Supplementary information for 'Substantial contribution of avalanches to glacier accumulation in the 21st century'

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Supplementary Tables

Supplementary Table 1: regional avalanche contribution metrics averaged over the period 01/2000 - 12/2019. *These values were used to compute Figure 2.*

RGI region	Regional positive avalanche contribution (%)	Regional negative avalanche contribution (%)	Regional net avalanche contribution (%)	Median avalanche contribution (%)	20th percentile of avalanche contribution (%)	80th percentile of avalanche contribution (%)	Glacier area (km^2)	Total snow accumulation (m w.eq. yr^{-1})
Alaska	5.2	-0.9	4.3	1.4	-0.4	11.9	86,492	2.5
Western Canada and USA	6.8	-1.5	5.2	2.4	-0.2	16.2	14,567	2.3
Arctic Canada North	0.0	-0.1	-0.1	-0.1	-0.2	0.1	105,253	0.7
Arctic Canada South	0.5	-0.2	0.3	0.0	-0.3	0.5	40,760	0.9
Greenland Periphery	2.4	-0.6	1.8	0.3	-0.3	6.6	74,766	1.5
Iceland	0.2	-0.1	0.1	0.2	-0.2	1.8	11,015	2.9
Svalbard and Jan Mayen	0.2	-0.1	0.1	0.1	-0.2	0.7	34,017	1.4
Scandinavia	3.4	-0.6	2.8	0.6	-0.3	9.5	2,958	2.4
Russian Arctic	0.0	-0.1	-0.1	-0.1	-0.2	0.1	52,020	1.0
North Asia	3.2	-1.0	2.1	0.8	-0.3	6.0	2,330	1.3
Central Europe	11.1	-1.9	9.1	4.8	-0.3	26.0	2,044	2.4
Caucasus and Middle East	11.1	-3.7	7.4	3.0	-1.5	15.6	1,139	2.5
Central Asia	3.0	-1.3	4.3	0.2	-0.3	1.6	49,344	1.0
South Asia West	5.9	-1.2	4.7	0.6	-0.5	5.7	33,669	1.2
South Asia East	19.2	-8.0	11.2	2.0	-0.7	15.6	14,492	2.1
Low Latitudes	5.7	-8.0	-2.3	-0.3	-5.9	2.6	2,251	1.9
Southern Andes	2.9	-4.4	-1.5	0.1	-1.7	2.1	29,137	1.5
New Zealand	21.8	-7.2	14.6	2.9	-9.3	30.8	1,125	3.4
Subantarctic and Antarctic Islands	0.5	-0.5	0.0	-0.0	-0.8	1.4	135,762	1.7
Global	3.0	-1.1	2.0	0.4	-0.4	5.9	693,150	1.5

Supplementary Table 2: Statistics of number and area of successfully modelled glaciers for each RGI region.

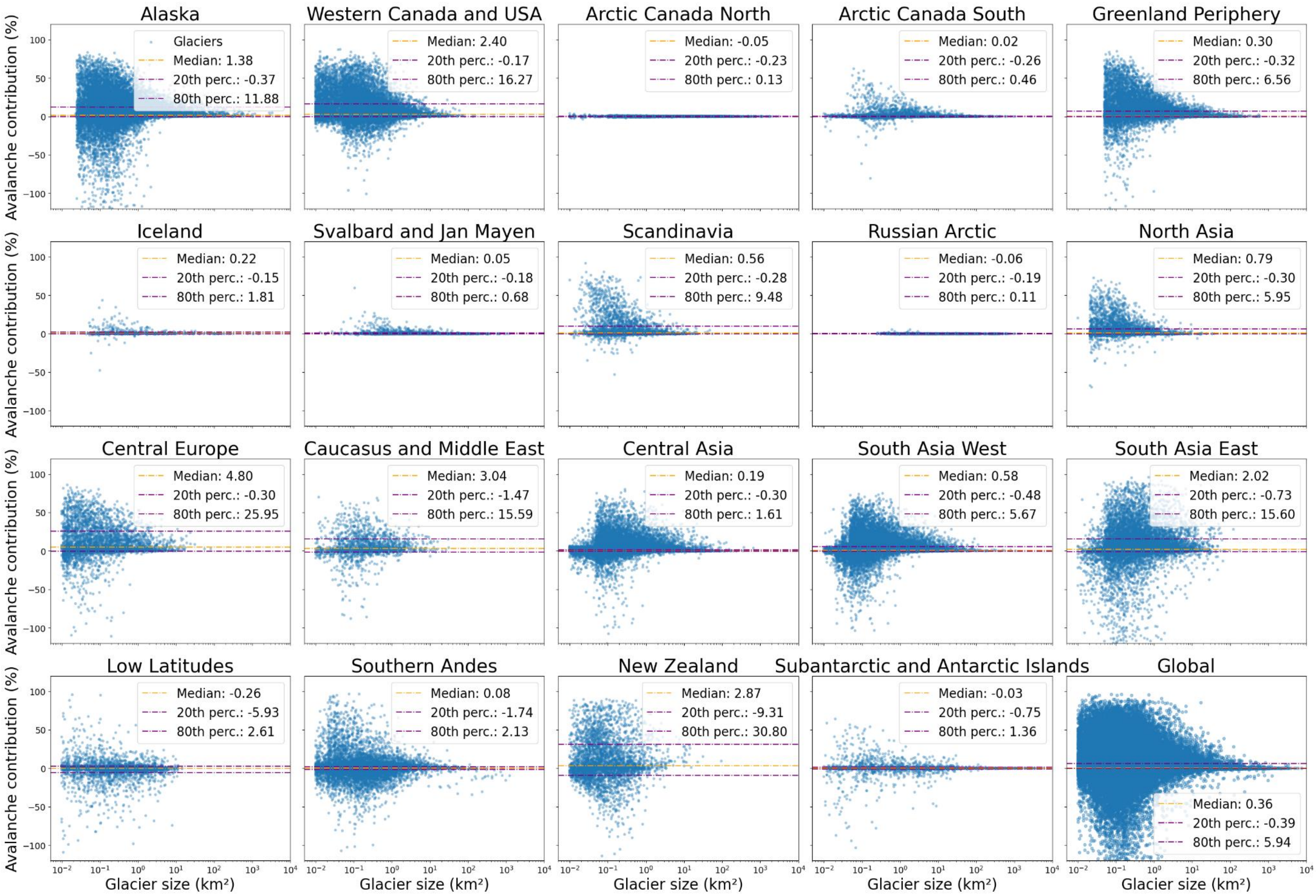
RGI region	Total number of glaciers	Total glacier area in 2000 (km^2)	Successfully modelled glaciers (%)	Successfully modelled area (%)
01	27108	86725	99.6	100.0
02	18855	14524	98.3	99.9
03	4556	105111	99.4	100.0
04	7415	40888	99.5	100.0
05	18306	89717	99.1	83.3
06	568	11060	100.0	100.0
07	1615	33959	100.0	100.0
08	3417	2949	99.6	100.0
09	1069	51592	99.7	100.0
10	5151	2410	96.5	96.3
11	3927	2092	96.5	99.8
12	1888	1307	80.7	87.9
13	54429	49303	99.3	99.8
14	27988	33568	99.6	99.9
15	13119	14734	99.1	99.7
16	2939	2341	94.2	97.3
17	15908	29429	98.6	99.1
18	3537	1162	97.1	93.9
19	2752	132867	80.4	99.8
Global	214547	705738	98.6	97.7

Supplementary Table 3: Effect of DEM spatial resolution on regional avalanche contribution. *Regional avalanche contribution metrics for Central Europe over the period 01/2000 - 12/2019 for the model run at 50 m, 100 m and variable spatial resolution.*

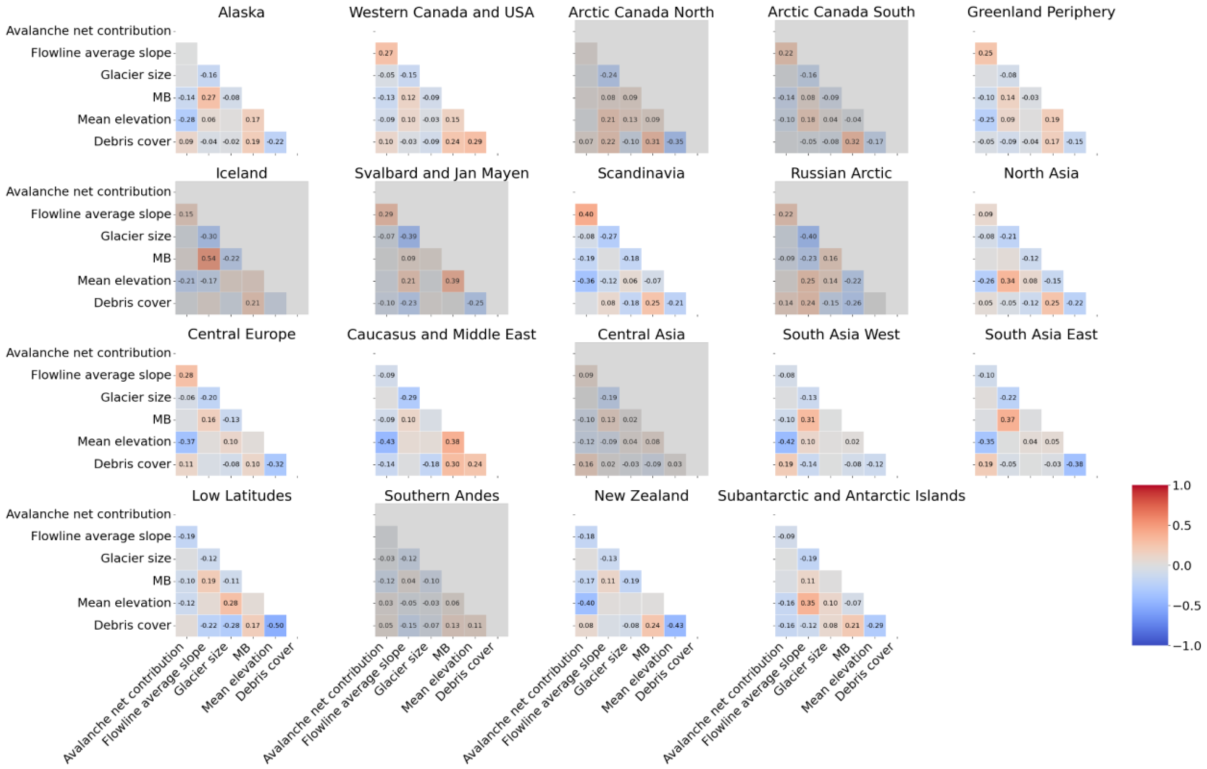
DEM spatial resolution (m)	50	100	Variable (reference)
Regional net avalanche contribution (%)	9.4	8.9	9.1
Regional positive avalanche contribution (%)	11.4	11.1	11.1
Regional negative avalanche contribution (%)	-2.1	-2.2	-1.9
Median avalanche contribution (%)	3.7	4.7	4.8
20th percentile of avalanche contribution (%)	-2.7	-1.0	-0.3
80th percentile of avalanche contribution (%)	24.2	18.5	26.0

Supplementary Figures

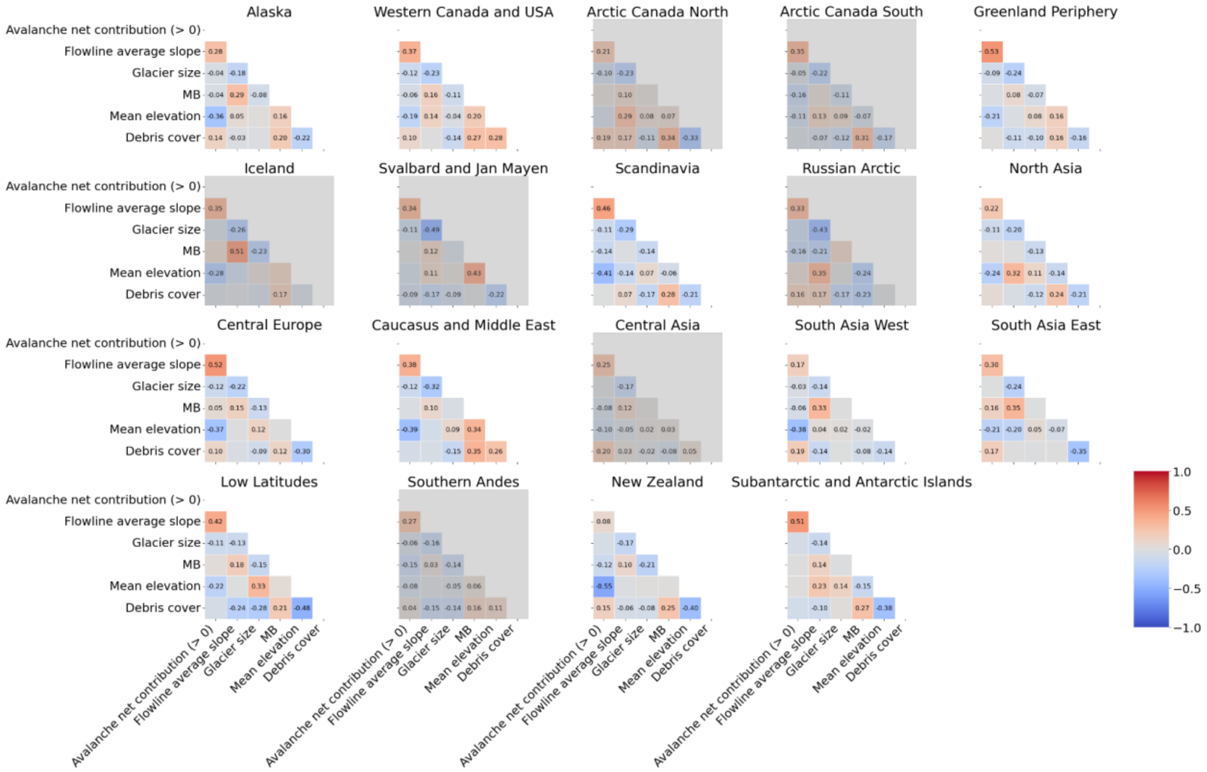
Glacier-wide avalanche contribution and glacier variables



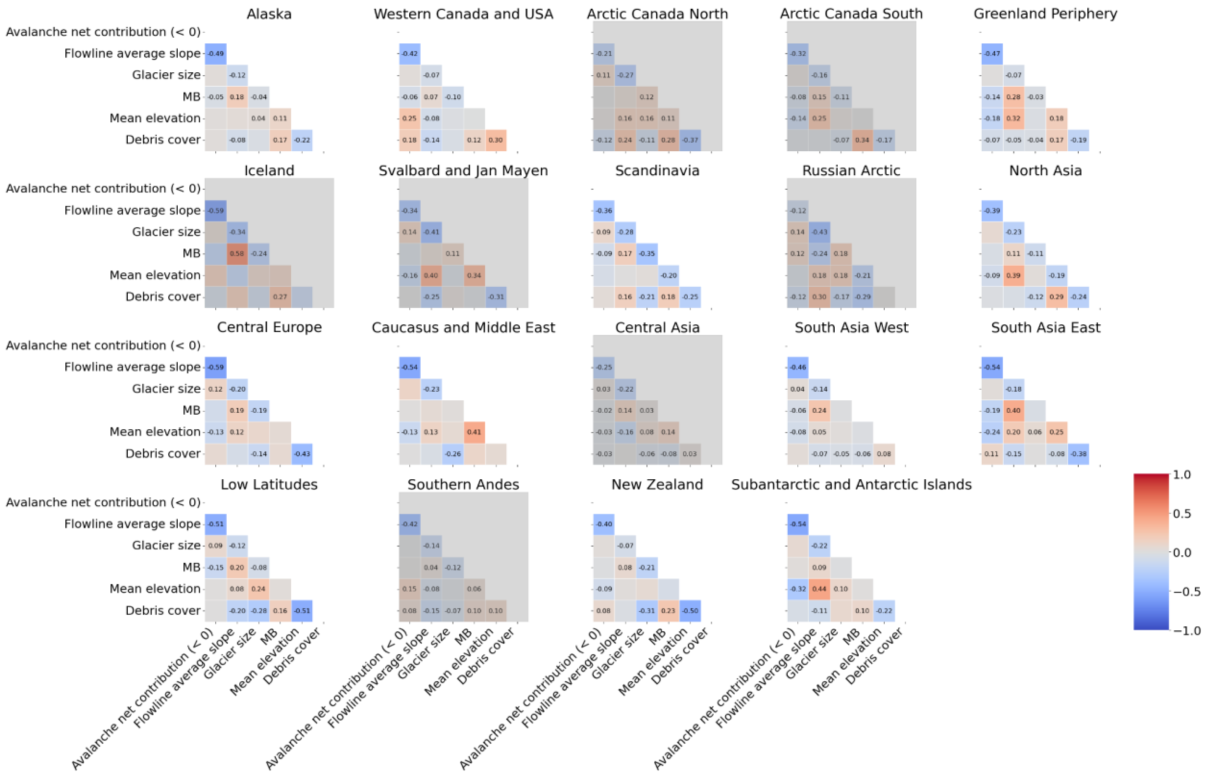
Supplementary Figure 1: Glacier-wide net avalanche contribution as a function of glacier size for each RGI region. *The yellow horizontal line corresponds to the median glacier-wide net avalanche contribution and the purple lines correspond to the 20th and 80th percentile values.*



Supplementary Figure 2: Characteristics of avalanche-fed glaciers. *Correlation matrices of the glacier-wide net avalanche contribution, glacier average slope along the flowline, size, geodetic mass balance, mean elevation and percentage of debris cover for each RGI region. The values correspond to Pearson's correlation coefficients, and only those with a significant correlation (p-value < 0.01) are shown. Regions with a 20th and 80th percentile of the net avalanche contribution within -5% and +5%, which corresponds to a generally low influence from avalanches, are shaded in gray.*

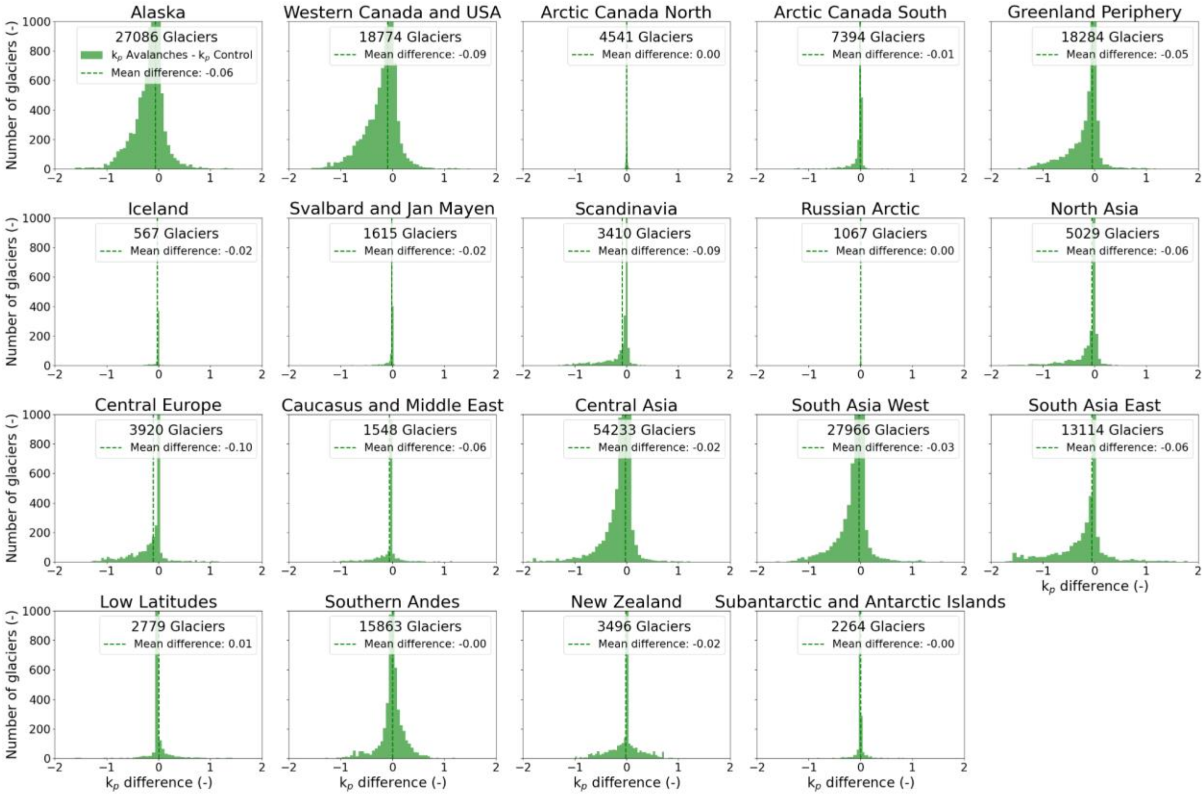


Supplementary Figure 3: Characteristics of positively avalanche-fed glaciers. *Same as Fig. S2 but only for a strictly positive glacier-wide net avalanche contribution to the glacier accumulation.*



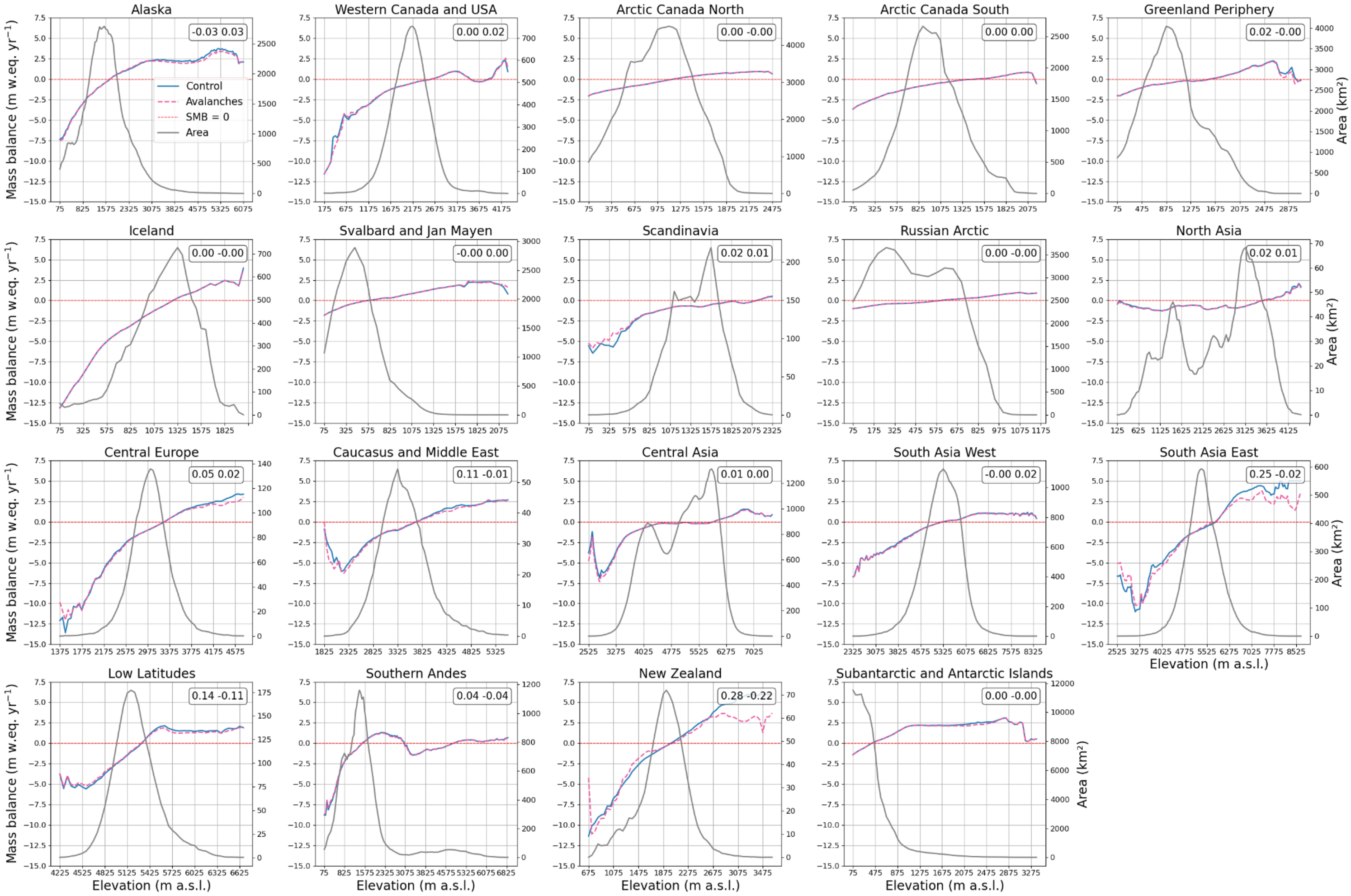
Supplementary Figure 4: ***Characteristics of negatively avalanche-fed glaciers.*** *Same as Fig. S2 but only for a strictly negative glacier-wide net avalanche contribution to the glacier accumulation.*

Influence of avalanches on the recalibration of the mass balance model



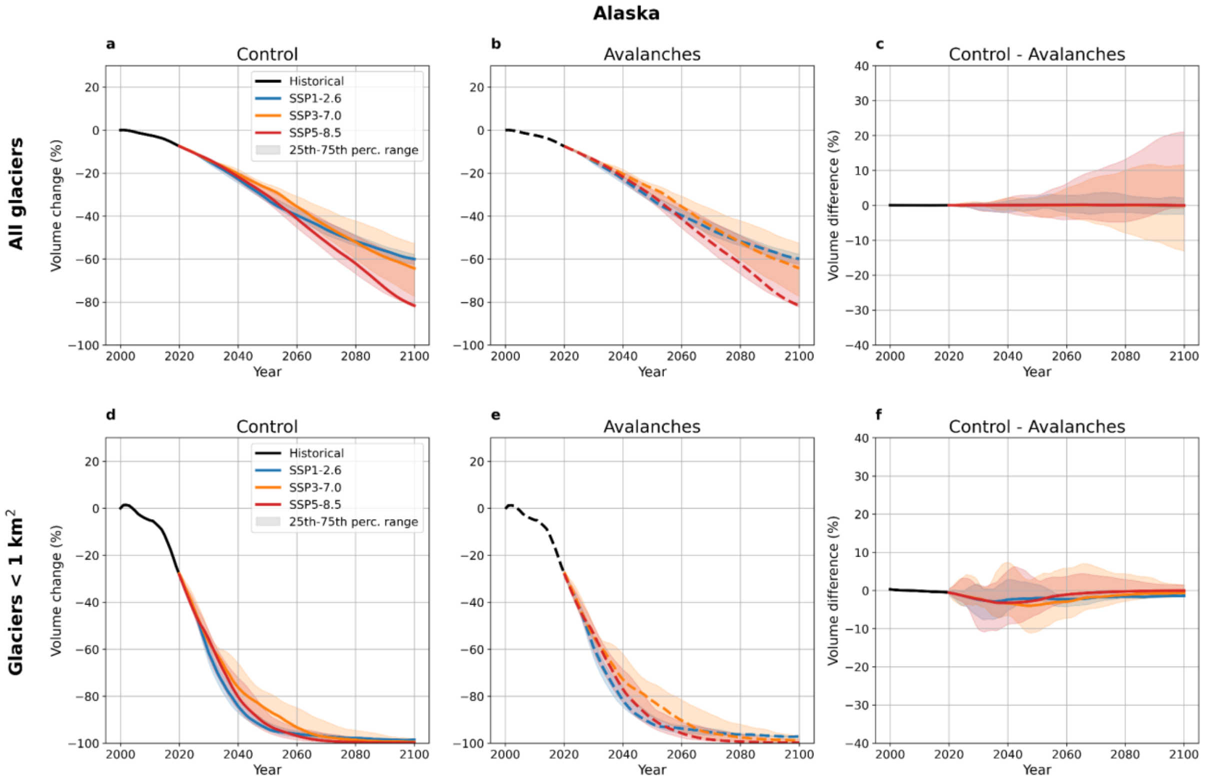
Supplementary Figure 5: Precipitation correction factor with and without avalanches. *Differences between precipitation correction factor (k_p) for all glaciers, with and without accounting for avalanches, after calibration of the 'Control' and 'Avalanches' models over the period 01/2000-12/2019. A negative value means that the precipitation correction factor is lower when explicitly accounting for avalanches.*

Altitudinal mass balance profiles

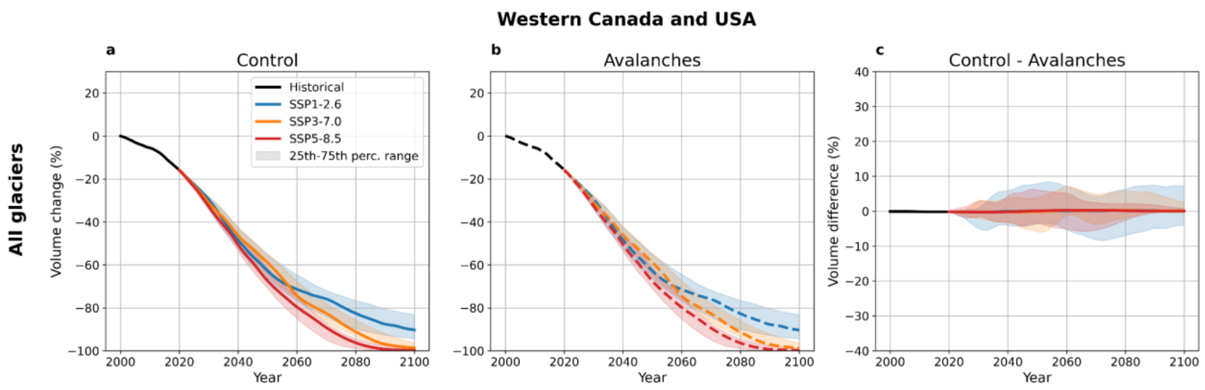


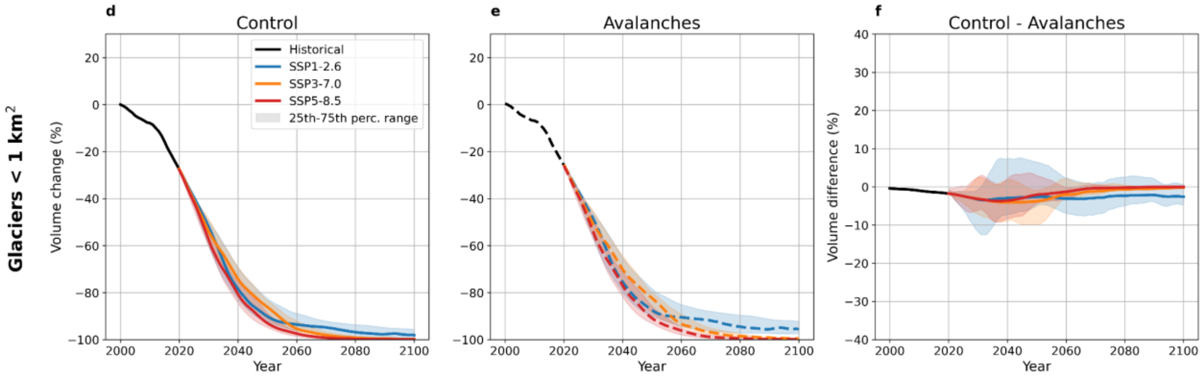
Supplementary Figure 6: Influence of avalanches on the regional mass balance altitudinal profiles. *Altitudinal mass balance profiles with (blue) and without (pink) avalanches for all RGI 6.0 regions. These profiles were obtained by taking the area-weighted average of the altitudinal profiles of all glaciers of the corresponding regions over the period 01/2000-12/2019. The gray line shows the glacier hypsometry and the red dashed line corresponds to a mass balance value of 0 m w.eq. yr^{-1}. The values in the upper right corner indicate the area-weighted mean difference between the mass balance with and without avalanches in the accumulation and the ablation zones.*

Projected ice volume changes

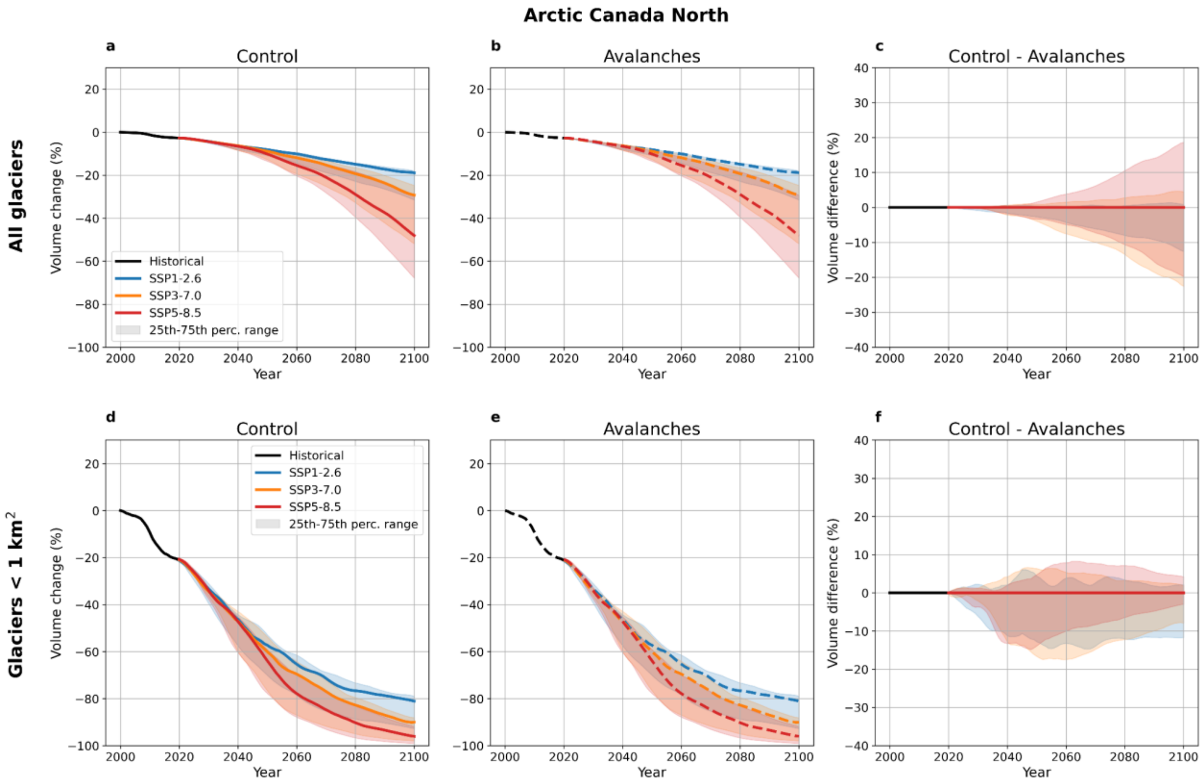


Supplementary Figure 7: Influence of avalanches on regional glacier volume changes in Alaska. *Projected ice volume changes of all glaciers (a-c) and the glaciers smaller than 1 km^2 (d-f) in Alaska, from the 'Control' (a, d) and 'Avalanches' (b, e) simulations. The right-hand plots (c, f) show the difference between the 'Control' and the 'Avalanches' simulations, so that negative values indicate more volume in the 'Avalanches' simulations. All percentages are given relative to the initial volume in 2000 in the 'Control' simulation. The black line corresponds to the historical period over which the mass balance model was calibrated using W5E5v2.0 data. The colored lines show the median future projections for different SSP scenarios, and the shaded areas indicate the 25th-75th percentile range. The different curves were smoothed using a 5-year rolling mean.*

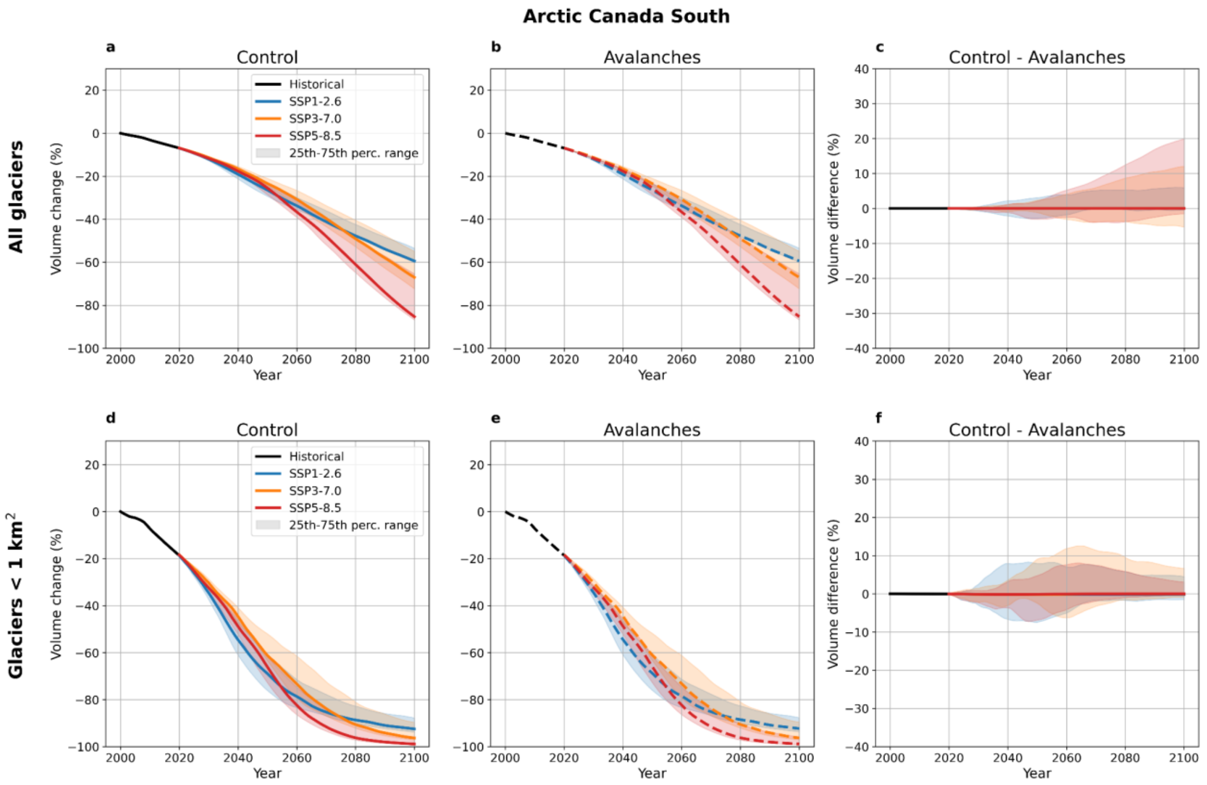




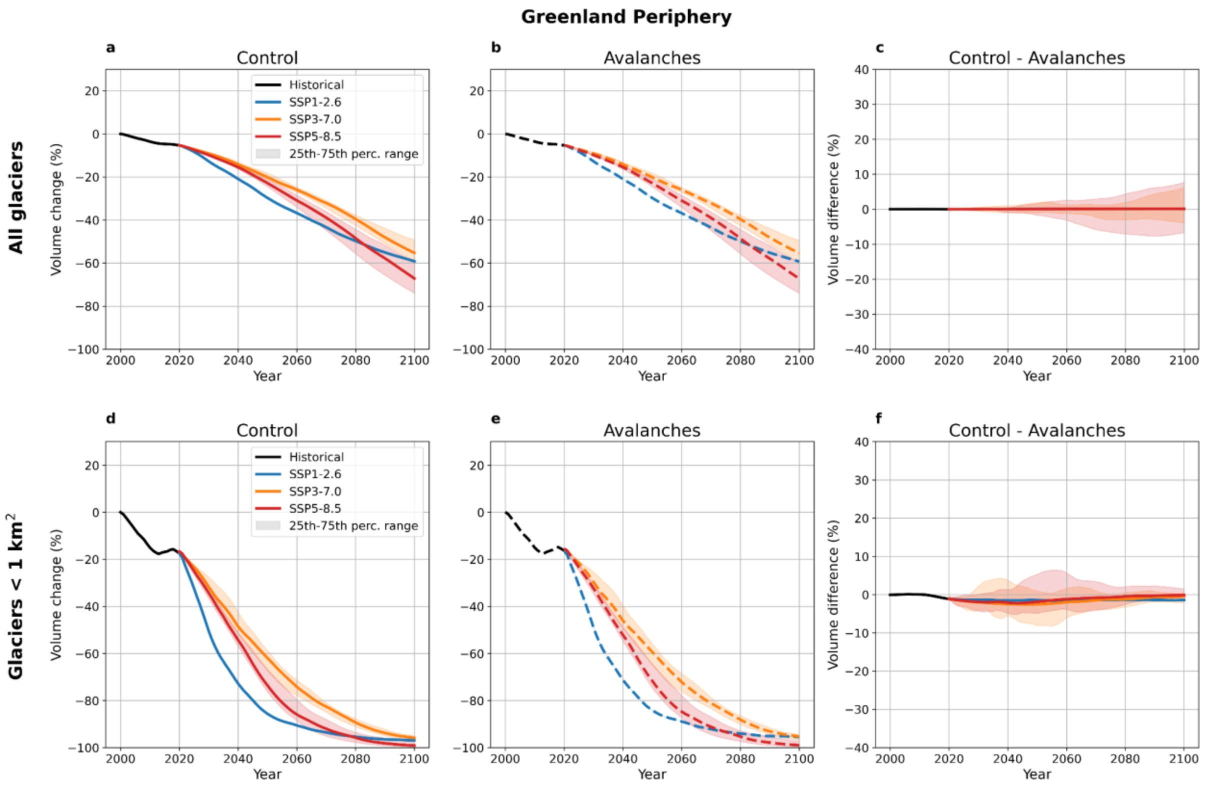
Supplementary Figure 8: Influence of avalanches on regional glacier volume changes in Western Canada and USA. *Same as Fig. S7 but for Western Canada & USA.*



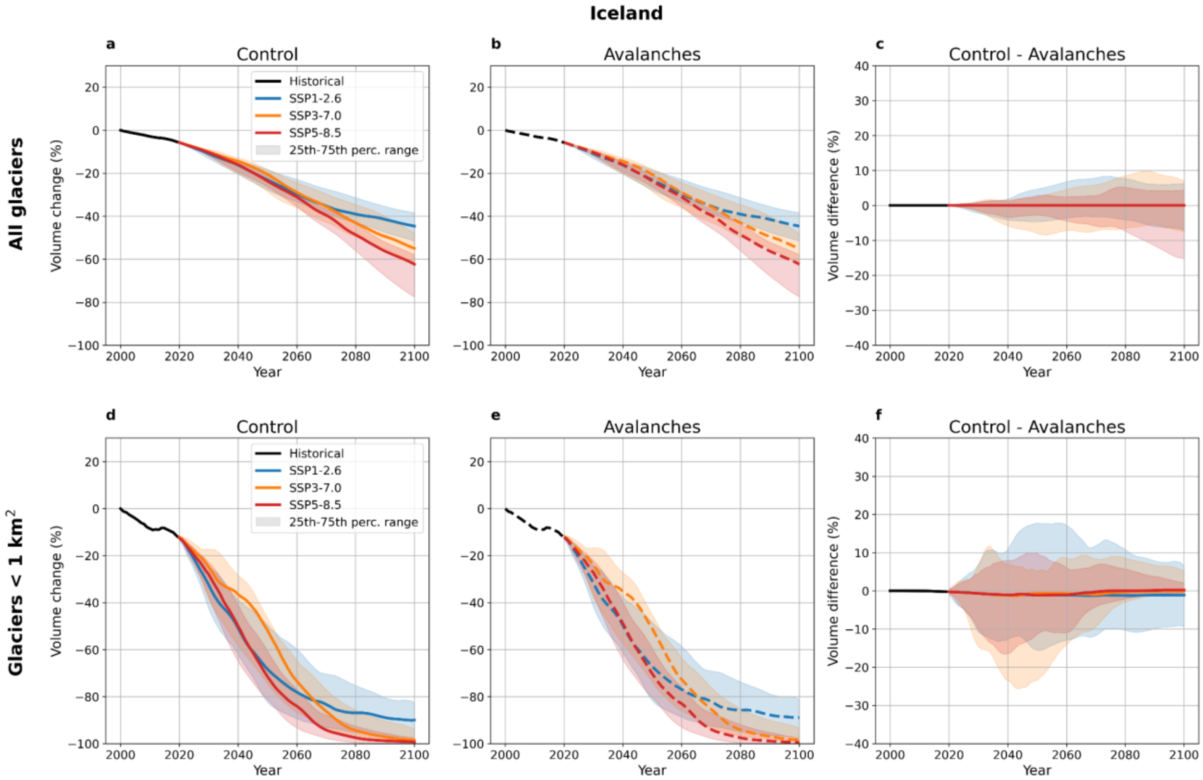
Supplementary Figure 9: Influence of avalanches on regional glacier volume changes in Arctic Canada North. *Same as Fig. S7 but for Arctic Canada North.*



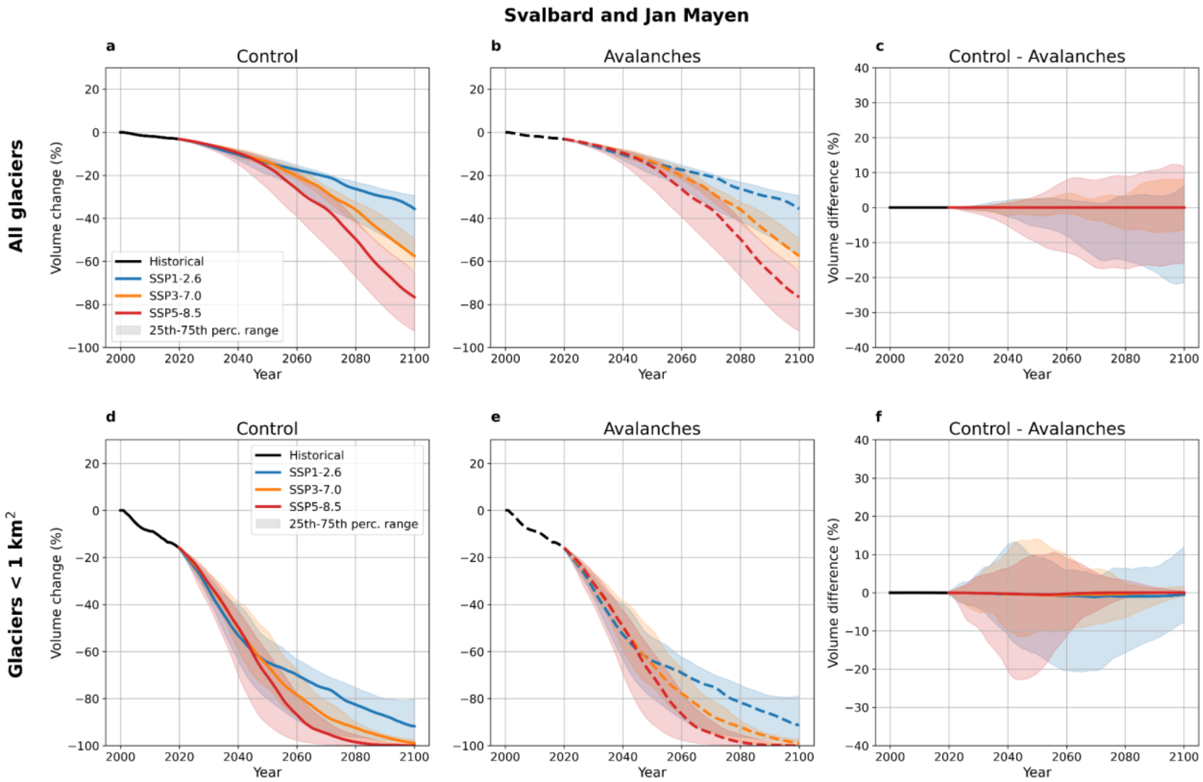
Supplementary Figure 10: Influence of avalanches on regional glacier volume changes in Arctic Canada South. *Same as Fig. S7 but for Arctic Canada South.*



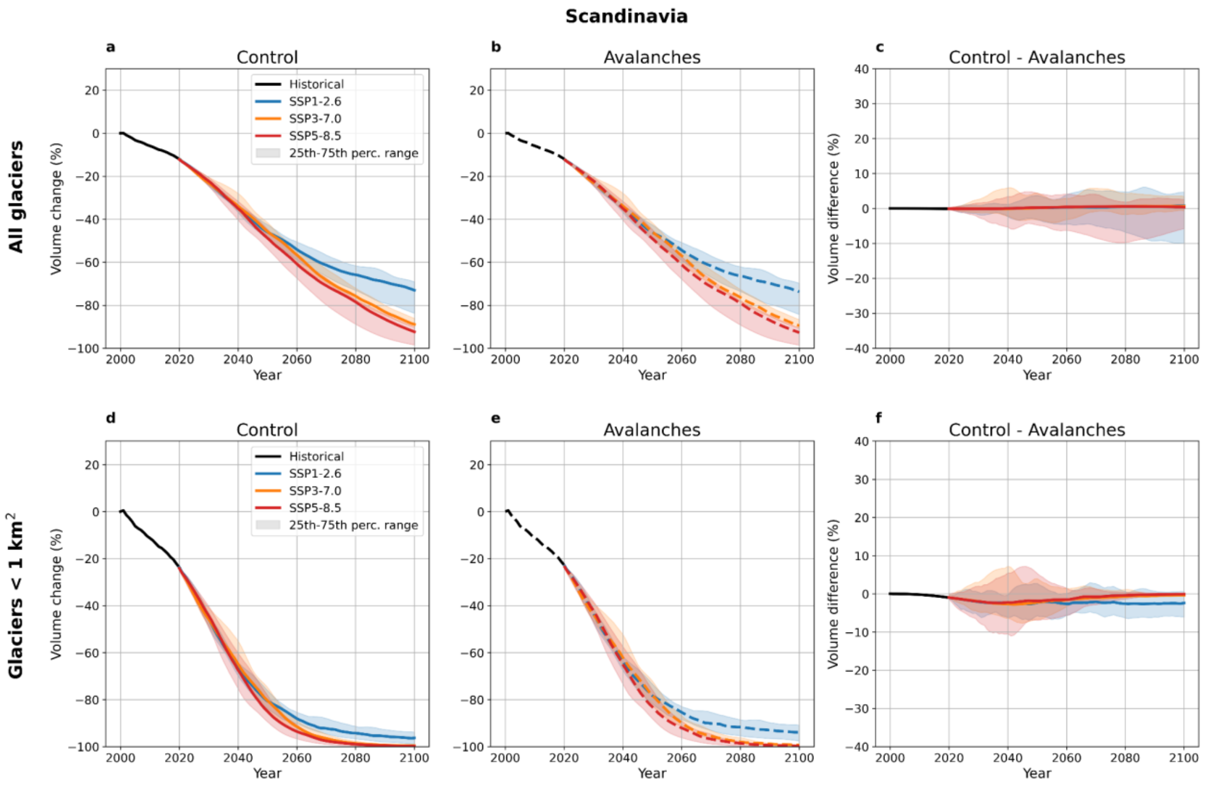
Supplementary Figure 11: Influence of avalanches on regional glacier volume changes in the Greenland Periphery. *Same as Fig. S7 but for Greenland Periphery.*



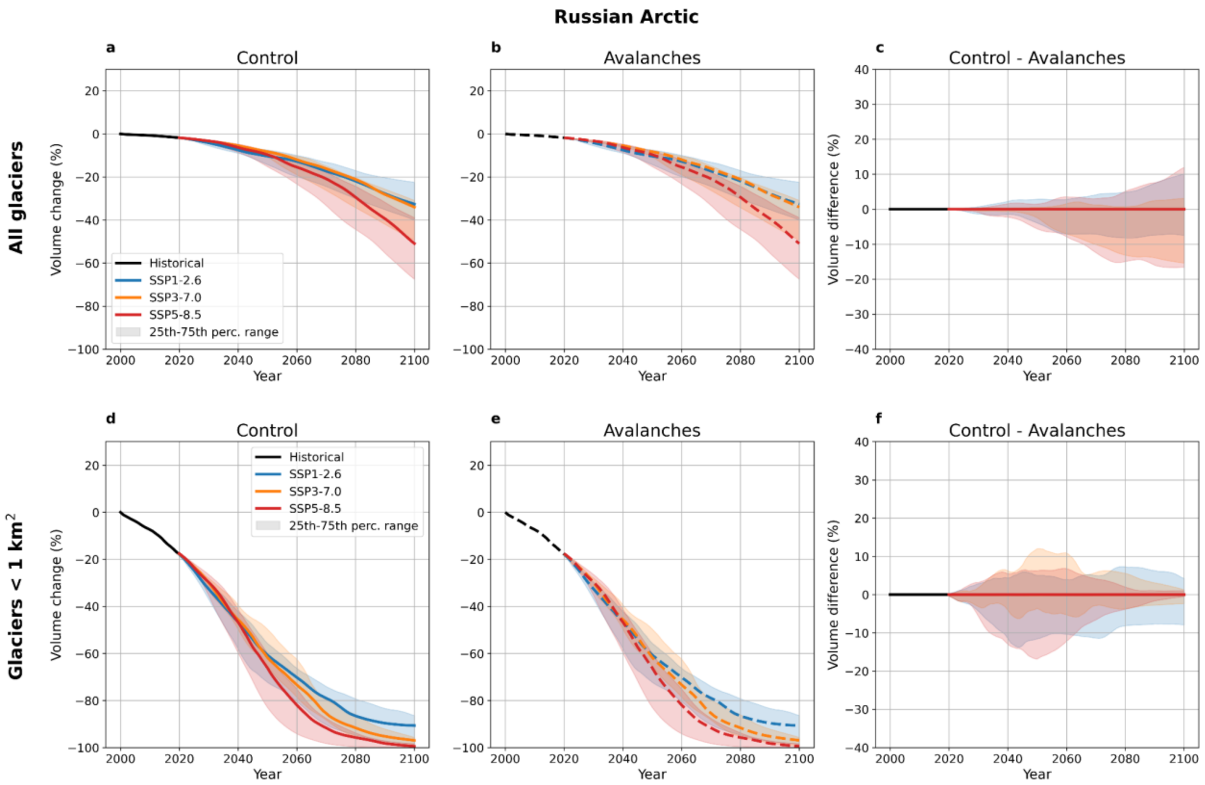
Supplementary Figure 12: Influence of avalanches on regional glacier volume changes in Iceland. *Same as Fig. S7 but for Iceland.*



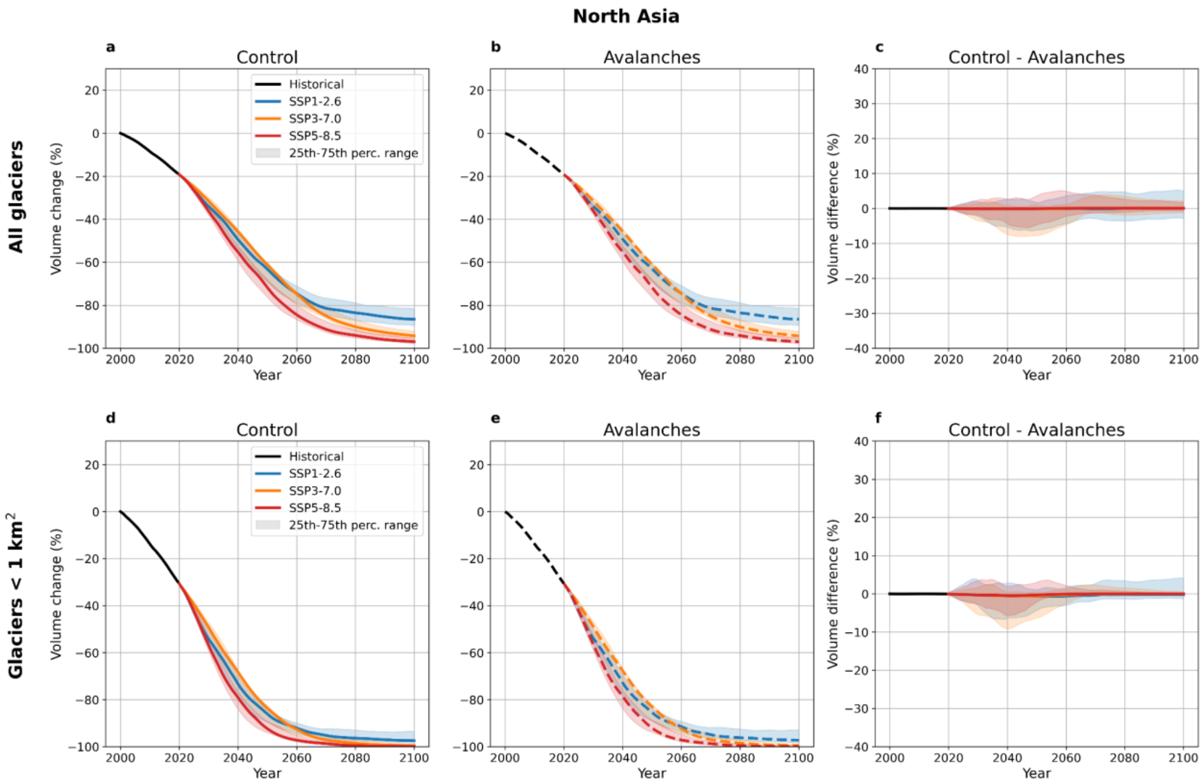
Supplementary Figure 13: Influence of avalanches on regional glacier volume changes in Svalbard and Jan Mayen. *Same as Fig. S7 but for Svalbard and Jan Mayen.*



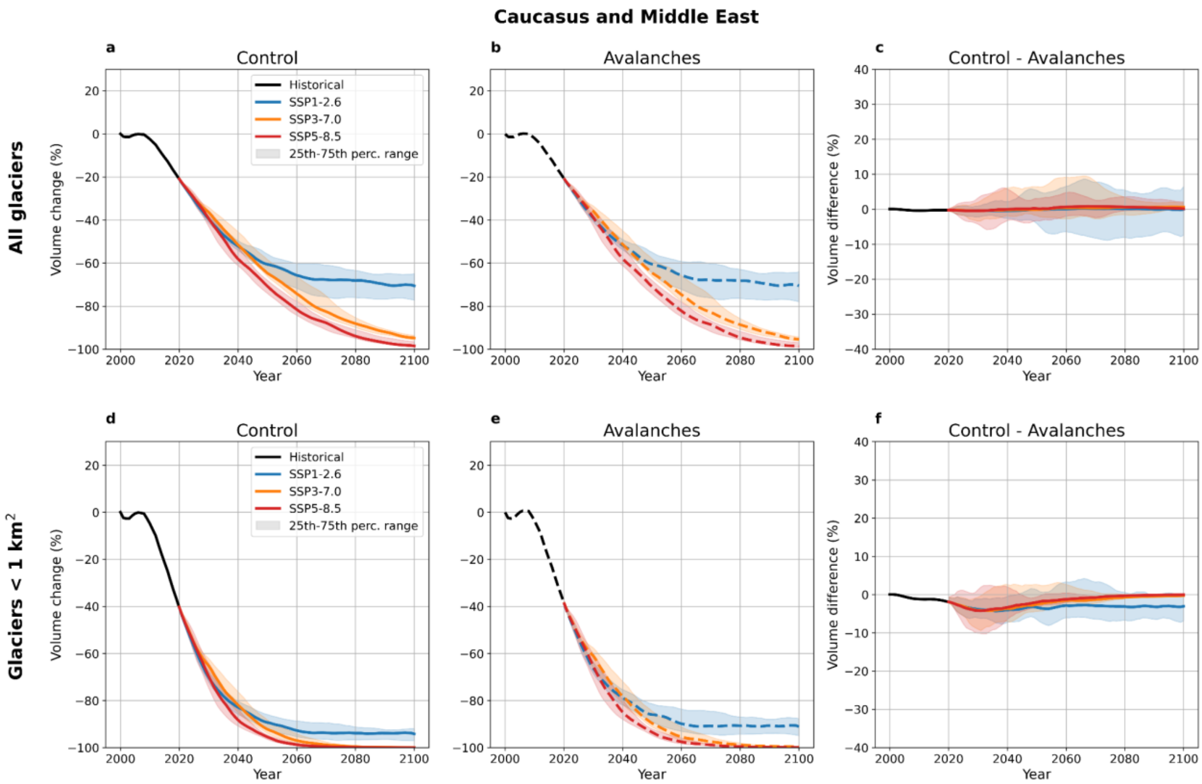
Supplementary Figure 14: Influence of avalanches on regional glacier volume changes in Scandinavia. *Same as Fig. S7 but for Scandinavia.*



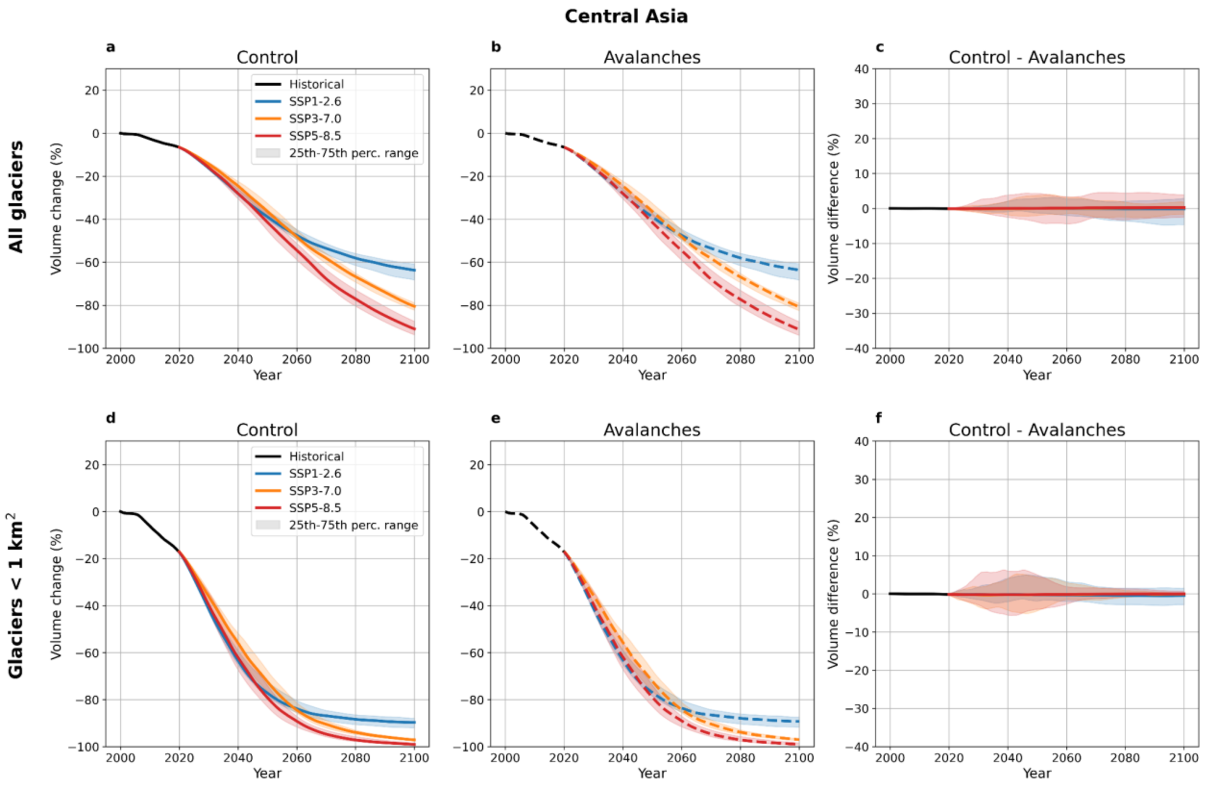
Supplementary Figure 15: Influence of avalanches on regional glacier volume changes in the Russian Arctic. *Same as Fig. S7 but for the Russian Arctic.*



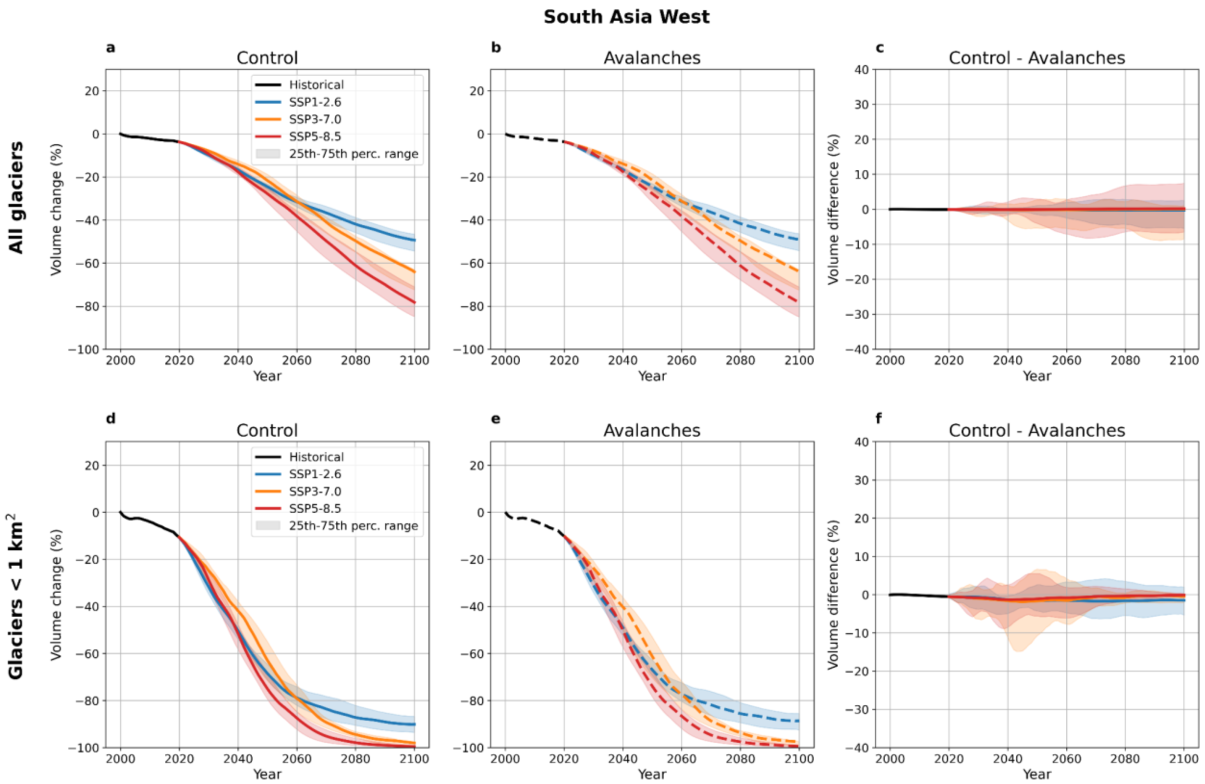
Supplementary Figure 16: Influence of avalanches on regional glacier volume changes in North Asia. *Same as Fig. S7 but for North Asia.*



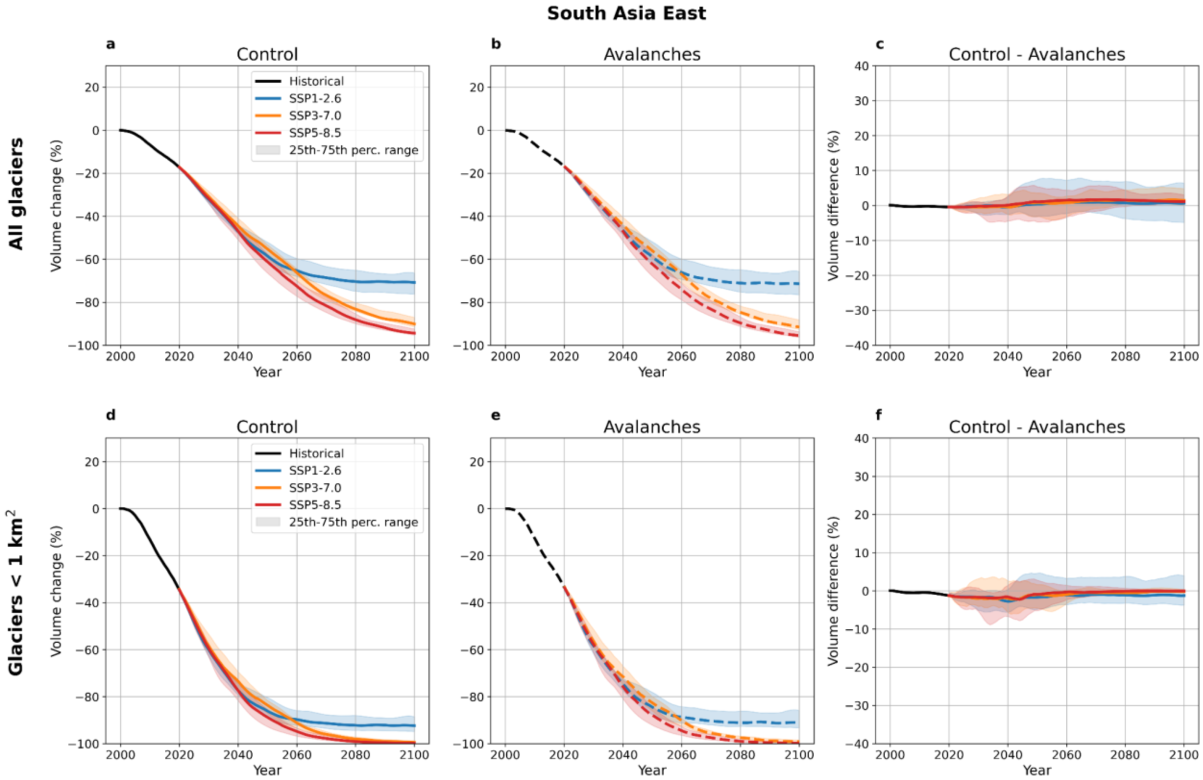
Supplementary Figure 17: Influence of avalanches on regional glacier volume changes in Caucasus and the Middle East. *Same as Fig. S7 but for Caucasus and the Middle East.*



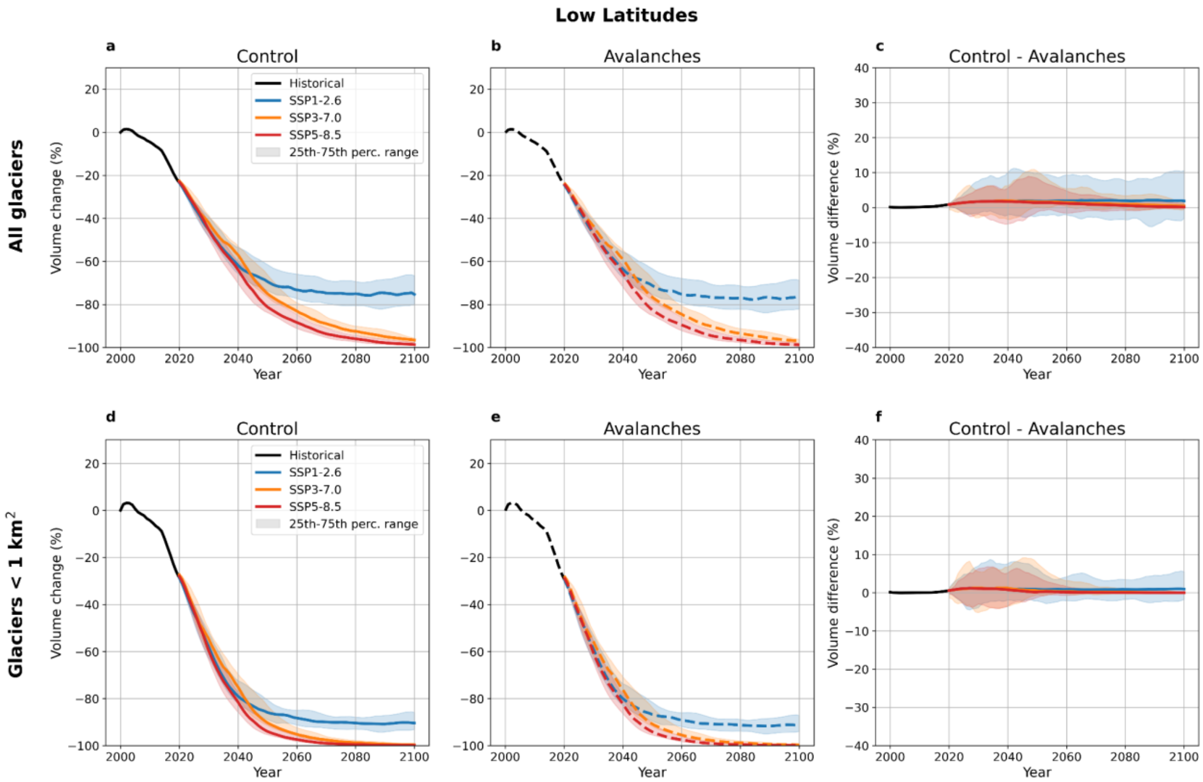
Supplementary Figure 18: Influence of avalanches on regional glacier volume changes in Central Asia. *Same as Fig. S7 but for Central Asia.*



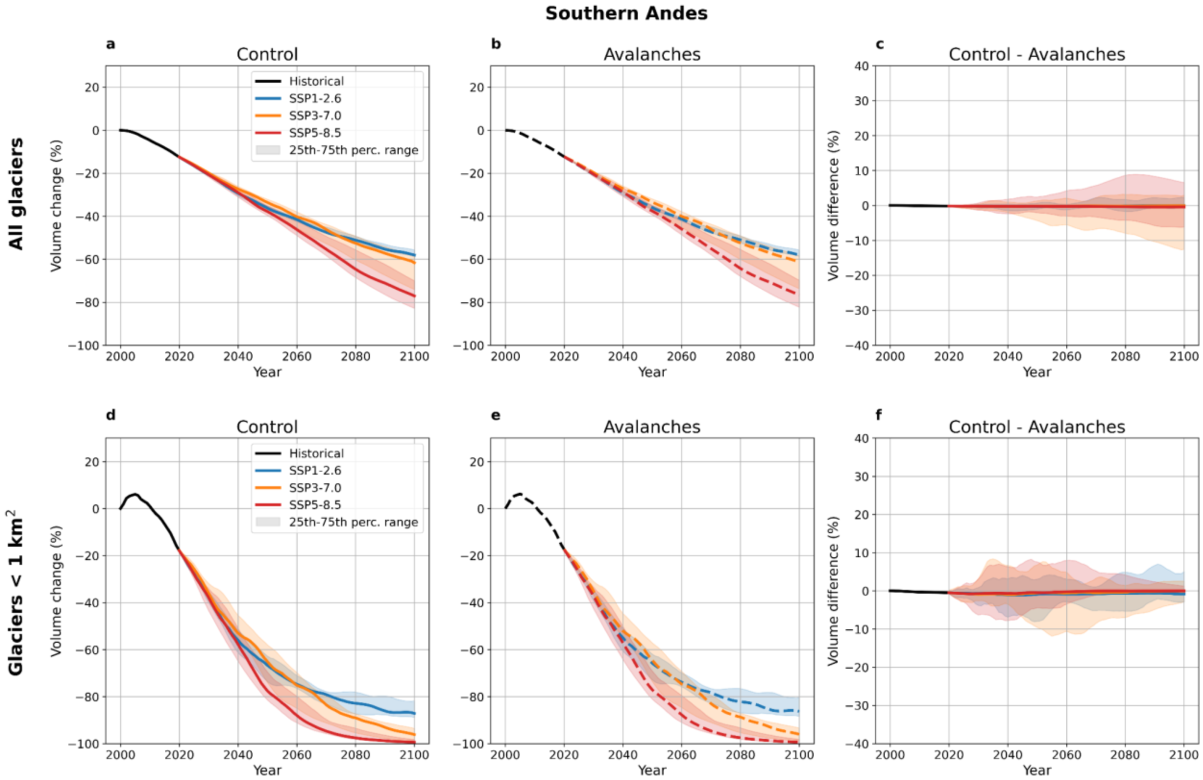
Supplementary Figure 19: Influence of avalanches on regional glacier volume changes in South Asia West. *Same as Fig. S7 but for South Asia West.*



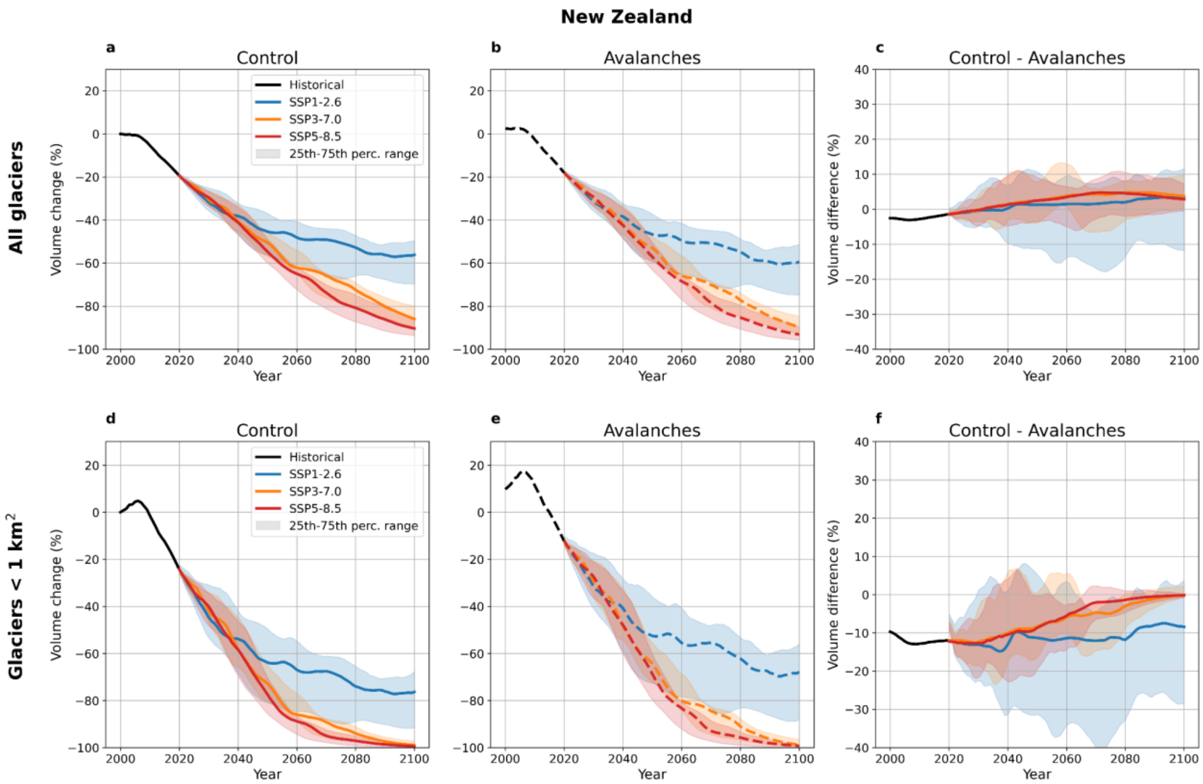
Supplementary Figure 20: ***Influence of avalanches on regional glacier volume changes in South Asia East.*** *Same as Fig. S7 but for South Asia East.*



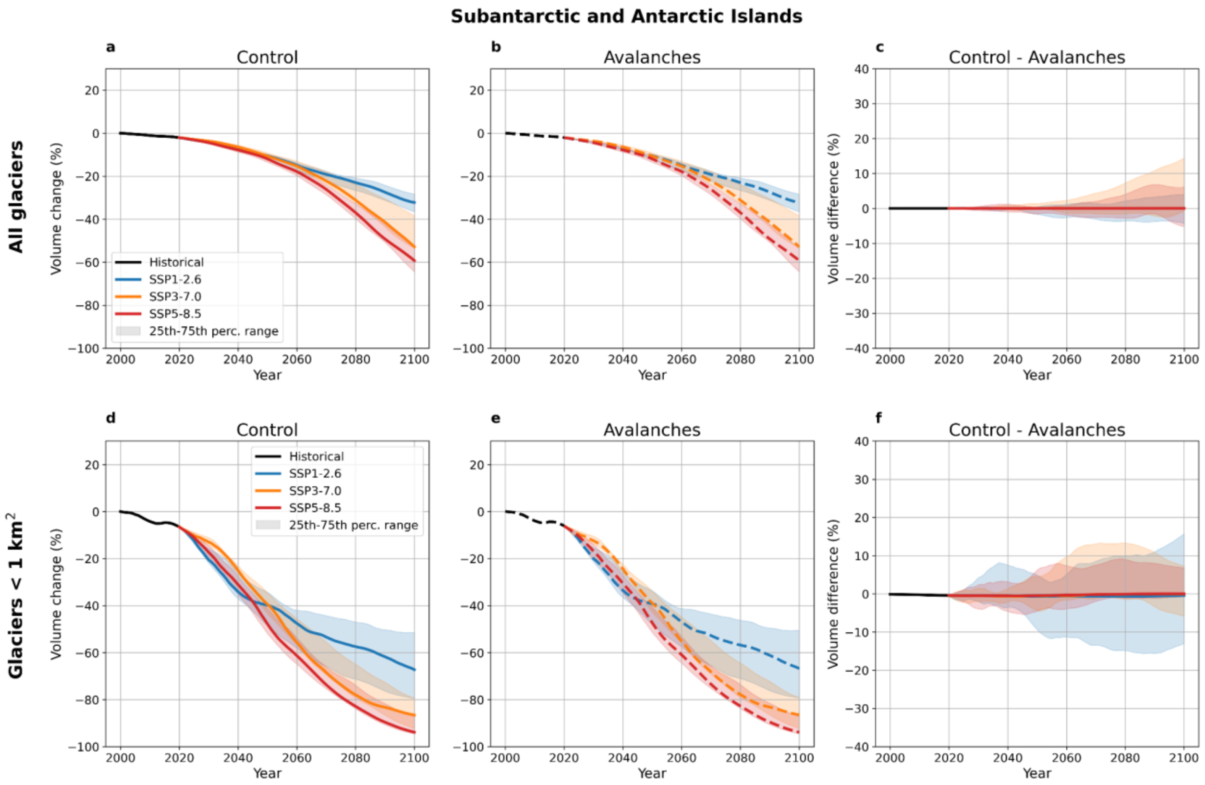
Supplementary Figure 21: Influence of avalanches on regional glacier volume changes in the Low Latitudes. *Same as Fig. S7 but for the Low Latitudes.*



Supplementary Figure 22: Influence of avalanches on regional glacier volume changes in the Southern Andes. *Same as Fig. S7 but for the Southern Andes.*

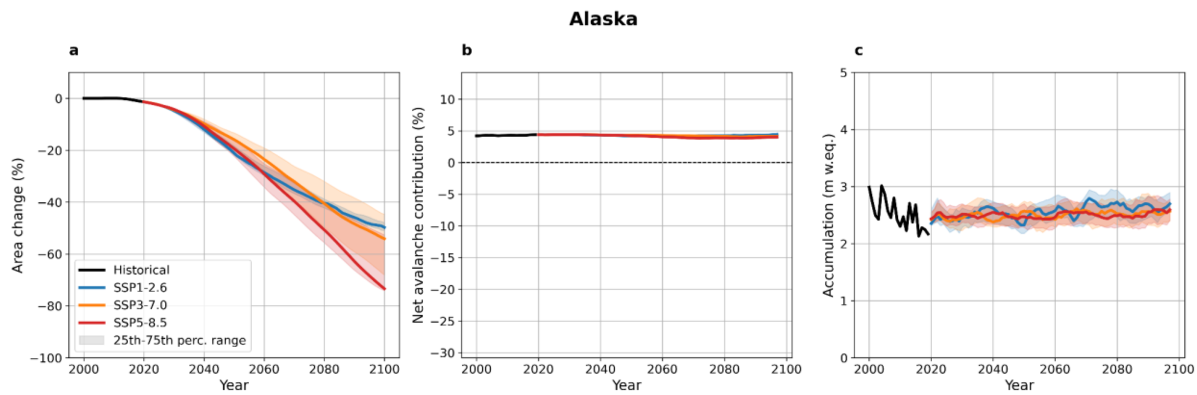


Supplementary Figure 23: Influence of avalanches on regional glacier volume changes in New Zealand. *Same as Fig. S7 but for New Zealand.*



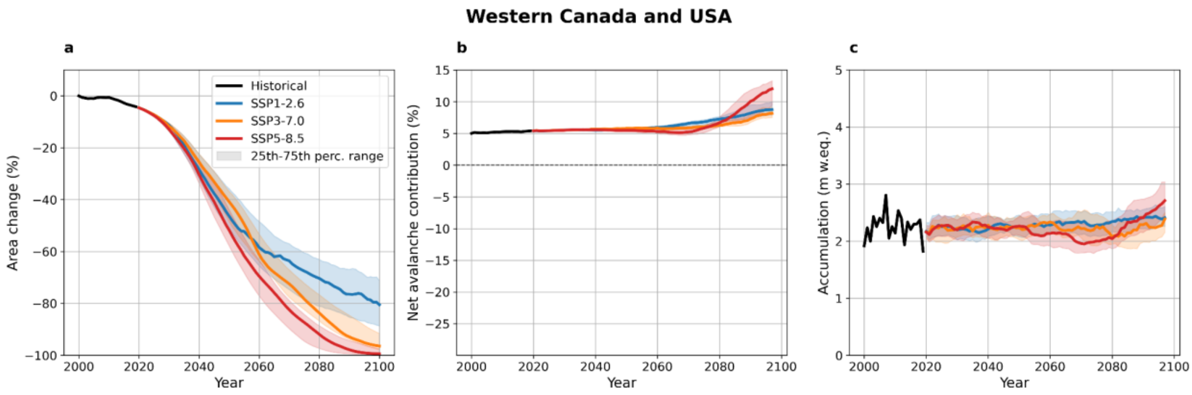
Supplementary Figure 24: Influence of avalanches on regional glacier volume changes in the Subantarctic and Antarctic Islands. *Same as Fig. S7 but for the Subantarctic and Antarctic Islands.*

Projected avalanche contribution changes

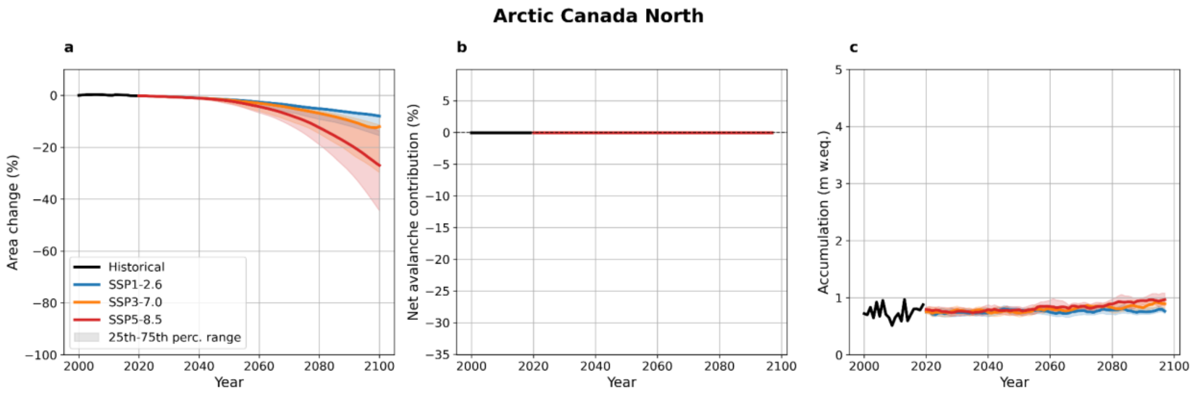


Supplementary Figure 25: Future evolution of regional avalanche contribution in Alaska. *Projected changes of glacier area (a), avalanche contribution to accumulation (b) and total snow accumulation (c) for Alaska. The black line corresponds to the historical period over which the mass balance model was calibrated using W5E5v2.0 data. The colored lines show the median future projections for different SSP scenarios, and the shaded areas indicate the*

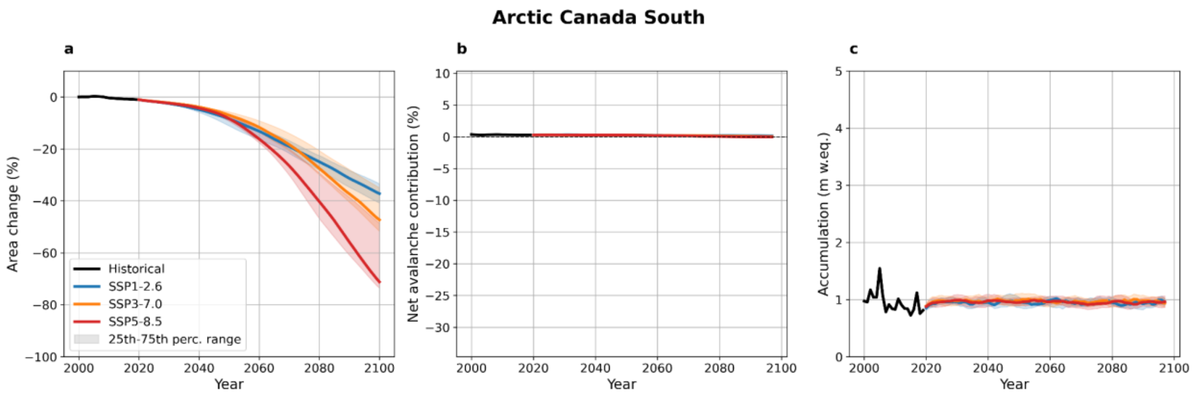
25th-75th percentile range. The different curves were smoothed using a 5-year rolling mean, except for the historical accumulation.



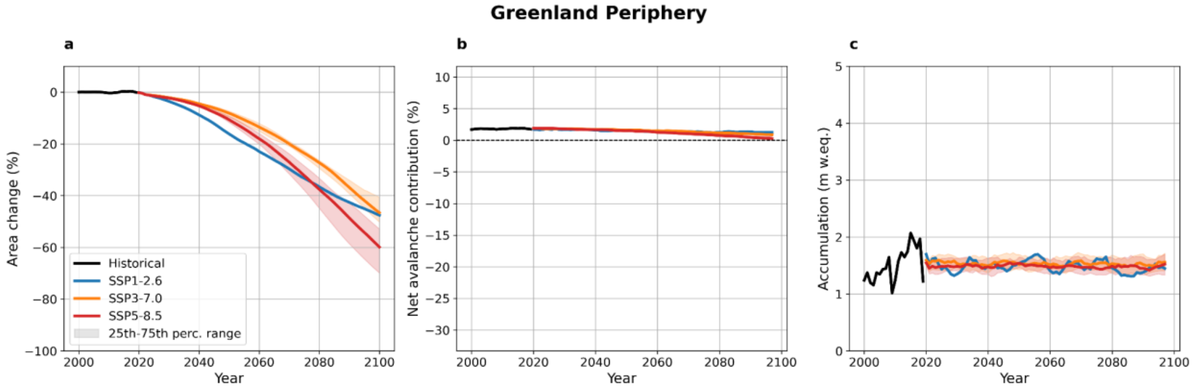
Supplementary Figure 26: Future evolution of regional avalanche contribution in Western Canada and USA. *Same as Fig. S25 but for Western Canada and the USA.*



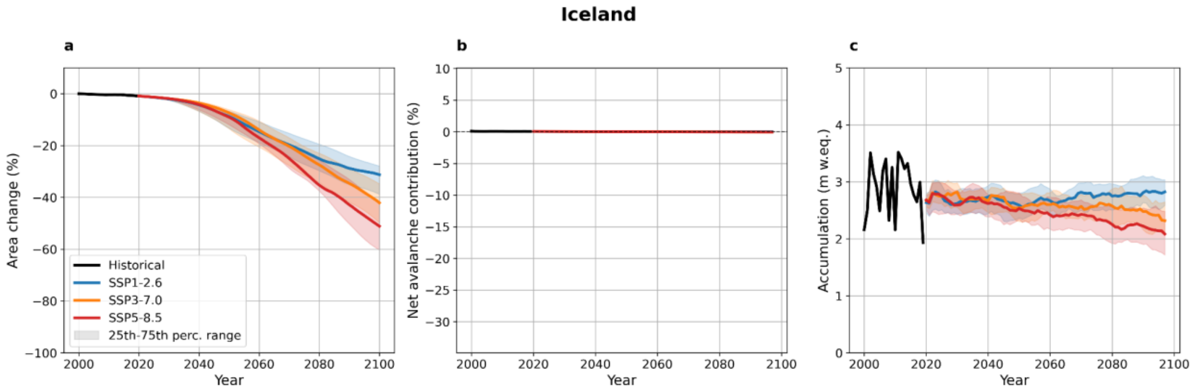
Supplementary Figure 27: Future evolution of regional avalanche contribution in Arctic Canada North. *Same as Fig. S25 but for Arctic Canada North.*



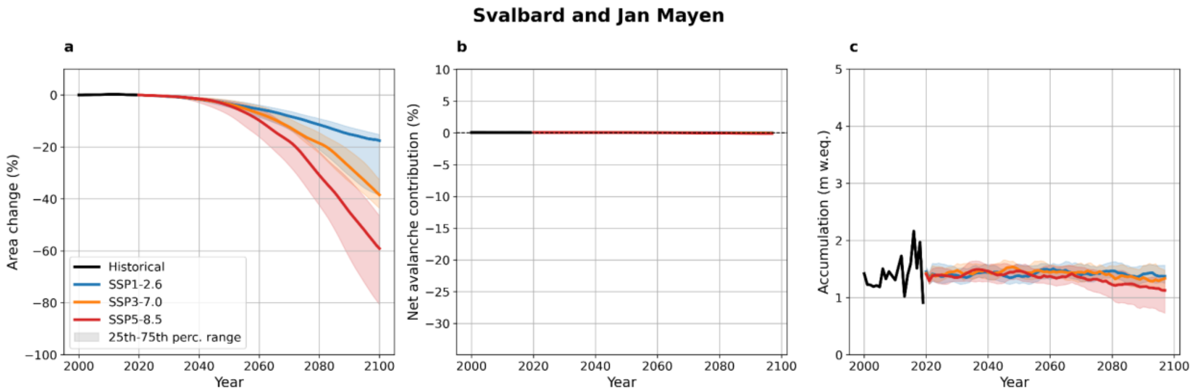
Supplementary Figure 28: Future evolution of regional avalanche contribution in Arctic Canada South. *Same as Fig. S25 but for Arctic Canada South.*



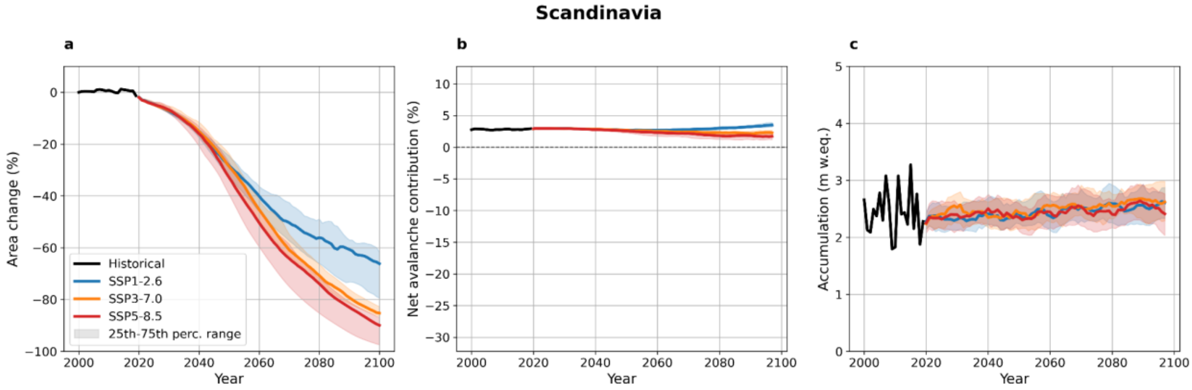
Supplementary Figure 29: Future evolution of regional avalanche contribution in the Greenland Periphery. *Same as Fig. S25 but for the Greenland Periphery.*



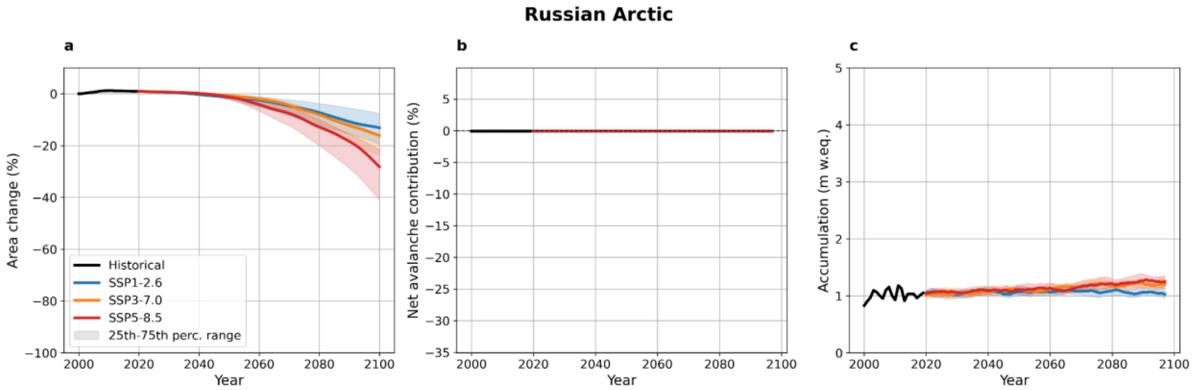
Supplementary Figure 30: Future evolution of regional avalanche contribution in Iceland. *Same as Fig. S25 but for Iceland.*



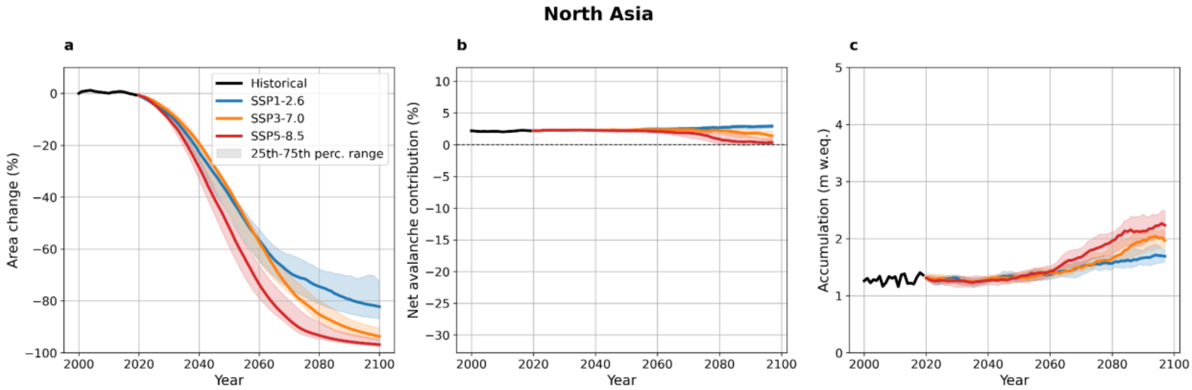
Supplementary Figure 31: Future evolution of regional avalanche contribution in Svalbard and Jan Mayen. *Same as Fig. S25 but for Svalbard and Jan Mayen.*



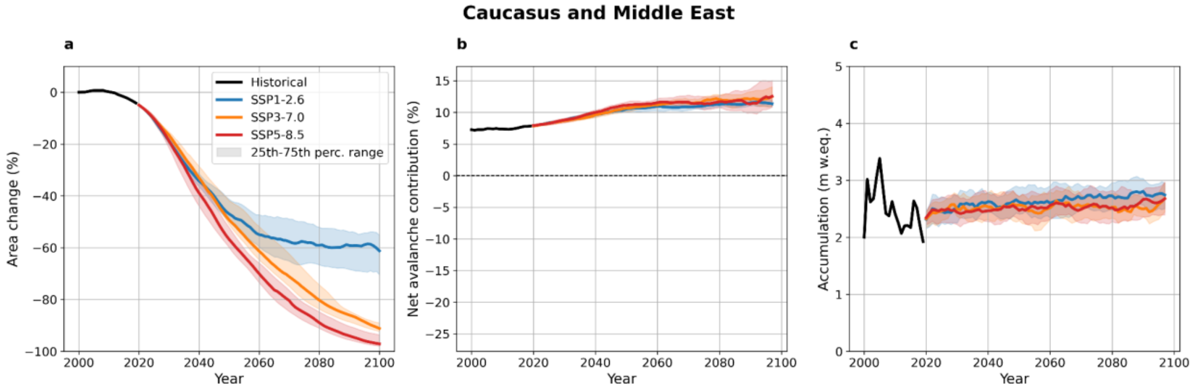
Supplementary Figure 32: Future evolution of regional avalanche contribution in Scandinavia. *Same as Fig. S25 but for Scandinavia.*



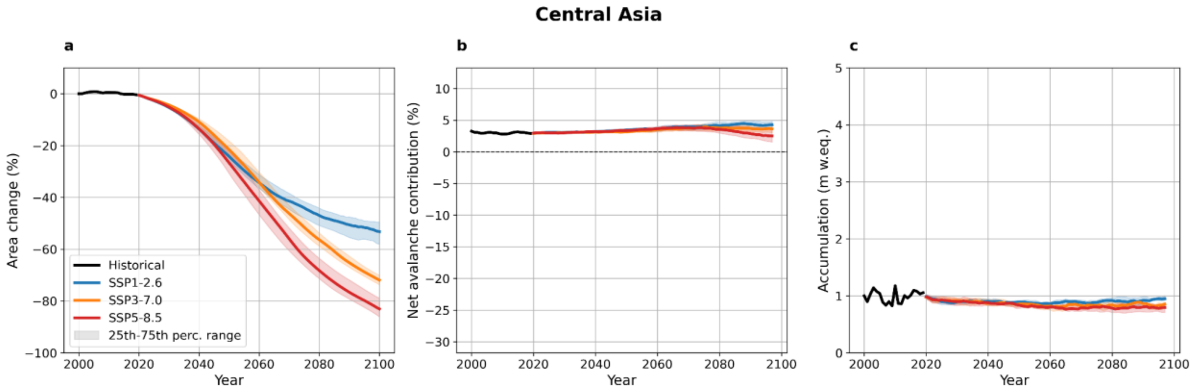
Supplementary Figure 33: Future evolution of regional avalanche contribution in the Russian Arctic. *Same as Fig. S25 but for the Russian Arctic.*



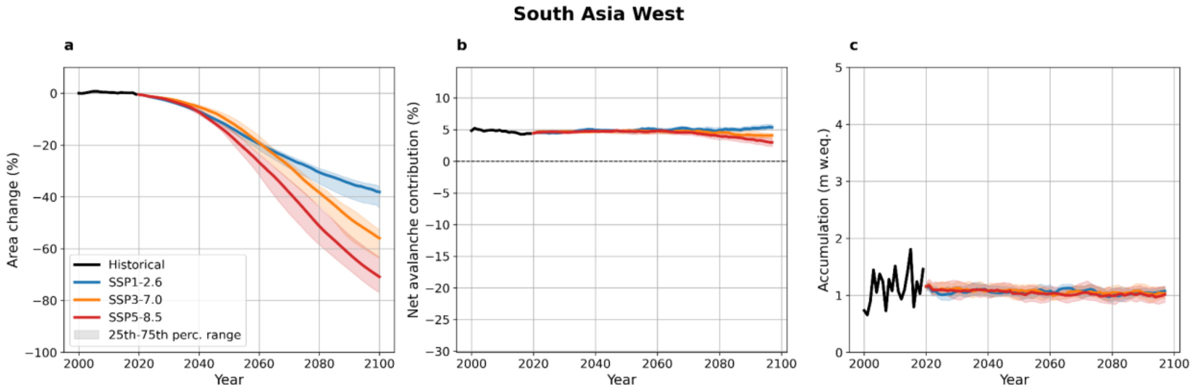
Supplementary Figure 34: Future evolution of regional avalanche contribution in North Asia. *Same as Fig. S25 but for North Asia.*



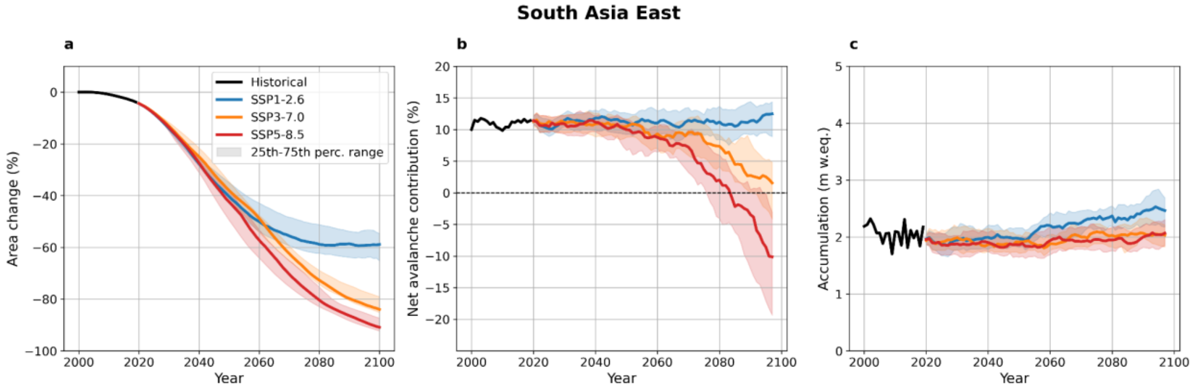
Supplementary Figure 35: Future evolution of regional avalanche contribution in Caucasus and the Middle East. *Same as Fig. S25 but for Caucasus and the Middle East.*



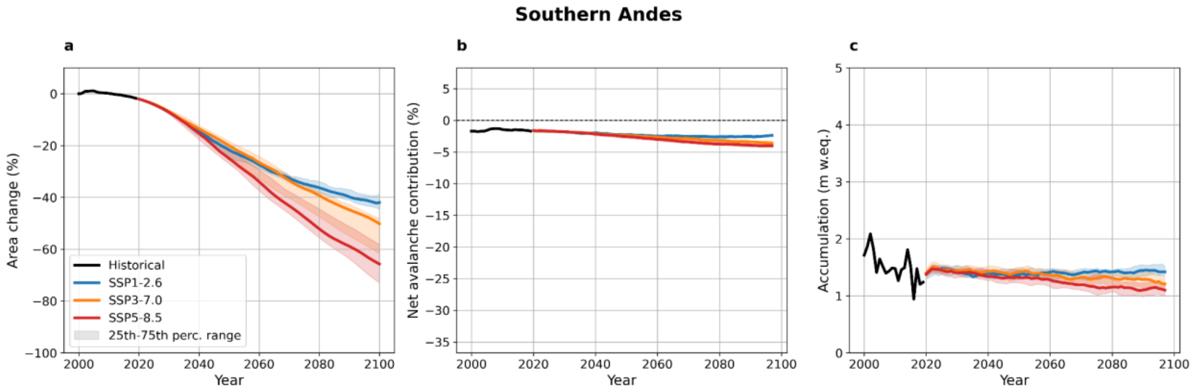
Supplementary Figure 36: Future evolution of regional avalanche contribution in Central Asia. *Same as Fig. S25 but for Central Asia.*



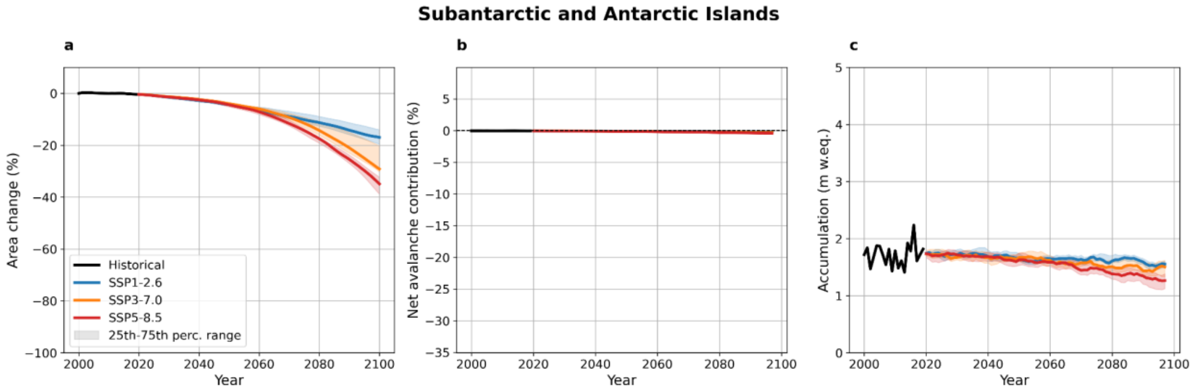
Supplementary Figure 37: Future evolution of regional avalanche contribution in South Asia West. *Same as Fig. S25 but for South Asia West.*



Supplementary Figure 38: Future evolution of regional avalanche contribution in South Asia East. *Same as Fig. S25 but for South Asia East.*

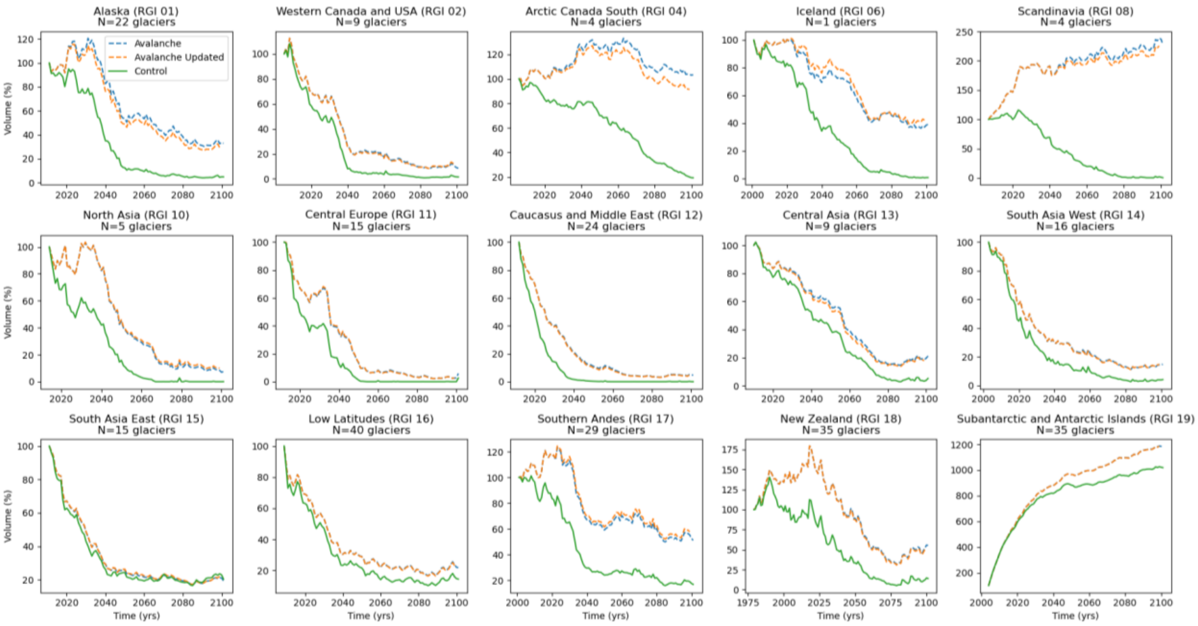


Supplementary Figure 39: Future evolution of regional avalanche contribution in the Southern Andes. *Same as Fig. S25 but for the Southern Andes.*

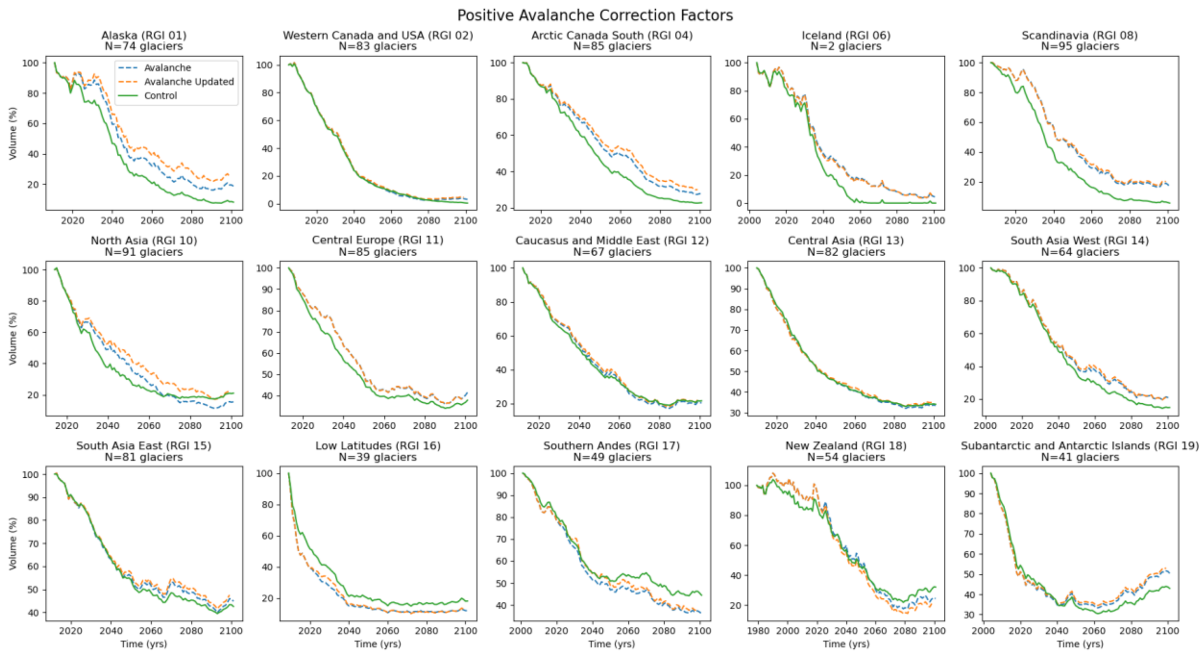


Supplementary Figure 40: Future evolution of regional avalanche contribution in the Subantarctic and Antarctic Islands. *Same as Fig. S25 but for the Subantarctic and Antarctic Islands.*

Influence of temporarily updating the avalanche contribution

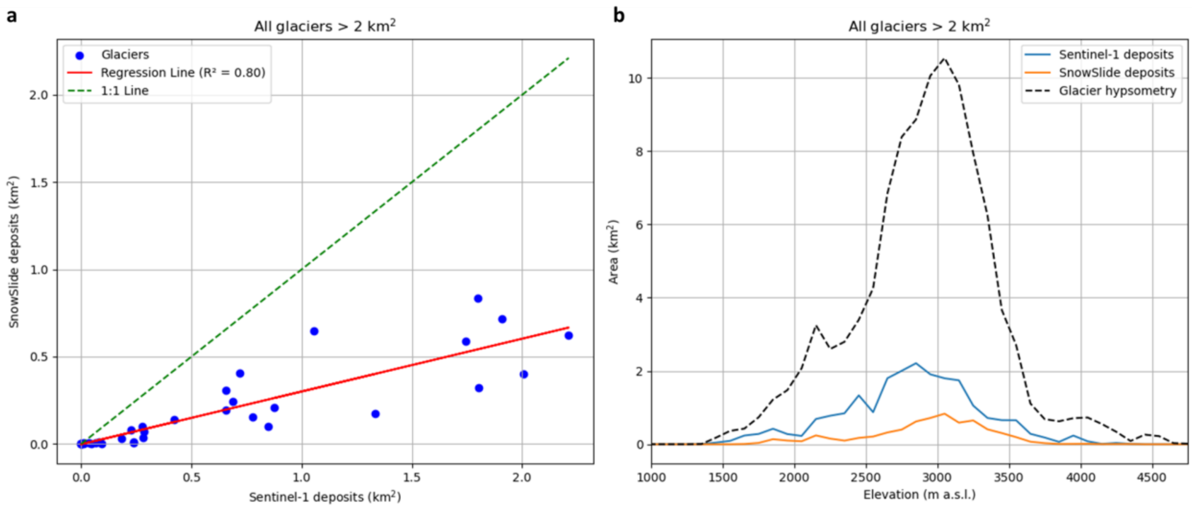


Supplementary Figure 41: Influence of temporarily updating the avalanche contribution on glaciers with a negative avalanche contribution*. Glacier volume changes for 263 randomly selected glaciers with a glacier-wide avalanche correction factor ($k_{ava,\ gl}$) lower than 0.8 in 15 RGI regions for the ipsl-cm6a-lr_r1i1p1f1 GCM under the SSP 1-2.6 scenario. The green line indicates the scenario without avalanches, the blue dashed line corresponds to the scenario with fixed avalanche contribution calculated over the period 2020-2100, and the orange line corresponds to the scenario with an avalanche contribution updated every 20 years.*



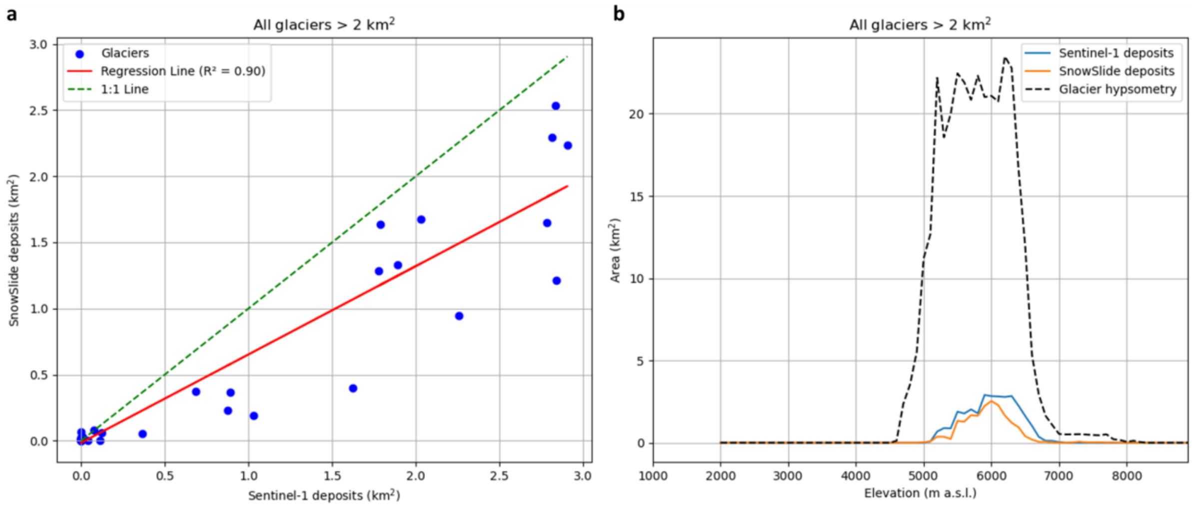
***Supplementary Figure 42:* Influence of temporarily updating the avalanche contribution on glaciers with a positive avalanche contribution**. *Glacier volume changes for 1003 randomly selected glaciers with a glacier-wide avalanche correction factor ($k_{ava,\ gl}$) higher than 1.2 in 15 RGI regions for the ipsl-cm6a-lr_r1i1p1f1 GCM under the SSP 1-2.6 scenario. The green line indicates the scenario without avalanches, the blue dashed line corresponds to the scenario with fixed avalanche contribution calculated over the period 2020-2100, and the orange line corresponds to the scenario with an avalanche contribution updated every 20 years.*

Evaluation against Sentinel-1 avalanche deposits

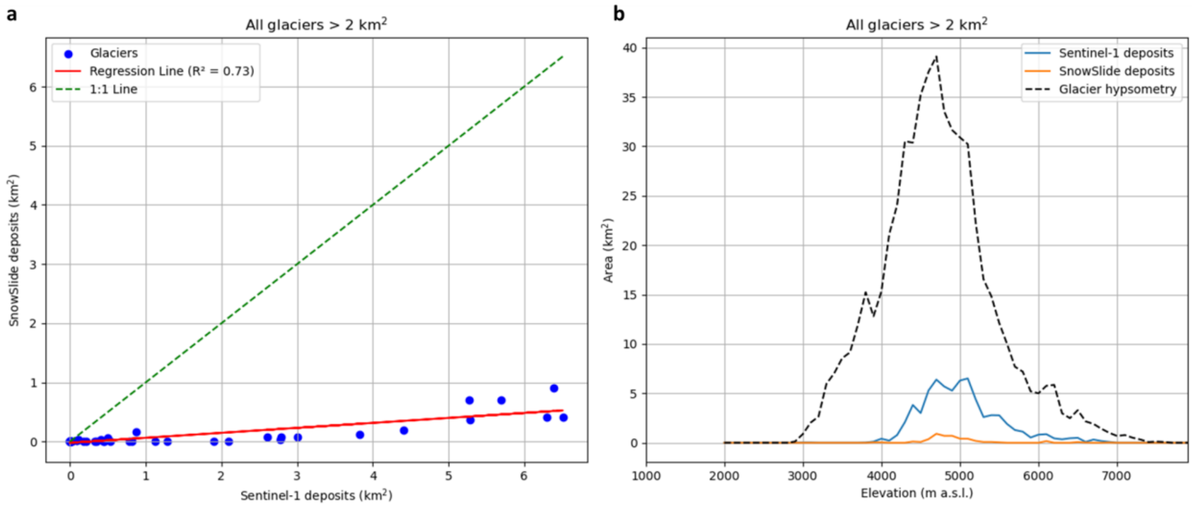


Supplementary Figure 43: Comparison of the SnowSlide and Sentinel-1 avalanche deposit extents over the glaciers larger than 2 km² in the Mt Blanc region*. *a *Area of*

SnowSlide and Sentinel-1 deposits for each individual glacier. ***b*** *Hypsometry of the SnowSlide and Sentinel-1 avalanche deposits and glaciers.*

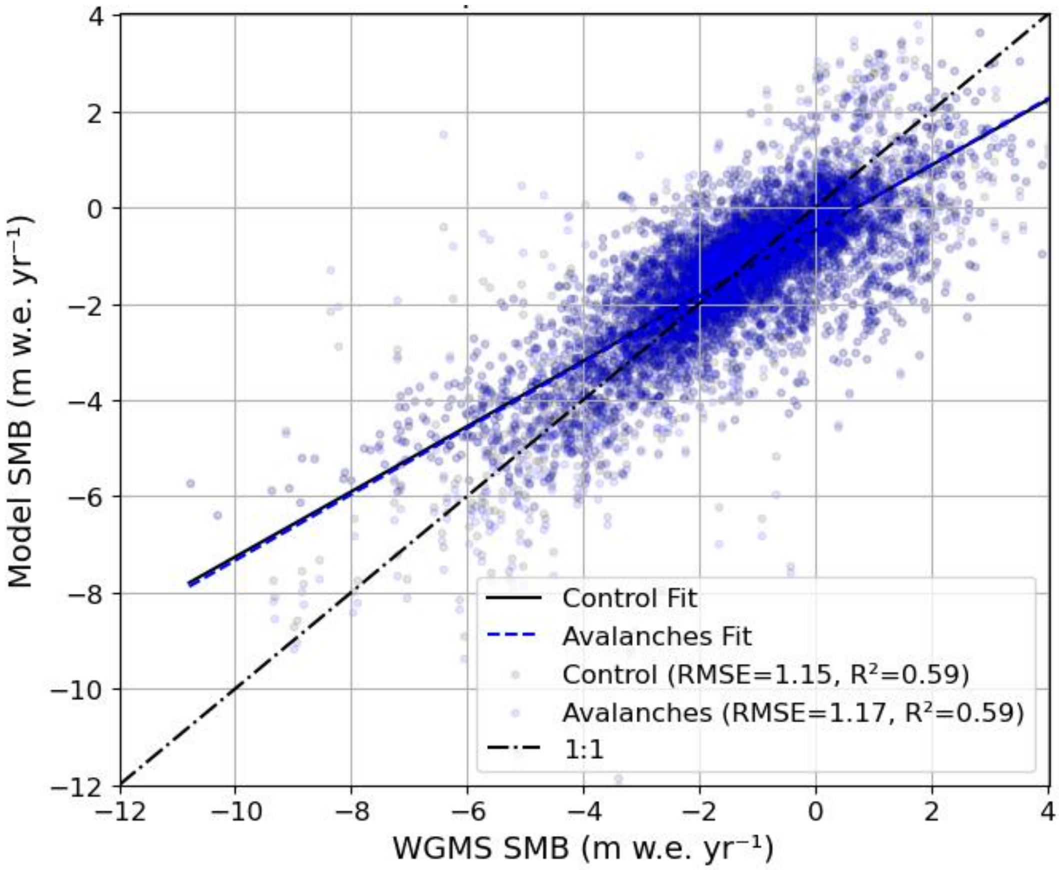


Supplementary Figure 44: Comparison of the SnowSlide and Sentinel-1 avalanche deposit extents over the glaciers larger than 2 km^2 in the Everest region. a *Area of SnowSlide and Sentinel-1 deposits for each individual glacier.* ***b*** *Hypsometry of the SnowSlide and Sentinel-1 avalanche deposits and glaciers.*

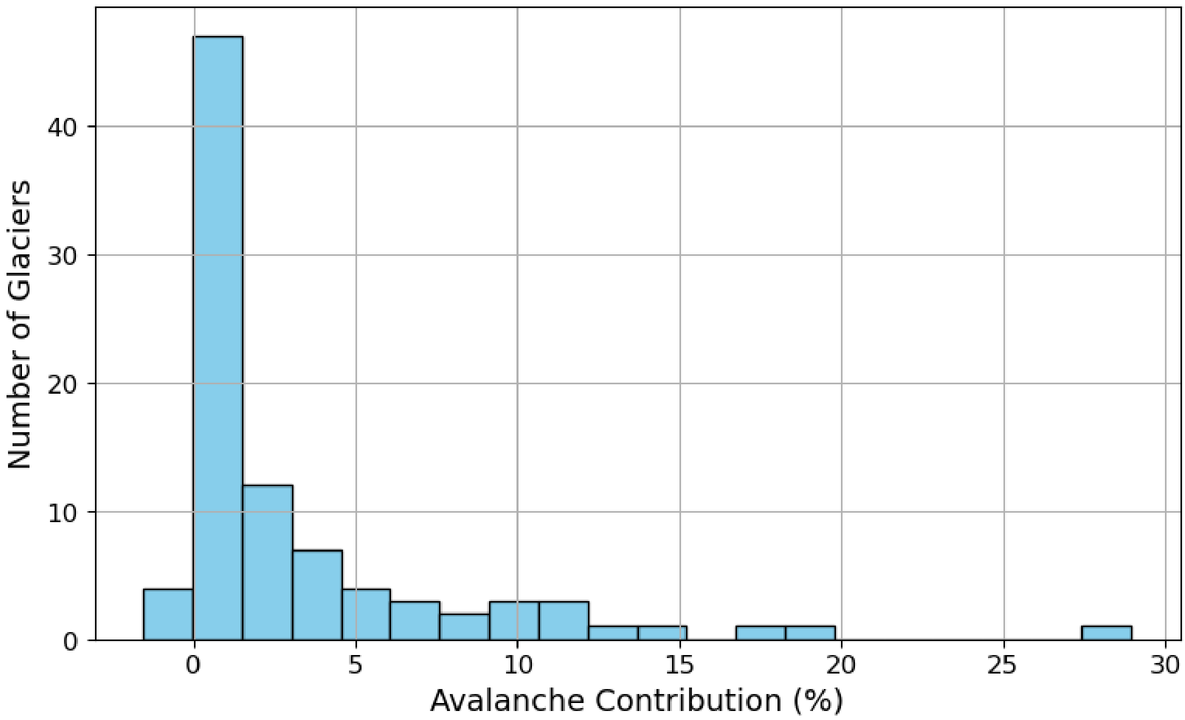


Supplementary Figure 45: Comparison of the SnowSlide and Sentinel-1 avalanche deposit extents over the glaciers larger than 2 km^2 in the Hispar region. a *Area of SnowSlide and Sentinel-1 deposits for each individual glacier.* ***b*** *Hypsometry of the SnowSlide and Sentinel-1 avalanche deposits and glaciers.*

Evaluation against mass balance measurements

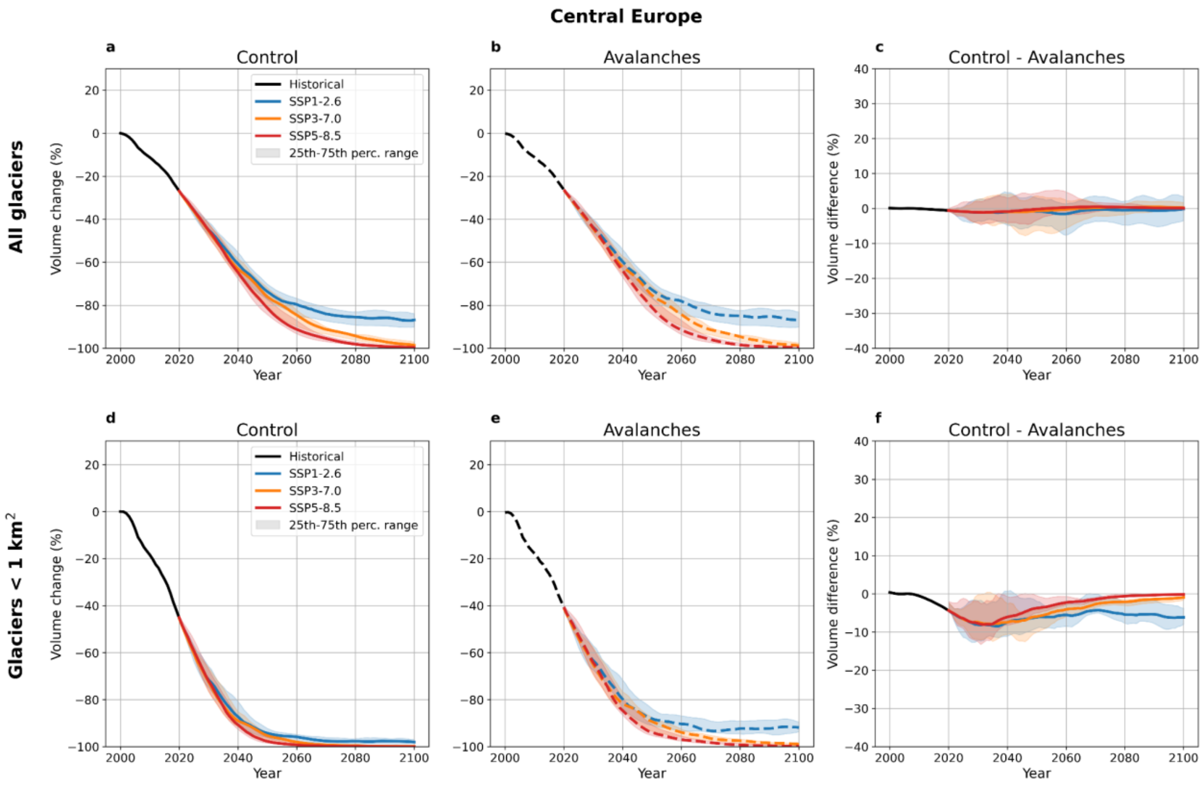


Supplementary Figure 46: Comparison of the modeled and measured annual point mass balance from the World Glacier Monitoring Service. *The observation period goes from 2000 to 2020. The results from the Control simulations are in black and from the Avalanches simulations in blue.*

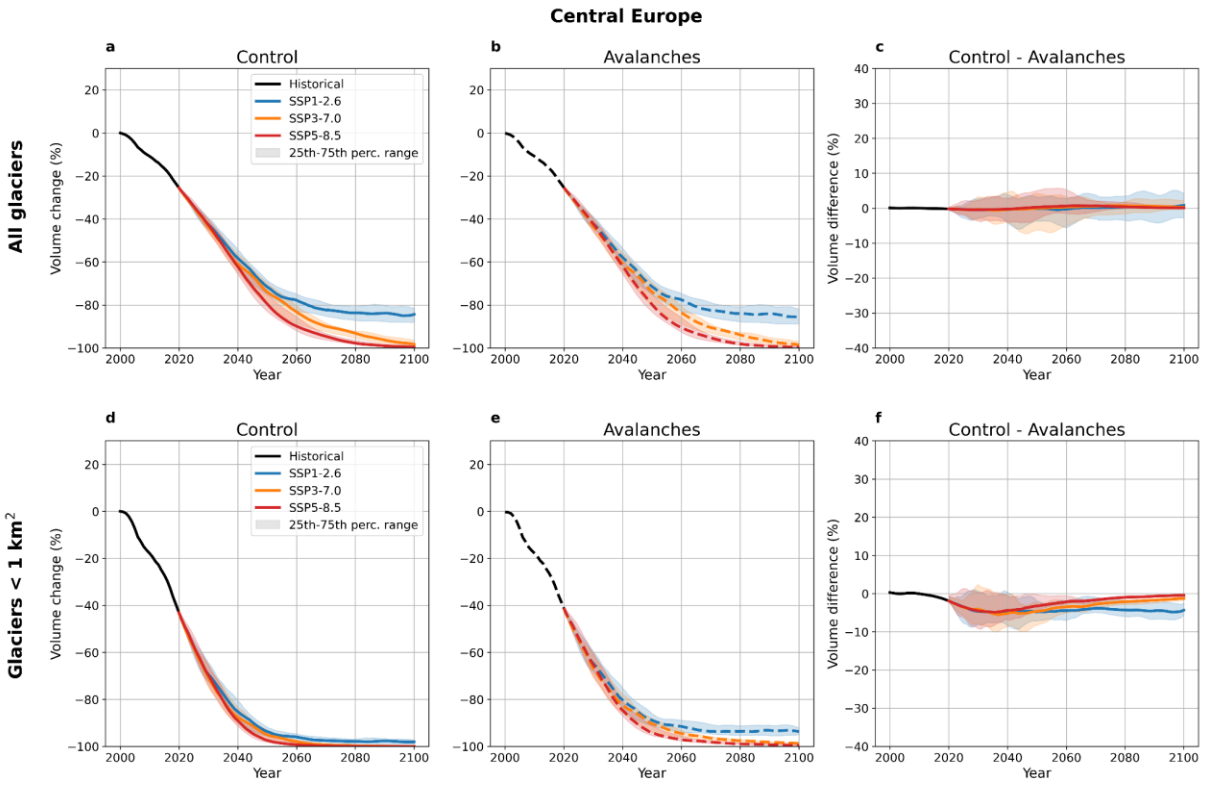


Supplementary Figure 47: Avalanche contribution of WGMS glaciers. *Histogram of the WGMS glaciers with at least one annual mass balance measurement in the period 2000-2020 as a function of their glacier-wide avalanche contribution.*

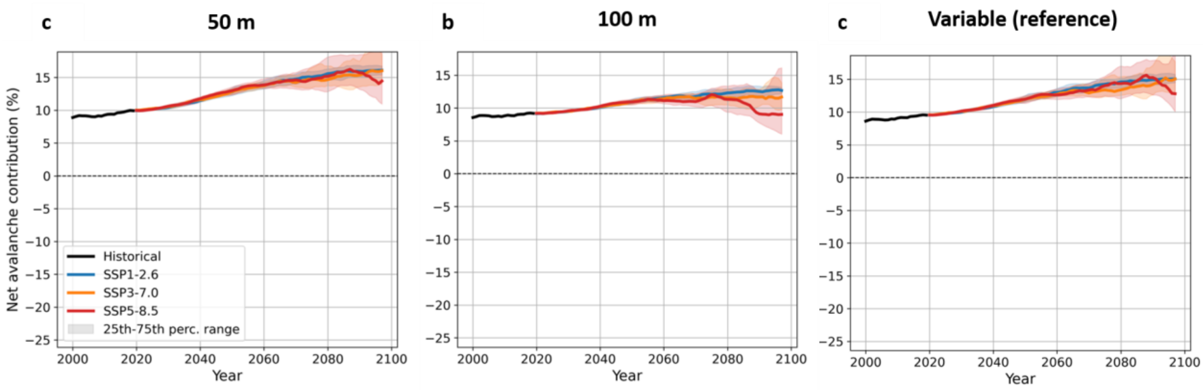
Influence of DEM spatial resolution



Supplementary Figure 48: Influence of avalanches on regional glacier volume changes in Central Europe at 50 m resolution. *Projected volume changes of all glaciers (**a-c**) and only the glaciers smaller than 1 km^2 (**d-f**) in Central Europe, from the 'Control' (**a, d**) and 'Avalanches' (**b, e**) simulations, using a fixed DEM resolution of 50 m. The right-hand plots (**c, f**) show the difference between the 'Control' and the 'Avalanches' simulations, so that negative values indicate more volume in the 'Avalanches' simulations. All percentages are given relative to the initial volume in 2000 in the 'Control' simulation. The black line corresponds to the historical period over which the mass balance model was calibrated using W5E5v2.0 data. The colored lines show the median future projections for different SSP scenarios, and the shaded areas indicate the 25th-75th percentile range. The different curves were smoothed using a 5-year rolling mean.*



Supplementary Figure 49: Influence of avalanches on regional glacier volume changes in Central Europe at 100 m resolution. *Same as Fig. S48 but with a fixed 100m spatial resolution.*



Supplementary Figure 50: Influence of DEM spatial resolution on projected avalanche contribution. *Projected changes of avalanche contribution to glacier accumulation for Central Europe at various spatial resolutions. The black line corresponds to the historical period over which the mass balance model was calibrated using W5E5v2.0 data. The colored lines show the median future projections for different SSP scenarios, and the shaded areas indicate the 25th-75th percentile range. The different curves were smoothed using a 5-year rolling mean.*