Supplementary Information: "Poleward shift of subtropical highs drives Patagonian glacier mass loss"

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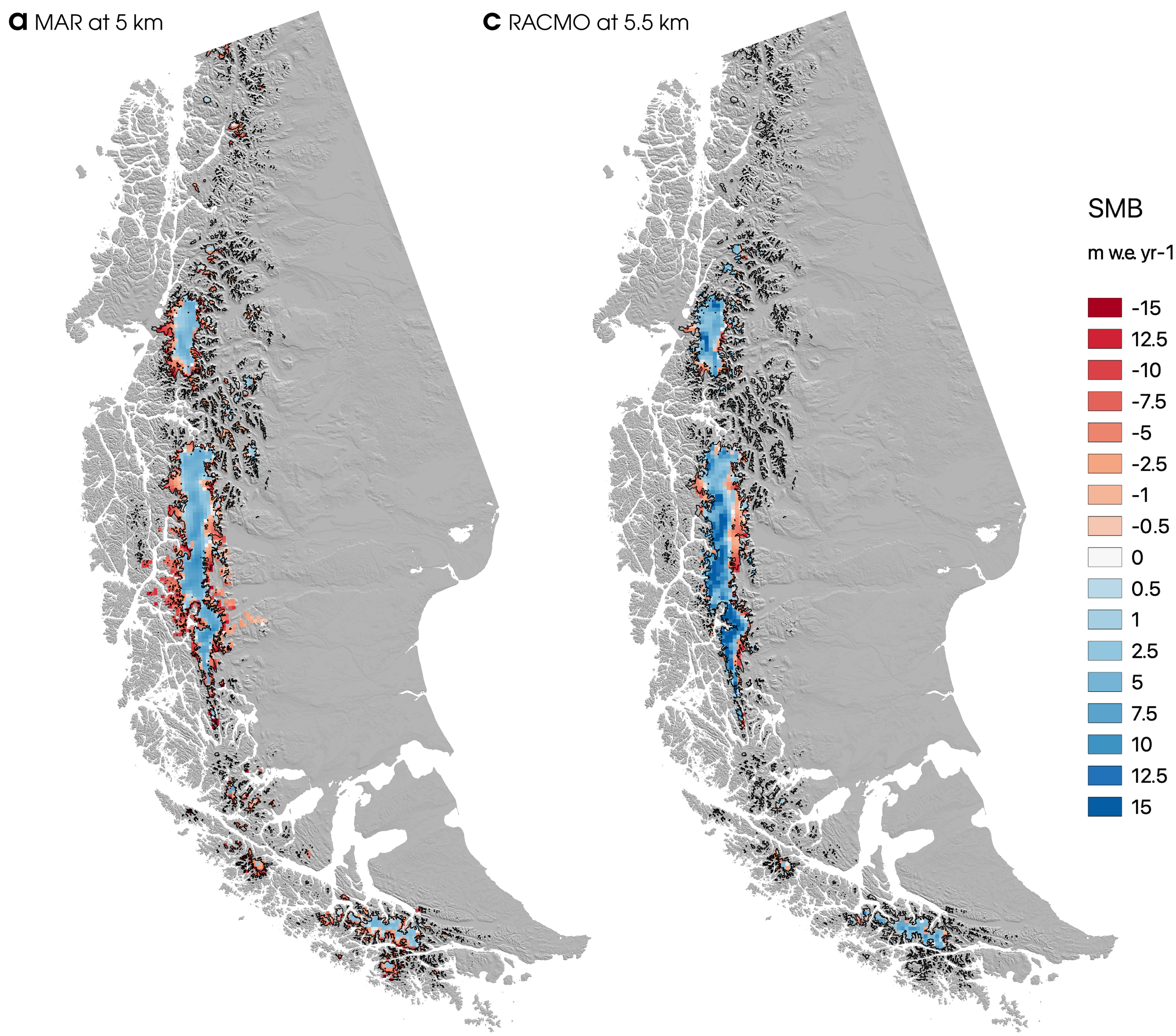
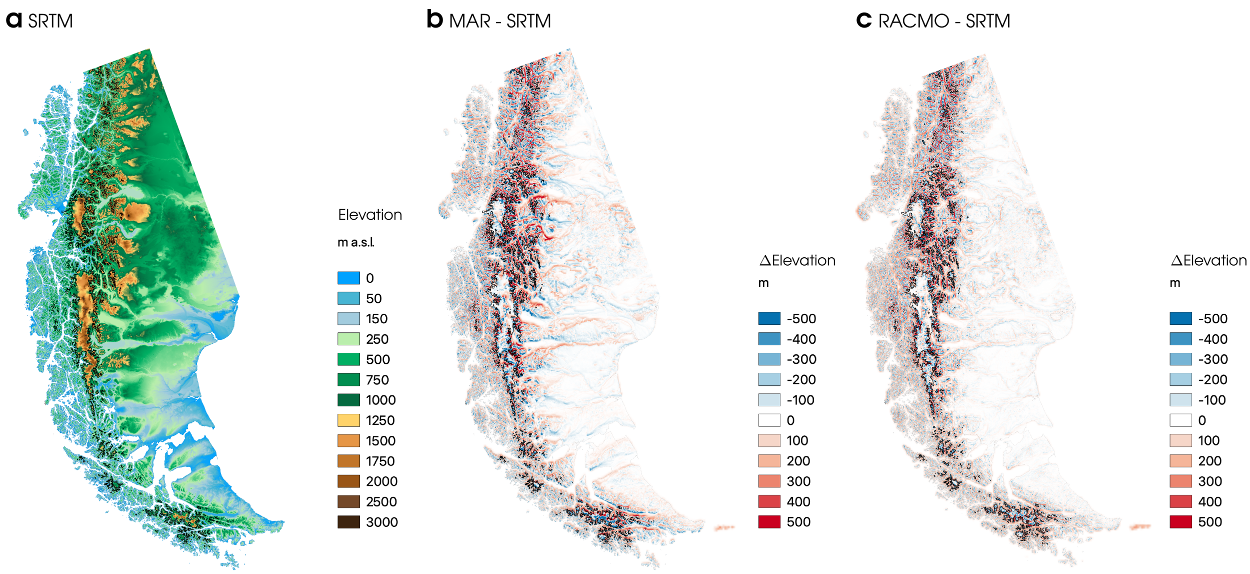
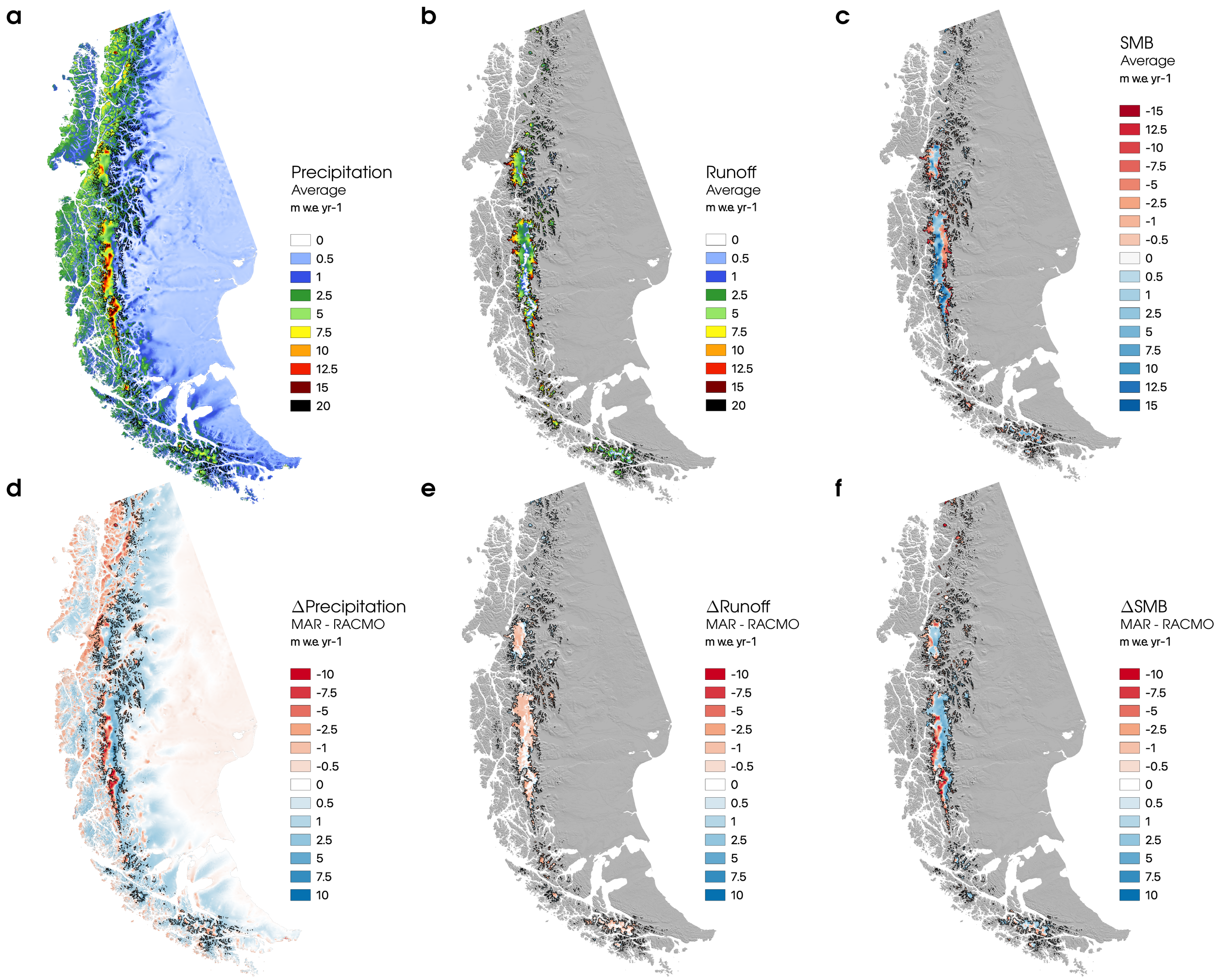


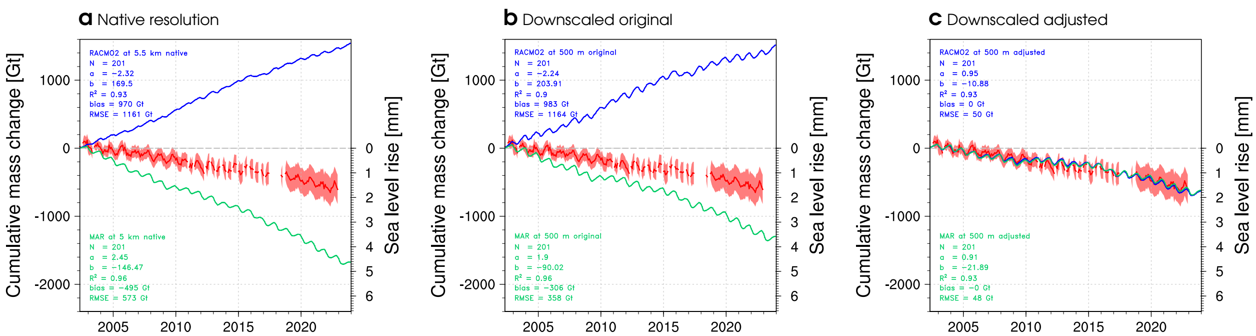
Supplementary Figure 1: **Low-resolution model surface mass balance.** Annual mean surface mass balance (SMB) as modelled by **a** MAR3v14 at 5 km, and **b** RACMO2.3p2 at 5.5 km spatial resolution averaged for the overlapping period 1979-2023.



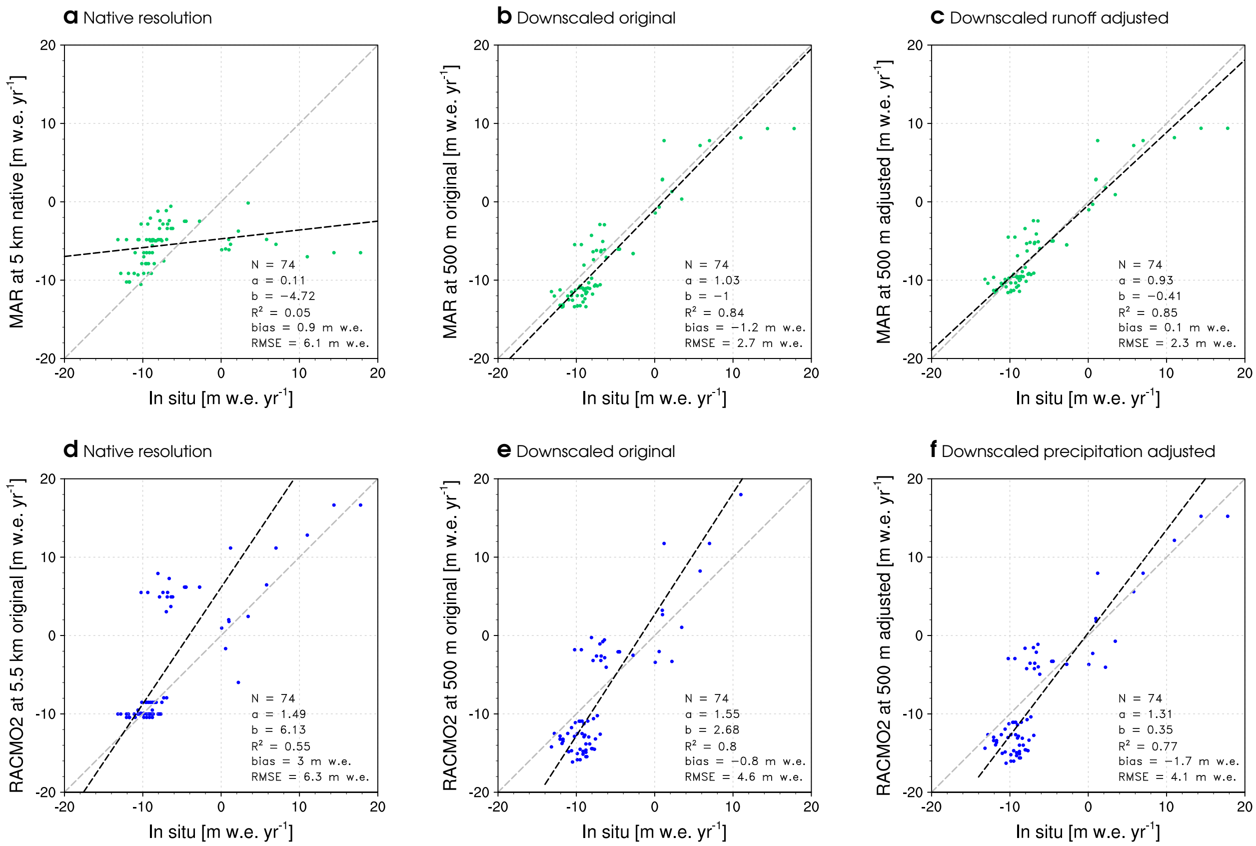
Supplementary Figure 2: **Topography of the Southern Andes.** Surface elevation of the Southern Andes including Patagonian icefields and glaciers as derived from **a** the high-resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) at 30 m resolution[1], down-sampled to a 500 m grid. Difference in surface elevation between **b** MAR at 5 km, **c** RACMO at 5.5 km, and the SRTM DEM at 500 m spatial resolution. Black contours outline Patagonian glaciers derived from the Randolph Glacier Inventory version 6 (RGIv6)[2].



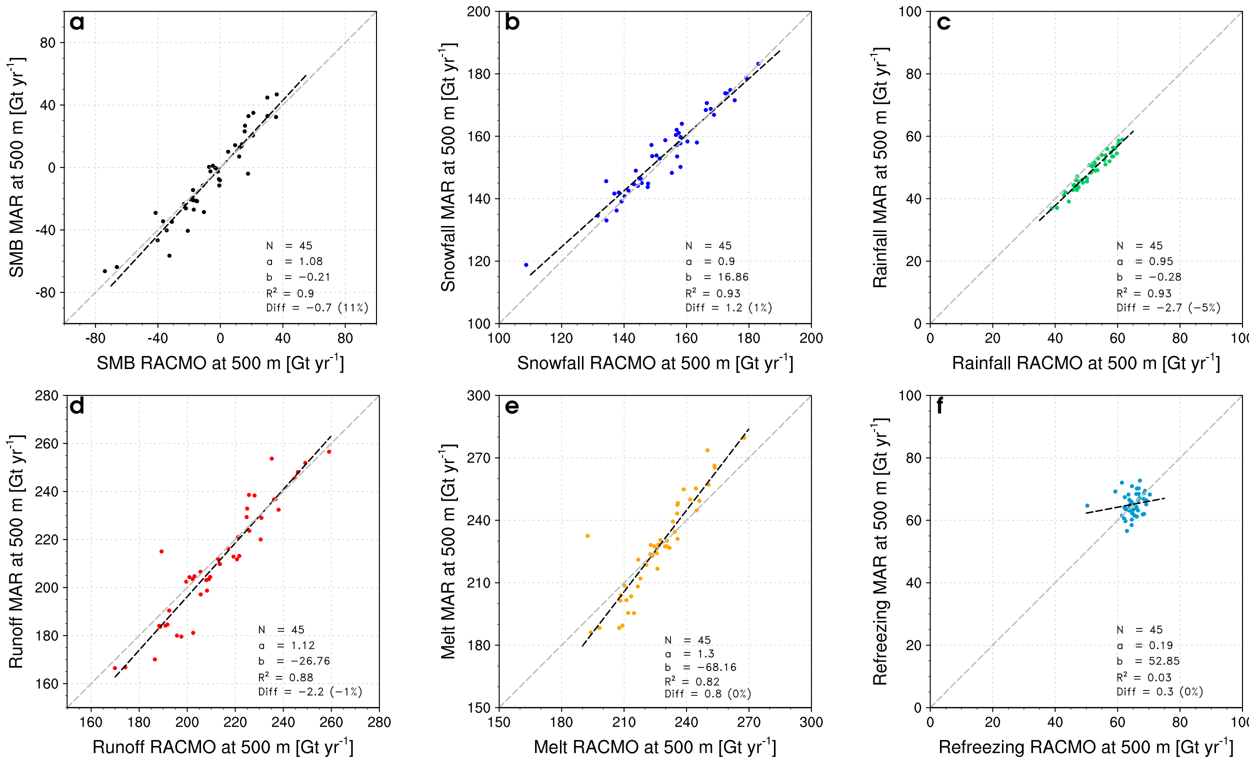
Supplementary Figure 3: **Contemporary SMB components and spatial model differences.** Annual mean **a** adjusted total precipitation, **b** surface runoff and **c** SMB as modelled by RACMO, statistically downscaled to 500 m, for the period 1979-2023. Model differences (MAR minus RACMO) in **d** total precipitation, **e** surface runoff, and **f** SMB for the overlapping period 1979-2023.



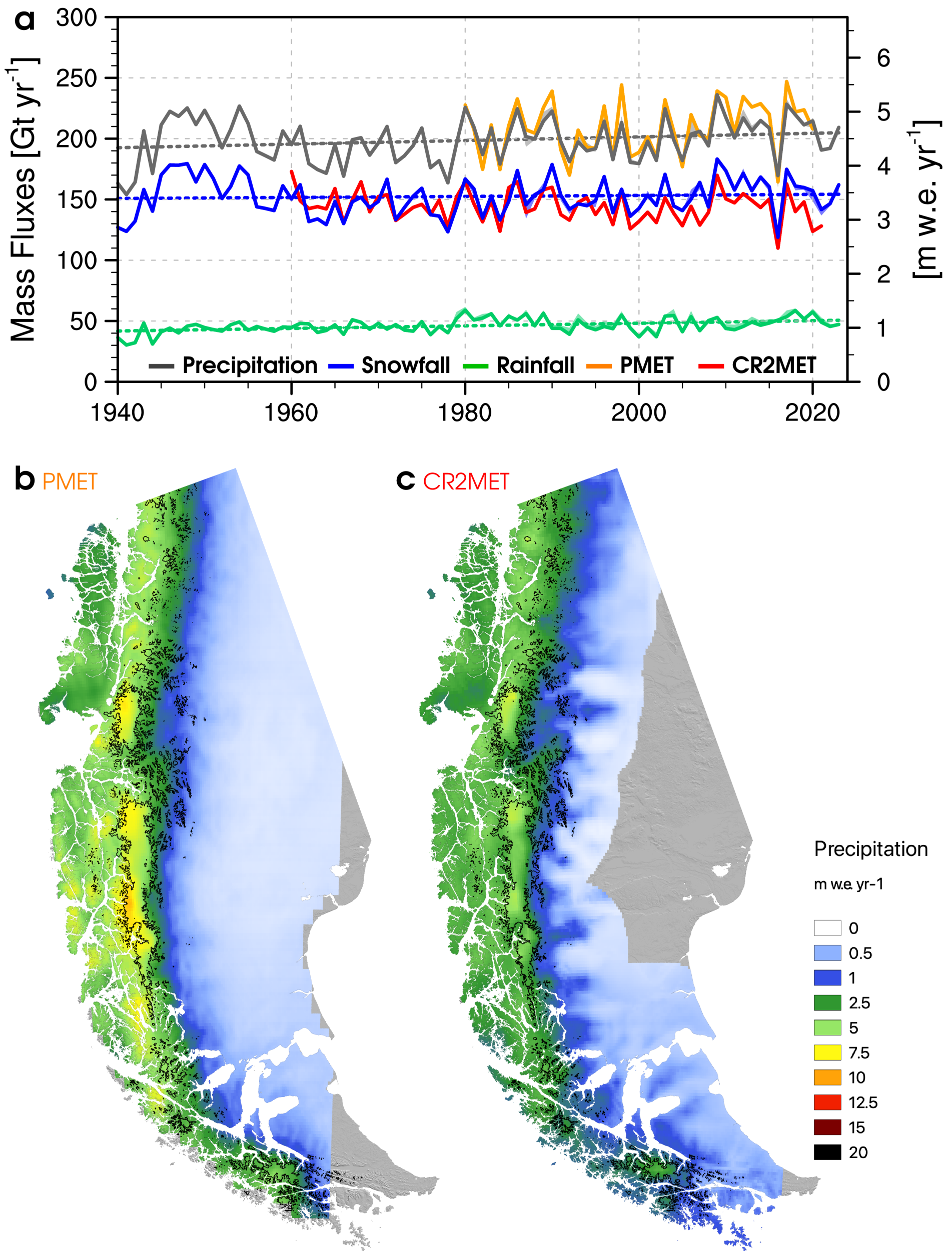
Supplementary Figure 4: **Patagonian glacier mass change since 2002.** Monthly cumulative mass change (MB = SMB - D) of Patagonian glaciers estimated as the difference between modelled surface mass balance (SMB) from MAR (green line, 1940-2023) and RACMO (blue line, 1979-2023) **a** as modelled at 5 km and 5.5 km respectively, **b** as statistically downscaled to 500 m without adjustments, **c** as statistically downscaled to 500 m with runoff (-12.5%) and total precipitation adjustments (-32.5%) for MAR and RACMO respectively (Methods). Solid ice discharge is derived from Rignot et al. (2003)[3] (1940-1999) and Minowa et al. (2021)[4] (2000-2023). Remote sensing mass change from GRACE/GRACE-FO (2002-2022) is shown in red. Coloured bands represent uncertainties. Relevant statistics including number of records (N), the slope (a) and intercept (b) of the regression line (y = ax + b), coordination coefficient (R^2), mean model bias and root mean square error (RMSE) relative to GRACE/GRACE-FO are also listed.



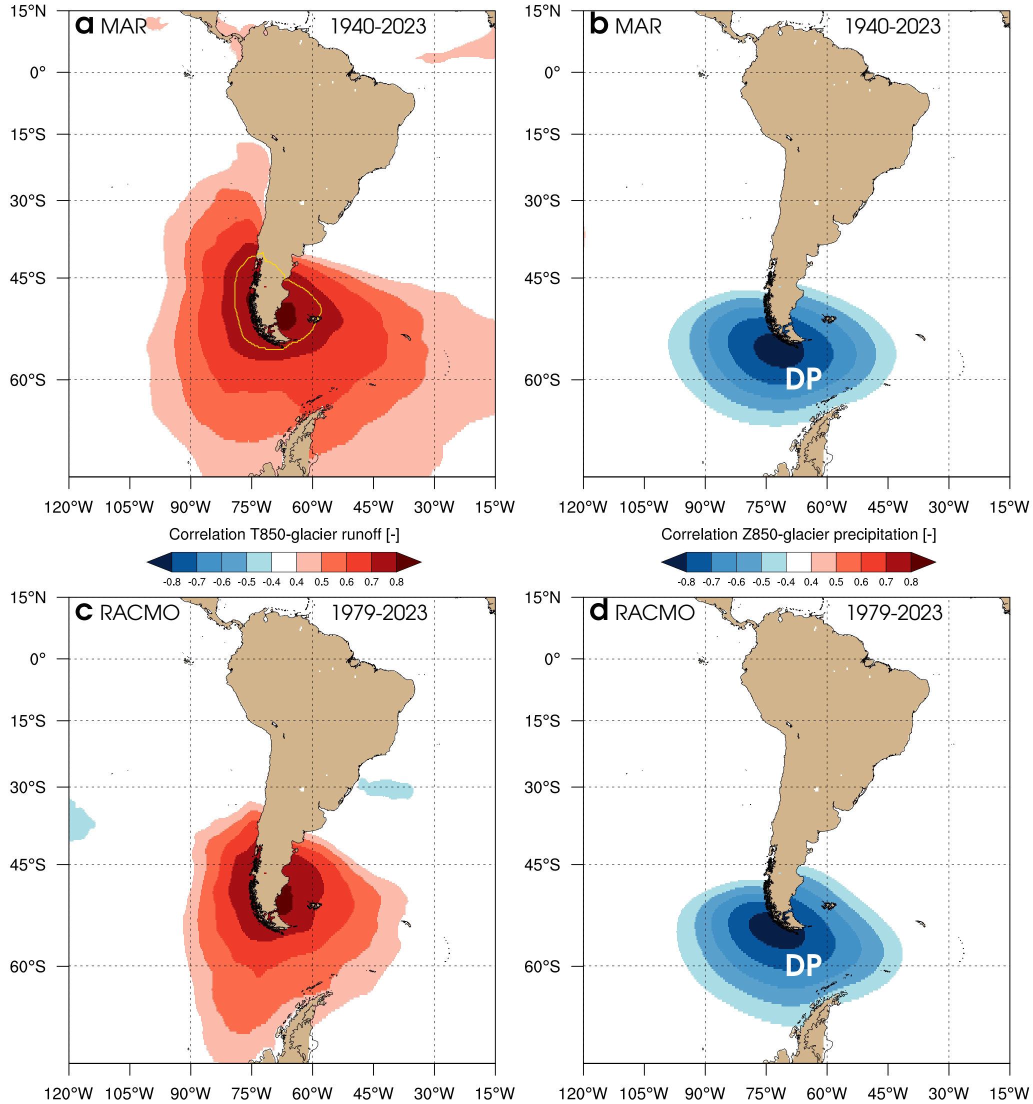
Supplementary Figure 5: **Model evaluation using in-situ SMB records.** Evaluation of modelled SMB in **a** MAR at 5 km, statistically downscaled to 500 m **b** excluding, and **c** including surface runoff adjustment (-12.5%), and in **d** RACMO at 5.5 km, statistically downscaled to 500 m **e** excluding, and **f** including total precipitation adjustment (-32.5%), with 74 in-situ SMB measurements (1980-2019) collected at 38 sites in NPI (2 sites), SPI (26 sites), and CDI (19 sites) (yellow stars in the inset maps of Fig. 1a). Relevant statistics including number of records (N), the slope (a) and intercept (b) of the regression line (y = ax + b), coordination coefficient (R^2), mean model bias and root mean square error (RMSE) are listed.



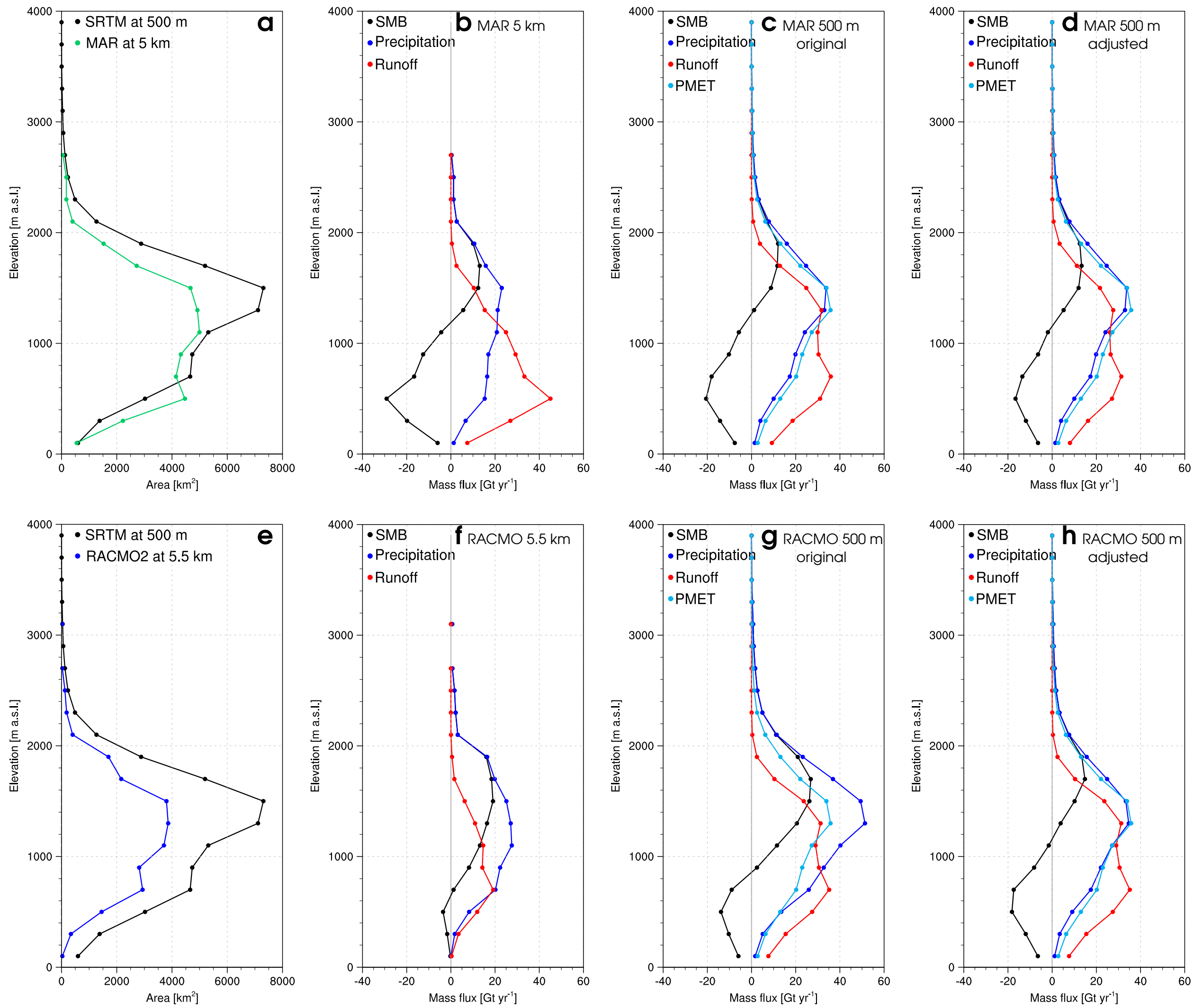
Supplementary Figure 6: **Cross-model correlation of SMB components.** Cross model correlation of **a** SMB, **b** snowfall, **c** rainfall, **d** runoff, **e** total melt, and **f** retention and refreezing, between MAR and RACMO statistically downscaled to 500 m resolution, and adjusted for surface runoff (-12.5%) and total precipitation (-32.5%) respectively. Relevant statistics including number of records (N), the slope (a) and intercept (b) of the regression line (y = ax + b), coordination coefficient (R^2), mean model differences, i.e., as an absolute and relative (%) value, are listed.



Supplementary Figure 7: **Precipitation evaluation across Patagonian glaciers.** **a** Annual mean glacier integrated total precipitation (grey), snowfall (blue) and rainfall (green) from MAR (coloured solid lines, 1940-2023) and RACMO (coloured bands, 1979-2023) at 500 m, i.e., including a -32.5% adjustment for RACMO. In **a**, long-term trends are derived from MAR (dashed lines). Total precipitation from two gridded meteorological data sets at 5 km are also shown, i.e., CR2MET[5] (red, 1960-2021) and PMET[6] (orange, 1980-2020). Note how CR2MET total precipitation aligns with snowfall production from both MAR and RACMO. Annual mean precipitation across the Southern Andes from **b** PMET and **c** CR2MET at 5 km. Black contours outline Patagonian glaciers derived from the RGIv6 product[2].



Supplementary Figure 8: **Correlation between 850 hPa atmospheric conditions and SMB components. a** Spatial correlation between glacier integrated runoff from MAR at 500 m and 850 hPa atmospheric temperature (T850) from ERA5 reanalysis (1940-2023). The yellow contour highlights correlation $r > 0.75$. **b** Spatial correlation between glacier integrated total precipitation from MAR at 500 m and 850 hPa geopotential height (Z850) from ERA5 reanalysis (1940-2023). **c-d** same as **a-b** but for RACMO at 500 m (1979-2023). The location of the Drake Passage (DP) is shown in **b** and **d**.



Supplementary Figure 9: **Patagonian glacier hypsometry and vertical SMB profiles. a** Patagonian glacier hypsometry, i.e., area-elevation distribution, cumulated in 200 m bins for MAR at 5 km resolution (green) and the SRTM DEM at 30 m resolution[1], down-sampled to 500 m (black). Vertical SMB profiles, i.e., glacier integrated SMB components cumulated in 200 m bins, derived from MAR **b** at 5 km, **c** statistically downscaled to 500 m without adjustment, **d** statistically downscaled to 500 m with runoff adjustment (-12.5%). SMB, total precipitation and runoff are displayed in black, blue and red respectively. **e** same as **a** but for RACMO at 5.5 km (green). **f-h** same as **b-d** but for RACMO **f** at 5.5 km, **g** statistically downscaled to 500 m without adjustment, **h** statistically downscaled to 500 m with total precipitation adjustment (-32.5%). In **c-d** and **g-h** total precipitation derived from the PMET meteorological data set at 5 km (cyan) is shown for comparison.

Supplementary Table 1: **Modelled SMB components at different resolutions.** Table listing averaged glacier integrated SMB components derived from the native (nat) MAR3v14 (1940-2023) and RACMO2.3p2 (1979-2023) data sets at 5 km and 5.5 km respectively. Statistically downscaled values at 500 m excluding (raw) and including adjustments (adj) are also listed. To estimate model uncertainty, we compute the absolute difference between MAR and RACMO adjusted SMB components at 500 m for the overlapping period 1979-2023 (MAR_{adj} minus $RACMO_{adj}$). SMB components include total precipitation (PR), snowfall (SF), rainfall (RA), runoff (RU), total melt (ME), refreezing and retention (RF), total sublimation (SU), and drifting snow erosion (ER). Note that MAR does not account for drifting snow erosion.

Data set	Resolution	Period	Units	SMB	PR	SF	RA	RU	ME	RF	SU	ER
MAR_{nat}	5 km	1940-2023	Gt yr^{-1}	-47.1	155.8	109.7	45.6	202.5	177.6	20.7	-0.8	-
MAR_{raw}	500 m	1940-2023	Gt yr^{-1}	-29.1	198.7	152.5	46.2	228.8	216.8	34.2	-1.1	-
MAR_{adj}	500 m	1940-2023	Gt yr^{-1}	0.1	198.7	152.5	46.2	199.7	216.8	63.3	-1.1	-
MAR_{adj}	500 m	1979-2023	Gt yr^{-1}	-7.0	202.8	154.1	48.7	211.0	227.5	65.1	-1.2	-
$RACMO_{nat}$	5.5 km	1979-2023	Gt yr^{-1}	94.2	179.8	146.0	33.7	87.0	65.8	12.2	-1.6	0.1
$RACMO_{raw}$	500 m	1979-2023	Gt yr^{-1}	92.1	302.7	226.5	76.2	213.2	202.1	83.3	-2.9	0.3
$RACMO_{adj}$	500 m	1979-2023	Gt yr^{-1}	-6.3	204.3	152.9	51.4	213.2	226.7	64.9	-2.9	0.3
Uncertainty	500 m	1979-2023	Gt yr^{-1}	0.7	1.5	1.2	2.7	2.2	0.8	0.3	1.7	-

Supplementary Table 2: **Model comparison to mass change records.** Table listing records of Patagonian glaciers mass change (Gt yr^{-1}) from previously published observational data sets, i.e., covering glaciers and icefields. The record method and period of observation are also listed. For a meaningful comparison, MAR and RACMO derived mass change (MB = SMB - D) accounts for solid ice discharge (D = 24.1 Gt yr^{-1})[4].

Data set	Method	Period	MB (Gt yr^{-1})	MAR (Gt yr^{-1})	RACMO (Gt yr^{-1})
Braun 2019[7]	Geodetic	2000-2015	-18.7 ± 1.6	-19.7 ± 2.4	-19.9 ± 2.4
Dussailant 2019[8]	Geodetic	2000-2018	-21.9 ± 5.8	-24.6 ± 2.4	-25.4 ± 2.4
Dussailant 2019[8]	Geodetic	2000-2009	-21.0 ± 6.6	-24.9 ± 2.4	-22.8 ± 2.4
Dussailant 2019[8]	Geodetic	2009-2018	-20.2 ± 6.2	-20.9 ± 2.4	-24.8 ± 2.4
Hugonnet 2021[9]	Geodetic	2000-2019	-20.7 ± 4.1	-24.6 ± 2.4	-25.7 ± 2.4
Zemp 2019[10]	Geodetic | Glaciological	1961-2016	-26.2 ± 11.0	-25.1 ± 2.4	-
Zemp 2019[10]	Geodetic | Glaciological	2006-2016	-34.0 ± 11.0	-23.8 ± 2.4	-24.6 ± 2.4
Jacob 2012[11]	Gravimetry GRACE	2003-2010	-23.0 ± 9.0	-24.5 ± 2.4	-23.0 ± 2.4
Gardner 2013[12]	Gravimetry GRACE	2003-2009	-29.0 ± 10.0	-31.2 ± 2.4	-28.0 ± 2.4
Reager 2016[13]	Gravimetry GRACE	2002-2014	-33.1 ± 12.1	-20.7 ± 2.4	-20.6 ± 2.4
Richter 2019[14]	Gravimetry GRACE	2002-2017	-24.4 ± 4.7	-24.9 ± 2.4	-25.8 ± 2.4
Wouters 2019[15]	Gravimetry GRACE	2002-2016	-30.3 ± 11.0	-25.6 ± 2.4	-26.2 ± 2.4
This study	Gravimetry GRACE	2002-2022	-28.8 ± 11.0	-28.1 ± 2.4	-29.3 ± 2.4

Supplementary References

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