Supplementary material:

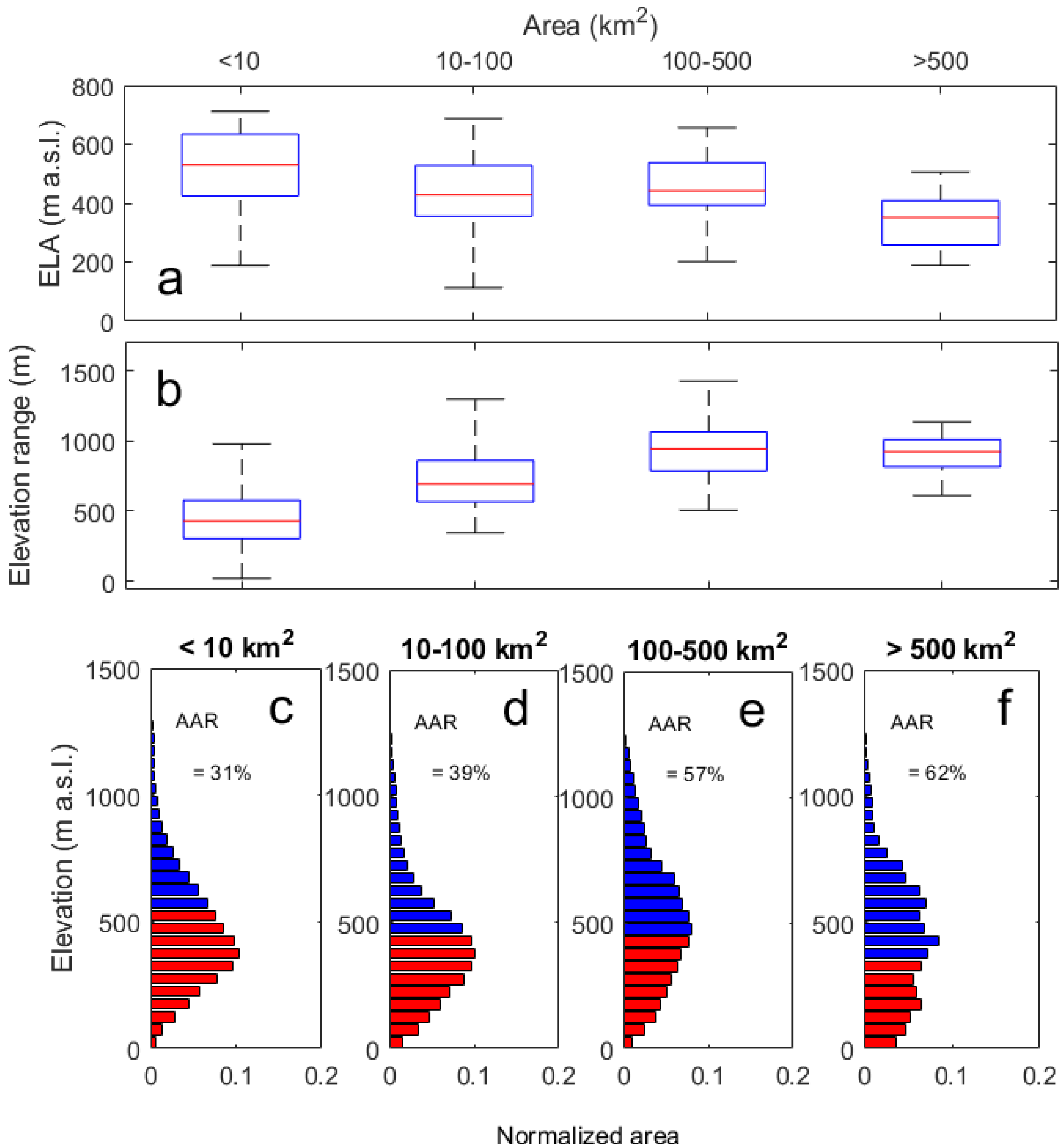
S1 Background for the glacier area – mass balance relationship used for upscaling

The glacier area – mass balance relationship found in the dataset of surveyed glaciers is strictly valid only for the investigated period 2000-2019, and for the glaciers in the sample. To support our upscaling method, we investigate whether this relation is just an artifact of the bias in the sampling locations or whether it has a more general applicability. In absence of comparable mass balance data for all glaciers, we analyze the distributions of equilibrium line altitude (ELA) and accumulation-area ratio (AAR) of all glaciers as proxies for CMB. With "all glaciers" we mean all entries of the Svalbard glacier database (König et al, 2014), which is identical to the corresponding region in the global Randolph Glacier Inventory RGI (Pfeffer et al., 2014).

In the glacier database, each entry comprises geographical coordinates of the centroid location. Each of these locations has been associated with an ELA, taken from the nearest grid point of van Pelt el at. (2019)'s simulation domain. Using the hypsometric information in the database, the area fraction above the ELA (=AAR) has been determined for each glacier and for each of the years in the period 2000-2019.

Supplementary Figure 1 shows that ELA decreases with increasing glacier area. We interpret this to mean that regions having lower ELA are more favorable for glaciers, and that therefore glaciers tend to be larger there, and conversely (SFig. 1 a). In addition, larger glaciers cover a larger elevation span than smaller ones (SFig 1 b), effectively reaching higher elevations in most cases. Furthermore, smaller glaciers tend to have less of their area above the ELA, meaning they have a lower AAR, compared to larger glaciers (SFig 1 c-f). In combination, this uneven distribution of ELA, together with the hypsometric differences between smaller and larger glaciers, leads to smaller glaciers experiencing higher rates of mass loss than larger ones. We exploit this glacier area-mass balance relationship for upscaling the glaciological measurements to estimate the CMB of all Svalbard glaciers.

Here, we show that AAR and glacier area of all Svalbard glaciers exhibit a qualitatively similar relationship as the measured CMB and glacier area for the surveyed glaciers, which provides support for our upscaling method. Further, and consistent with findings by McGrath et al. (2017), we argue that smaller glaciers are most sensitive to relatively small ELA perturbations, which may shift the ELA above the elevations of the accumulation area (for example SFig 1 c). Larger glaciers, having a more top-heavy hypsometric distribution (for instance ice fields and ice caps), preserve more of their surface area above the ELA (SFig 1 f), but can also suddenly become extremely sensitive when the ELA reaches the elevation bands of the accumulation area.



Supplementary Figure 1: Analysis of equilibrium line altitude (ELA), elevation range, accumulation-area ratio (AAR) and area-elevation distribution for the different size classes and for all Svalbard glaciers represented in RGI (Pfeffer et al. 2014; König et al., 2014). The ELA is according to Van Pelt et al., 2019. a) Boxplot of ELA for the different size classes; the red line represents the median, the blue box the 25 and 75 percentiles and the whiskers indicate the extend of the data. b) Boxplot of elevation ranges, determined as the difference between maximum and minimum elevation of the glacier. c)-f) Area-elevation distributions for each size class, for comparison, the area values have been normalized using the total area in each class. The colors indicate the elevation of the median ELA such that red (blue) denotes elevation below (above) the ELA. The collective AAR of each class is marked in the respective panel.

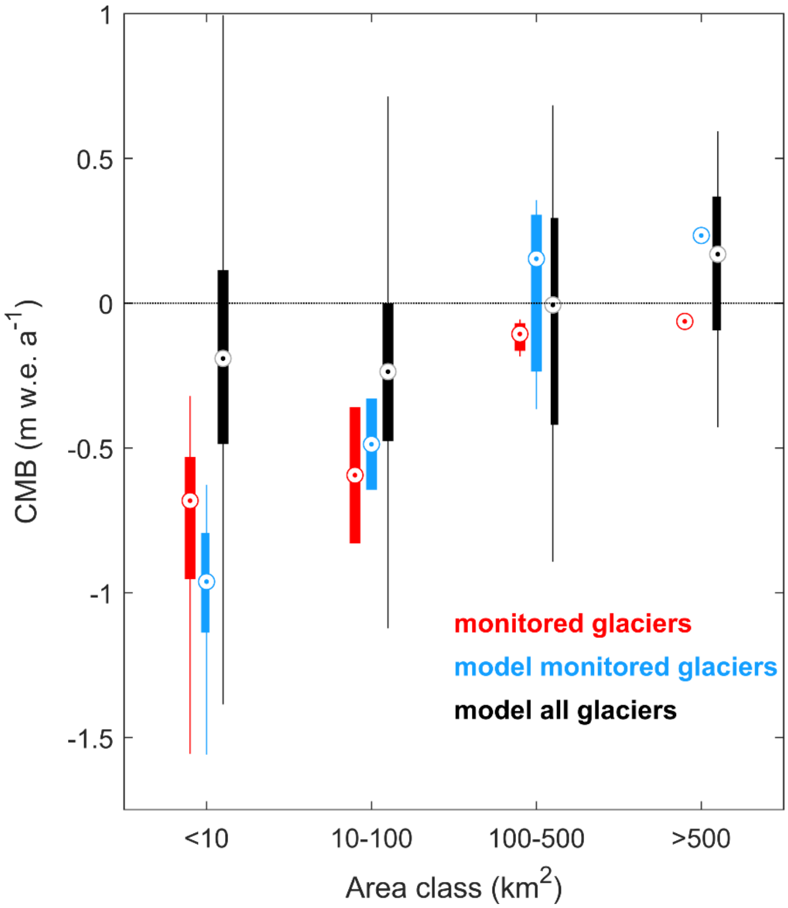
S2: Representativeness of measured glaciers

In addition, we have investigated whether such a relationship was also found in CMB simulations for all of Svalbard. Here, we used the simulated CMB by Van Pelt et al. (2019) for the period 2000-2018. The difficulty is that it is not possible to simply calculate the mass balance for small glaciers, given the 1-km model resolution. To overcome this limitation, we establish linear CMB-elevation relationships from available model CMB values against elevation in a moving 11-km search window. In each window, this relation is applied on a 50-m DEM to produce a high-resolution CMB field from which glacier-wide mass balances were determined for each glacier in the Svalbard glacier database. The figure below demonstrates that there is generally good agreement between measured and simulated CMB for the individual glaciers in the glaciological record, suggesting the absence of a fundamental bias between model and measurements. However, when considering all Svalbard glaciers, this agreement disappears for the class of small glaciers (<10 km2). This suggests a representativeness issue with the small glaciers selected for CMB monitoring.

Nevertheless, this class only occupies 8% of the total glacier area on Svalbard: therefore this has only a minor effect on our Svalbard-wide estimate sine the larger size classes (occupying 92% of the glacier area) are relatively well represented by the field measurements.

This analysis provides additional support for our upscaling procedure since it limits the effects of imperfect representativeness on the Svalbard-wide estimate. If available glaciological records were simply averaged and multiplied by the total glacier area, the Svalbard-wide estimate would have been -17.3 Gt a-1, instead of -7 Gt a-1 that we obtain by area-dependent upscaling. The latter is much more in line with other independent estimates (cf Fig. 3).

In apparent contrast to our discussion above, Zemp et al. (2020) did not find a systematic bias when comparing their ad-hoc estimate (based on averaging of small glacier records) to geodetic estimates. However, the geodetic record (with appropriate density conversion) represents the total mass balance, whereas the glaciological method samples the climatic mass balance. Frontal ablation is without doubt a significant component on Svalbard, hence, the total mass balance must be lower than the climatic mass balance. We argue above that the small glaciers with very negative mass balance are overrepresented in the glaciological sample, thereby introducing a negative bias into the arithmetic mean of the glaciological record. Zemp et al. (2020) find that this biased average of surface mass balance is similar to the geodetically derived, total mass balance, hence suggesting that the bias is similar to the frontal ablation. We regard this as pure coincidence.

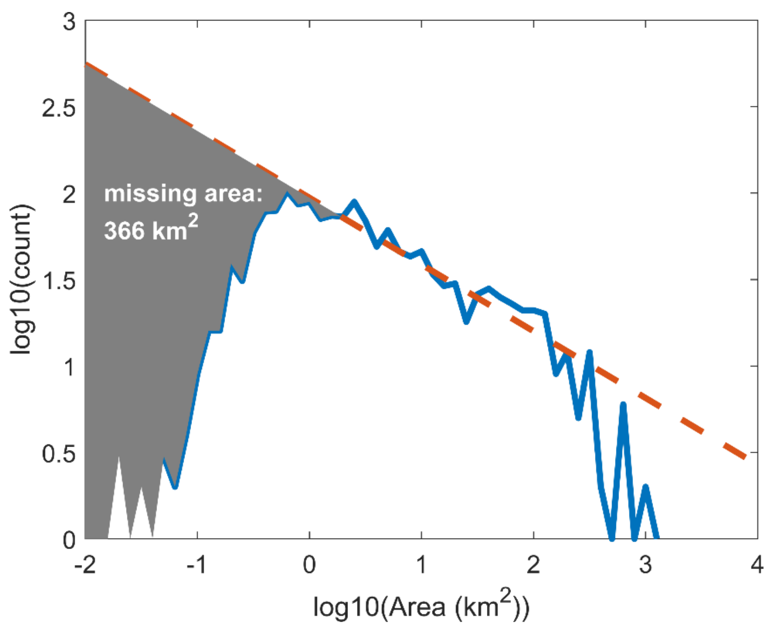


Supplementary Figure 2: Box plots of CMB (2000-2018) for different classes of glacier area. Red color refers to the 12 measured glaciers, blue boxes represent simulated CMB by Van Pelt et al. (2019) for the same glaciers, and black represents simulated CMB for all glaciers.

S3: Estimating uncharted glacier area

Adopting the methodology proposed by Parkes & Marzeion (2018), we have estimated the "missing" area of glaciers that are under-represented in the database due to their small size. Assuming a scaling relationship between glacier area and frequency of occurrence, the "missing" area is determined by extrapolating this relationship to the 10^{-2} km^2 end of the distribution and subtracting the mapped glacier area. In doing so, we obtain a "missing" area for the Svalbard glacier database of 366 km^2, corresponding to about 1% of the total mapped glacier area.

To estimate the effect this "missing" area on our estimate of CMB derived from glaciological measurements, we multiply this area with the specific mass balance for the class of smallest glaciers. For the latter, we use the median and minimum of the measured values, -0.7 m a^{-1} and -1.6 m a^{-1} and obtain the bounds of the additional mass loss from the "missing" area of 0.25 and 0.58 Gt a^{-1}. This corresponds to about 5% of the 7 Gt a^{-1} that we have estimated for all glaciers on Svalbard.



Supplementary Figure 3: Glacier area distribution for all glaciers in the Svalbard glacier database (König et al., 2014) contained in the RGI (Pfeffer et al.,2014). The blue line represents the frequency for each $10^{0.25}$ km^2 wide bin. The stippled red line is a linear function fitted to the $10^{-0.5}$ – $10^{2.5}$ km^2 subset of the data in a log-log plot. The difference between the two curves at the lower end of the distribution represents the "missing" area, shown as green shading, according to Parkes & Marzeion (2018).

References:

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