude with a brief outlook on possible applications and remaining limitations of the glaciological observation network of the World Glacier Monitoring Service (WGMS).

## 2 Data and methods

### 2.1 Regional glacier areas and related change rates

The global distribution of glaciers is taken from the Randolph Glacier Inventory (RGI) version 6.0 (RGI, 2017). This dataset lists 215,547 glaciers covering a total area of 705,739 km$^2$, mainly for survey years between 2000 and 2010. The glaciers in the RGI are grouped into 19 first-order regions, which seems to be appropriate with respect to the spatial correlation distance of glacier mass-balance variability (that is, several hundred kilometres; Cogley and Adams (1998), Letréguilly and Reynaud (1990)). We consider changes in glacier area over time by using annual change rates for all first-order regions from Zemp et al. (2019, and references therein). The regional glacier area $S$ for a given year $t_1$ was calculated as:

$$S_{t_1} = S_{t_0} + (t_1 - t_0) \cdot \frac{\delta S}{\delta t} = S_{t_0} + n \cdot \frac{\delta S}{\delta t} \quad , \qquad (1)$$

where $S_{t_0}$ is the regional glacier area in the survey year of the RGI, $\delta S/\delta t$ the annual area-change rate, and $n$ the number of years between $t_0$ and $t_1$.

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019




### 2.2 Regional glacier mass changes

We use the regional and global glacier mass changes (based on spatial interpolation) from 1961/62 to 2015/16 from Zemp et al. (2019) as a reference dataset. For each region, this data set combines the temporal variability from the glaciological sample, obtained using a spatiotemporal variance decomposition model, with the glacier-specific values of the geodetic sample. These calibrated annual time series in the unit meter water equivalent (1 m w.e. = 1,000 kg $m^{-2}$) were extrapolated from the observational to the full glacier sample within the region and multiplied by regional areas, resulting in regional mass changes in the unit Gt (1Gt = $10^{12}$ kg). Full details are found in Zemp et al. (2019).

### 2.3 Glaciological observations

Glacier-wide specific mass-balance data based on the glaciological method (cf., Cogley et al., 2011) are used as available from the Fluctuations of Glaciers (FoG) database of the WGMS (WGMS, 2018, updated 2019/07/26). This dataset is basically consistent with the glaciological data from 1961/62 to 2015/16 as used by Zemp et al. (2019) but includes updated mass balances for 2016/17 and preliminary estimates for 2017/18, as well as some corrections and addenda for earlier years. In total, this dataset contains 6,955 annual mass balances from 453 glaciers. For 2016/17 and 2017/18, it contains annual balances from 150 and 70 glaciers, respectively. The WGMS provides glaciological balances for hydrological years, which begin near the start of the accumulation season and end near the end of the ablation season (cf., Cogley et al., 2011). As a consequence, the results refer to different time periods when comparing regions from the Northern to the Southern Hemisphere, or to the Low Latitudes.

### 2.4 *Ad hoc* estimation of regional mass changes and sea-level equivalents

For a given *ad hoc* year of observations *Y* (e.g. 2017/18), we calculated the annual *ad hoc* estimate for regional mass changes and corresponding sea-level equivalents in five steps.

(i) For each glacier $g$ with observations in *Y*, we calculated the centred glaciological balance $\beta$ similar to Vincent et al. (2017) as the annual anomaly from the mean balance over the calibration period from 2006/07 to 2015/16:

$$\beta_{Y,g} = B_{\mathrm{glac}.Y,g} - \frac{\sum_{i=2007}^{2016} B_{\mathrm{glac},g,i}}{10} \quad . \qquad (2)$$

Over the calibration period results show that $\sum_{i=2007}^{2016} \beta_{i,g} = 0$. Here, the calibration period was set to the last decade of available reference data as these years best reflect the current mass-change conditions.

(ii) For each RGI region *r*, the mean centred glaciological balance $\bar{\beta}$ was calculated as the arithmetic average anomaly of the glaciers *G* with available data in *Y*:

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019



$$\bar{\beta}_{Y,r} = \frac{\sum_{g=1}^{G} \beta_{Y,g}}{G} \quad . \tag{3}$$

(iii) For each region *r*, the *ad hoc* estimate of the specific regional mass change $B_{\text{adhoc}}$ (in m w.e. yr$^{-1}$) was calculated by adding the regional anomaly $\bar{\beta}$ of the *ad hoc* year to the mean specific mass change $\bar{B}_{ref}$ of the corresponding region from the reference data over the calibration period from 2006/07 to 2015/16:

$$B_{\text{adhoc}.Y,r} = \bar{\beta}_{Y,r} + \bar{B}_{\text{ref},2007\text{–}16,r} \quad . \tag{4}$$

We note that for a stable glacier sample, the present approach corresponds to a simple bias correction of the glaciological sample with respect to the reference data. The corresponding regional bias $\varepsilon$ of the glaciological sample can be calculated as:

$$\varepsilon_{\text{glac},2007\text{–}16,r} = \bar{B}_{\text{glac},2007\text{–}16,r} - \bar{B}_{\text{ref},2007\text{–}16,r} \, . \tag{5}$$

(iv) For each region *r*, we calculated the *ad hoc* estimate of the regional mass change $\Delta M$ (in Gt yr$^{-1}$) by multiplying the regional specific mass change (in m w.e. yr$^{-1}$) by the regional glacier area *S* (in km$^2$), considering the cumulative area changes since the survey year of the RGI (cf. Eq. 1):

$$\Delta M_{\text{adhoc},Y,r} = \frac{B_{\text{adhoc},Y,r}}{1000} \cdot S_{Y,r} \quad . \tag{6}$$

(v) Finally, we calculated the *ad hoc* estimate of the corresponding worldwide sea–level equivalent *SLE* (in mm) as:

$$SLE_{\text{adhoc},Y} = (-1 \cdot \sum_{r=1}^{R} \Delta M_{\text{adhoc},Y,r}) / S_{\text{ocean}} * 10^{6} \quad , \tag{7}$$

where $S_{\text{ocean}}$ is the area of the ocean with 362.5 x 10$^6$ km$^2$ (Cogley, 2012).

For regions with no glaciological observations in the *ad hoc* year, we use available data from WGMS *reference* glaciers in neighbouring regions as shown in Table S1.

### 2.5 Uncertainty estimates

The regional mass changes from Zemp et al. (2019) come with error bars considering uncertainties from four independent sources: the temporal variability in the glaciological sample, the long-term geodetic mass changes, the extrapolation to

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019



unmeasured glaciers, and the regional glacier area. We combined these overall error bars with an additional uncertainty related to the estimation of the mass–balance anomaly. For each region, we calculated the latter uncertainty as 1.96 times the (sample) standard deviation of the mean centred glaciological balance over the calibration period from 2006/07 to 2015/16 (cf. Eq. 3). In cases with only one glacier in the glaciological sample (resulting in a standard deviation of zero), we set the uncertainty to 100% of the anomaly. The two errors were combined according to the law of random error propagation. For global sums, the overall error was calculated by cumulating the regional errors according to the law of random error propagation for independent terms.

## 3 Results and discussion

### 3.1 *Ad hoc* estimates for 2016/17 and 2017/18

For 2016/17, the glaciological observations from 150 glaciers (from 16 of 19 regions) give a global average specific mass change of –0.5 m w.e. $yr^{-1}$. The above presented *ad hoc* estimation suggests a global mass change of –311 ± 249 Gt $yr^{-1}$ corresponding to 0.9 ± 0.7 mm SLE (Table 1). Glaciers suffered most in Central Europe, Alaska and in the low latitudes with regional specific mass changes being more negative than –1 m w.e. $yr^{-1}$ (Table 1, Fig. 1). The largest contributions to global sea-level originated from Alaska (–116 Gt $yr^{-1}$), the Antarctic (–64 Gt $yr^{-1}$), and High Mountain Asia (–40 Gt $yr^{-1}$). For New Zealand and the Southern Andes, investigators reported positive mass balances indicating a mass gain of 8 Gt $yr^{-1}$ (essentially from the latter region).

For 2017/18, data reported thus far from 70 glaciers (from 13 out of 19 regions) comprises less than half of the currently observed glaciers. This is related to the one-year retention period that is granted to allow investigators time to properly analyse, document, and publish their data before submission to the WGMS. Based on this preliminary data, the global average specific mass change was –1.0 m w.e. $yr^{-1}$. The *ad hoc* estimation results in a global mass loss of 512 ± 138 Gt $yr^{-1}$ (not considering mass changes in Antarctica), corresponding to 1.4 ± 0.4 mm SLE. All regions reported negative mass balances. Regional specific mass balances were more negative than –1 m w.e. $yr^{-1}$ in seven regions, with New Zealand and Alaska even exceeding –2 m w.e. $yr^{-1}$ (Table 1, Fig. 1). With respect to sea-level rise, Alaska (–190 Gt $yr^{-1}$) and the Canadian Arctic (north and south combined: –129 Gt $yr^{-1}$) were the biggest contributor.

The *ad hoc* estimates for 2016/17 and 2017/18 indicate both a global glacier contribution of about one millimetre SLE – a benchmark that was only exceeded three times during the period from 1961/62 to 2015/16, when compared to the reference data (Fig. 2). The latest glaciological observations, hence, provide evidence of continued increasing glacier mass losses since the 1980s.

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019




### 3.2 Comparison to global reference dataset

We calculated annual *ad hoc* estimates for all years back to 1961/62 using the period from 2006/07 to 2015/16 for anomaly calculation and bias correction (Fig. 2a). These can be compared to the global reference data over the 45 years before 2006/07. We note that this is not a validation against independent data but an approach to test the ability of the glaciological sample of a given year to estimate the global glacier contribution to sea-level rise. Overall, the *ad hoc* estimates are in good agreement with the reference data but feature a slightly larger variability. The latter can be partially explained by the smaller sample size available for the *ad hoc* estimates. The best agreement is found over the more recent period back to 1990, followed by a strong variability and corresponding over and underestimations during the 1980s, and again relative good agreements again in the 1970s and 1960s. The strongest deviations occur in 1963/64, 1964/65, and between 1977/78 and 1987/88 and seem to be correlated with years in which many regions had positive glaciological balances. At the same time, the variance decomposition model as used by Zemp et al. (2019) tends to reduce the variance for statistically small samples since it only extracts the common year-to-year variability found in all glaciological time series of a region. The variability (at each glacier) that is not found at other locations is assigned to the residual (i.e. unexplained variance). As a consequence, our *ad hoc* estimate is generally well-suited to assess the global value of the more representative reference data. However, in years with small data samples and strong anomalies it remains arguable which of the two approaches better represents the true global glacier mass changes. The uncertainty range of the *ad hoc* estimates is larger than that of the reference data in the most recent validation period, since it combines the error bars of the reference data with those from the bias estimates. For the earlier validation periods, the uncertainty range of the reference data gets larger whereas the one from the *ad hoc* estimates is still based on reference data from the calibration period. This is arguably an artefact from the optimization of our approach to the estimation of mass changes for the most recent years 2016/17 and 2017/18.

The use of Zemp et al. (2019) as reference dataset has the advantage of analysing the performance of the *ad hoc* estimation at annual time resolution and back to the 1960s. However, our approach can be applied to other reference datasets that provide regional mass changes for a multi-year period. In Fig. S2, we demonstrate this with *ad hoc* estimations for selected regions (with large glacierization but limited data coverage in Zemp et al. (2019)) and different reference datasets (Bolch et al., 2013; Gardner et al., 2013; Wouters et al., 2019). The relative difference between the anomalies (derived from the glaciological sample) of the two *ad hoc* years are consistent but the absolute values vary between the different reference datasets (due to different mass change rates over the calibration periods).

### 3.3 Lessons learned for the glaciological observation network

In the field of glacier monitoring one outstanding question is, how representative are the local glaciological observations for regional to global mass changes (Fountain et al., 2009; Kaser et al., 2006). With the availability of a global reference dataset Zemp et al. (2019), the present approach allows us assessing the bias in the glaciological observations for all regions (cf. Eq.

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019


5, basically the difference between $B_{glac}$ and $B_{adhoc}$ in Table 1). The regional biases range between –0.6 and +0.5 m w.e. $yr^{-1}$ but average out for the global (area-weighted) mean. The latter is rather coincidental and can change with the use of a different reference dataset (e.g., Gardner et al., 2013; Wouters et al., 2019).

Another question is whether a glaciological observation network reduced to the long-term observation series is good enough to estimate the temporal variability of global glacier mass changes. We thus performed another *ad hoc* estimate with a glaciological sample reduced to the current 41 WGMS *reference* glaciers (Fig. 2b), all with more than 30 years of ongoing mass-balance measurements (WGMS, 2017). The WGMS *reference* glaciers provide a more stable sample over time but come at the price of a much reduced sample size. As such, the sample is reduced from 150 to 38 glaciers with observations in 2016/17 and, hence, neighbouring glaciers are needed in 10 (instead of 4) out of 19 regions (Table S1). The *ad hoc* estimates for the WGMS *reference* glacier sample from 1975/76 (i.e., the first year with *reference* data from the southern hemisphere) to 2016/17 show a much-increased variability, strong offsets over certain periods, and an increased uncertainty by about 40% (Fig. 2, Fig. S2). This low performance suggests that the WGMS *reference* glacier sample alone is too small and represents too few regions for an *ad hoc* estimation of global glacier contributions to sea-level rise. It is worthwhile to note that regions with large areas of glacierization (e.g. Arctic Canada South, Russian Arctic, South Asia East & West, peripheral Greenland, and peripheral Antarctica) lack long-term mass-balance series.

## 4 Conclusions

Direct glaciological observations, as currently conducted for about 150 glaciers worldwide, are able to satisfactorily capture the temporal mass-balance variability but are often not representative of the total mass change of a region. We presented a new approach to provide *ad hoc* estimates of regional glacier mass changes for the most recent years based on the anomaly of glaciological mass-balance observations and a bias correction to a reference dataset over a common calibration period from 2006/07 to 2015/16. The *ad hoc* estimates for 2016/17 and 2017/18 indicate that global glacier mass loss has further increased (with respect to the previous decade) and resulted in annual global glacier contributions to sea-level rise, which exceeded 1 mm SLE. Our new approach allows for the timely reporting of global glacier mass changes and can be applied to a new consensus estimate as reference data, once available. To increase the accuracy of the global *ad hoc* estimates, we need to extend the glaciological sample into so far underrepresented and strongly glacierized regions such as High Mountain Asia, the Southern Andes, Russian Arctic, Greenland or Antarctica, and we need additional geodetic coverage to further improve the reference dataset.

## Code availability

The analytical scripts are available from the lead author on request.

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019




**Data availability**

The full sample of glaciological (and geodetic) observations for individual glaciers is publicly available from the WGMS (https://doi.org/10.5904/wgms-fog-2018-11). The regional and global reference datasets are available from the Zenodo repository (https://doi.org/10.5281/zenodo.1492141).

**Supplementary material related to this article is available online at: [URL]**

**Author contribution**

MZ, FP and MH developed the basic concept of the study consulting with ET and NE for statistical backup; MZ, IG, and SN compiled and quality-checked the glaciological data with the support of the WGMS collaboration network; MZ performed all computations, designed the figures and wrote the manuscript. All authors commented on the manuscript.

**Competing interests**

The authors declare no competing interests.

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**References**

Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A., Zemp, M., Blunt, A. and Souch, C.: The concept of Essential Climate Variables in support of climate research, applications, and policy, Bull. Am. Meteorol. Soc., 95(9), 1431–1443, doi:10.1175/BAMS-D-13-00047.1, 2014.

Bolch, T., Sandberg Sørensen, L., Simonsen, S. B., Mölg, N., Machguth, H., Rastner, P. and Paul, F.: Mass loss of Greenland's glaciers and ice caps 2003-2008 revealed from ICESat laser altimetry data, Geophys. Res. Lett., 40(5), 875–881, doi:10.1002/grl.50270, 2013.

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019



Cogley, J. G.: Mass and energy balances of glaciers and ice sheets, in Encyclopedia of hydrological sciences, edited by M. G. Anderson and J. J. McDonnell, pp. 2555–2573, John Wiley & Sons., 2005.

Cogley, J. G.: Geodetic and direct mass-balance measurements: comparison and joint analysis, Ann. Glaciol., 50(50), 96–100, doi:10.3189/172756409787769744, 2009.

Cogley, J. G.: Area of the Ocean, Mar. Geod., 35(4), 379–388, doi:10.1080/01490419.2012.709476, 2012.

Cogley, J. G. and Adams, W. P.: Mass balance of glaciers other than the ice sheets, J. Glaciol., 44(147), 315–325, doi:10.3189/S0022143000002641, 1998.

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., Jansson, P., Kaser, G., Möller, M., Nicholson, L. and Zemp, M.: Glossary of glacier mass balance and related terms. IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris, France. [online] Available from: unesdoc.unesco.org/images/0019/001925/192525e.pdf, 2011.

Dyurgerov, M. B. and Meier, M. F.: Glaciers and the changing Earth system: a 2004 snapshot, Boulder CO, USA., 2005.

Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F. and Pandit, A.: A consensus estimate for the ice thickness distribution of all glaciers on Earth, Nat. Geosci., 12(3), 168–173, doi:10.1038/s41561-019-0300-3, 2019.

Fountain, A. G., Hoffman, M. J., Granshaw, F. and Riedel, J.: The 'benchmark glacier' concept – does it work? Lessons from the North Cascade Range, USA, Ann. Glaciol., 50(50), 163–168, doi:10.3189/172756409787769690, 2009.

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J.-O. O., van den Broeke, M. R. and Paul, F.: A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009, Science (80-. )., 340(6134), 852–857, doi:10.1126/science.1234532, 2013.

Hock, R., Bliss, A., Marzeion, B., Giesen, R. H., Hirabayashi, Y., Huss, M., Radic, V. and Slangen, A. B. A.: GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections, J. Glaciol., 65(251), 453–467, doi:10.1017/jog.2019.22, 2019.

Huss, M. and Hock, R.: Global-scale hydrological response to future glacier mass loss, Nat. Clim. Chang., 8(2), 135–140, doi:10.1038/s41558-017-0049-x, 2018.

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(19), 1–5, doi:10.1029/2006GL027511, 2006.

Kaser, G., Grosshauser, M. and Marzeion, B.: Contribution potential of glaciers to water availability in different climate regimes, Proc. Natl. Acad. Sci., 107(47), 20223–20227, doi:10.1073/pnas.1008162107, 2010.

Letréguilly, A. and Reynaud, L.: Space and time distribution of glacier mass-balance in the Northern Hemisphere, Arct. Alp. Res., 43–50, 1990.

Marzeion, B., Kaser, G., Maussion, F. and Champollion, N.: Limited influence of climate change mitigation on short-term glacier mass loss, Nat. Clim. Chang., 8(4), 305–308, doi:10.1038/s41558-018-0093-1, 2018.

Meier, M. F.: The contribution of small glaciers to sea level rise, Science (80-. )., 226, 1418–1421, 1984.

Ohmura, A.: Cryosphere during the twentieth century, in The State of the Planet: Frontiers and Challenges in Geophysics Geophysical Monograph 150, IUGG Volume 19, edited by R. S. J. Sparks and C. J. Hawkesworth, pp. 239–257., 2004.

RGI: Randolph Glacier Inventory - a dataset of global glacier outlines: version 6.0, technical report., 2017.

Trupin, A. S., Meier, M. F. and Wahr, J. M.: Effect of melting glaciers on the Earth's rotation and gravitational field: 1965-1984, Geophys. J. Int., 108(1), 1–15, doi:10.1111/j.1365-246X.1992.tb00835.x, 1992.

UNFCCC: Paris Agreement, , 27 [online] Available from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, 2016.

Vincent, C., Fischer, A., Mayer, C., Bauder, A., Galos, S. P., Funk, M., Thibert, E., Six, D., Braun, L. and Huss, M.: Common climatic signal from glaciers in the European Alpsover the last 50 years, Geophys. Res. Lett., 44, 1376–1383, doi:10.1002/2016GL072094, 2017.

WGMS: Global Glacier Change Bulletin No. 2 (2014-2015), edited by M. Zemp, S. U. Nussbaumer, I. Gärtner-Roer, J. Huber, H. Machguth, P. F., and M. Hoelzle, ICSU(WDS) / IUGG(IACS)/ UNEP / UNESCO / WMO, World Glacier Monitoring Service. Publication based on database version: doi:10.5904/wgms-fog-2017-10., Zurich, Switzerland. [online] Available from: http://wgms.ch/ggcb/, 2017.

WGMS: Fluctuations of Glaciers Database, , doi:10.5904/wgms-fog-2018-11, 2018.

Wouters, B., Gardner, A. S. and Moholdt, G.: Global Glacier Mass Loss During the GRACE Satellite Mission (2002-2016), Front. Earth Sci., 7, doi:10.3389/feart.2019.00096, 2019.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S. R., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila, L. R., Delgado Granados, H., Demuth, M. N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J.-O., Holmlund, P., Karimi, N., Li, Z., Pelto, M. S., Pitte, P., Popovnin, V. V., Portocarrero, C., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R. and Vincent, C.: Historically unprecedented global glacier decline in the early 21st century, J. Glaciol., 61(228), 745–762, doi:10.3189/2015JoG15J017, 2015.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S. and Cogley, J. G.: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016, Nature, 568(7752), 382–386, doi:10.1038/s41586-019-1071-0, 2019.

https://doi.org/10.5194/tc-2019-180
Preprint. Discussion started: 26 August 2019


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**Table 1** *Ad hoc* estimates of glacier mass changes in 2016/17 and 2017/18. For both years, the table shows glacier areas (S) based on RGI (2017) and corrected for annual area change rates from Zemp et al. (2019), specific mass changes (*B*) calculated as arithmetic mean of glaciological sample (glac) and based on the *ad hoc* estimation (adhoc, Eq. 4), as well as anomaly-corrected mass change ($\Delta M$, Eq. 6) for all regions and global totals. Global specific mass changes and related biases are calculated as area-weighted regional means, excl. Antarctica for 2017/18. Uncertainties correspond to 95% confidence intervals. The global mass changes in 2016/17 and 2017/18 correspond to 0.9 ± 0.7 and 1.4 ± 0.4 mm SLE per year, respectively. Glaciological input data are from WGMS (2018), updated 2019/07/26.

| Region | Area (km$^2$) | | Specific mass change (m w.e. yr$^{-1}$) | | | | Mass change (Gt yr$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | *S* 2017 | *S* 2018 | $B_{glac}$ 2017 | $B_{adhoc}$ 2017 | $B_{glac}$ 2018 | $B_{adhoc}$ 2018 | $\Delta M$ 2017 | $\Delta M$ 2018 |
| 01 Alaska | 83,395 | 82,978 | –1.19 | –1.39±0.61 | –1.85 | –2.29±0.56 | –116±51 | –190±47 |
| 02 Western Canada & USA | 13,661 | 13,583 | –0.54 | –0.68±1.12 | –0.65 | –0.85±0.74 | –9±15 | –12±10 |
| 03 Arctic Canada North | 103,860 | 103,787 | 0.03 | 0.07±0.99 | –0.82 | –0.9±0.87 | 8±103 | –93±91 |
| 04 Arctic Canada South | 40,332 | 40,299 | –0.22 | –0.22±1.18 | –0.82 | –0.9±0.78 | –9±48 | –36±31 |
| 05 Greenland | 77,946 | 77,210 | –0.41 | –0.27±0.65 | –0.33 | –0.44±0.6 | –21±50 | –34±46 |
| 06 Iceland | 10,383 | 10,343 | –0.29 | –0.32±1.01 | –1.17 | –1.42±1.45 | –3±11 | –15±15 |
| 07 Svalbard & Jan Mayen | 32,546 | 32,458 | –0.7 | –0.68±0.59 | –0.62 | –0.73±0.39 | –22±19 | –24±13 |
| 08 Scandinavia | 2,830 | 2,822 | –0.04 | –0.09±1.35 | –1.42 | –1.53±0.92 | 0±4 | –4±3 |
| 09 Russian Arctic | 51,138 | 51,097 | –0.72 | –0.69±0.45 | –0.82 | –0.8±0.45 | –35±23 | –41±23 |
| 10 North Asia | 2,348 | 2,337 | –0.9 | –0.67±0.76 | –0.39 | –0.17±0.64 | –2±2 | 0±2 |
| 11 Central Europe | 1,820 | 1,800 | –1.71 | –1.65±1.15 | –1.53 | –1.43±1.31 | –3±2 | –3±2 |
| 12 Caucasus & Middle East | 1,196 | 1,189 | –0.84 | –0.89±0.9 | –0.22 | –0.28±1.67 | –1±1 | 0±2 |
| 13 Central Asia | 48,061 | 47,972 | –0.75 | –0.36±0.81 | –0.5 | –0.11±0.61 | –18±39 | –5±29 |
| 14 South Asia West | 31,876 | 31,755 | –0.9 | –0.34±0.69 | –0.39 | 0.17±0.55 | –11±22 | 5±18 |
| 15 South Asia East | 13,765 | 13,695 | –1.06 | –0.77±1.04 | –1.37 | –1.1±0.44 | –11±14 | –15±6 |
| 16 Low Latitudes | 1,867 | 1,840 | –1.08 | –1.15±1.53 | –0.83 | –0.75±1.52 | –2±3 | –1±3 |
| 17 Southern Andes | 28,528 | 28,476 | 0.74 | 0.27±4.95 | –1.13 | –1.47±1.95 | 8±141 | –42±56 |
| 18 New Zealand | 849 | 841 | 0.41 | 0.13±1.78 | –2.34 | –2.62±1.77 | 0±2 | –2±2 |
| 19 Antarctic & Subantarctic | 122,822 | 122,464 | –0.28 | –0.52±1.16 | n.a. | n.a. | –64±143 | n.a. |
| Global total, excl. 05 & 19 | 468,455 | 467,272 | –0.51 | –0.48±0.42 | –0.97 | –1.02±0.28 | –226±197 | –478±130 |
| Global total | 669,223 | 666,946 | –0.46 | –0.47±0.37 | –0.88 | –0.94±0.25 | –311±249 | –512±138 |

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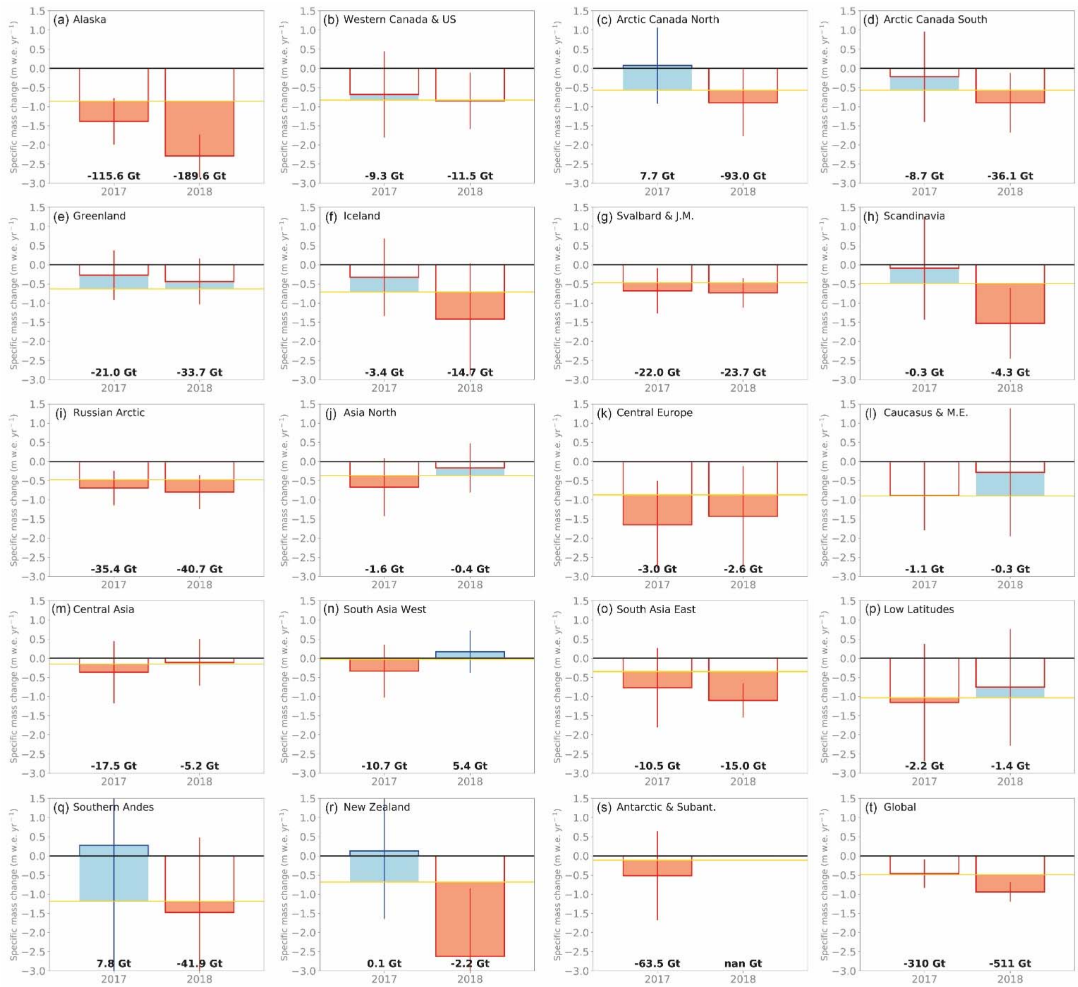


**Figure 1** *Ad hoc* estimates of regional mass changes in 2016/17 and 2017/18. The regional (**a–s**) and global (**t**) bar plots show the annual specific mass changes with related error bars (indicating 95% confidence intervals), with positive and negative values in blue and red, respectively. The golden line indicates the annual mass-change rate of the reference data Zemp et al. (2019) over the calibration period (2006/07–2015/16). Positive and negative annual mass-change anomalies (with respect to reference data and calibration period) are indicated in pale blue and pale red, respectively. The plots show specific mass changes in m w.e. yr$^{-1}$ with the exception of the black values (bottom) indicating annual mass changes in Gt yr$^{-1}$. Plots are ordered from top left to bottom right according to the region numbers in RGI 6.0 (see Table 1).

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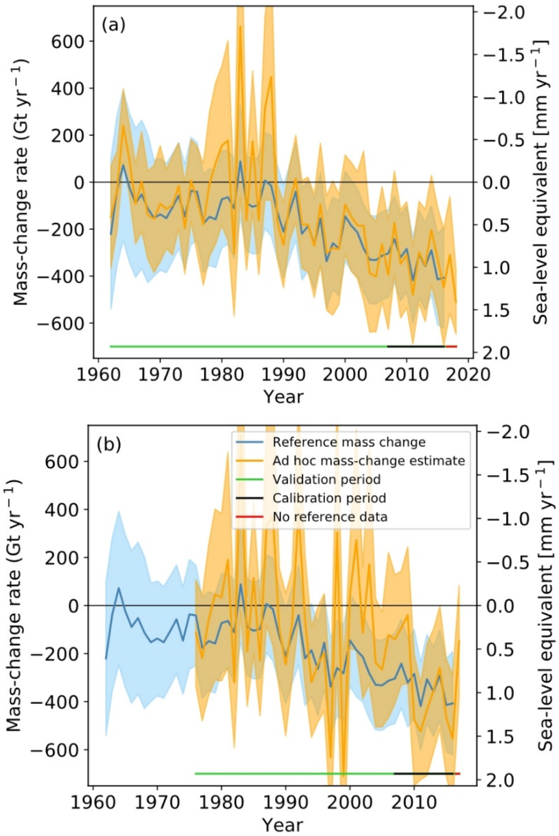


**Figure 2** Global glacier contributions to sea-level rise from 1961/62 to 2017/18. (**a**) Annual mass-change rates (left y-axis) and global sea-level equivalents (right y-axis) are shown with related error bars (indicated by shadings) corresponding to 95% confidence intervals. The *ad hoc* estimates (orange), based on the full glaciological samples of corresponding years, are shown with the reference dataset (blue) by Zemp et al. (2019), which was used for calibration. The bottom line indicates the time periods used for calibration (black), validation (green), and without reference data (red). (**b**) Same plot but for *ad hoc* estimates (orange) solely based on glaciological data from the 41 WGMS *reference* glaciers (with more than 30 years of ongoing measurements). Due to limited data coverage, no *ad hoc* estimates were possible for 2017/18 and before 1975/76.