



How well do climate models estimate the historical surface mass balance of the Antarctic ice sheet?

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Abstract. Earth System Model (ESM)-derived Surface Mass Balance (SMB) serves as input for ice sheet models and to make estimates of sea level rise. However, there are few previous studies examining the biases in ESMs when modelling SMB under the historical (1985-2014) period, which may elucidate biases in future projections. Regional Climate Models (RCMs) are often used as a computationally expensive step in improving modelled SMB at the present day and for future projections. It is also unclear whether they add value to SMB estimates on the Antarctic Ice Sheet (AIS), where the topography of the Plateau is relatively smooth. We evaluate SMB from 4 ESMs, 13 ESM-driven RCM simulations, 3 reanalyses and 13 reanalysis-driven RCM simulations, with 76003 AIS SMB observations compiled in the SUMup dataset. We find that ESMs can have consistent Antarctic-wide biases that are related to their temperature biases, and regional biases specific to each ESM. Downscaling with RCMs greatly improves the modelling of SMB relative to ESMs: they systematically increase the correlation coefficient (R; from 0.71 for ESMs to 0.86 for ESM-driven RCMs) and Perkins Skill Score (PSS; from 0.38 to 0.67), and reduce the Root-Mean-Squared Error (RMSE; from 17.90 cm to 15.60 cm). However, RCM downscaling does not systematically outperform reanalyses according to the same metrics (R from 0.88 to 0.90; PSS from 0.58 to 0.69; and RMSE from 11.45 cm to 11.22 cm). When downscaling, RCMs carry strong biases from their driving models, and performance improvement often stems from regional rather than continent-wide improvements. An important caution in interpreting our results is that observations are unevenly distributed in both time and space, hindering a truly unbiased ice sheet-wide assessment of SMB. However, we



find that the density of observations is sufficient to identify the biases between models and observations in Dronning Maud Land and West Antarctica, but there are insufficient measurements in the rest of East Antarctica and the Peninsula, where high added value of RCMs is expected, suggesting that these regions should be a target for future observational campaigns.

1 Introduction

20 The mass budget of ice bodies is one of the dominant controls on sea level change (Cross-Chapter 9.1, Figure 1, Fox-Kemper et al., 2021). Rising sea levels caused by melting ice have wide societal and economic impacts which will require adaptation and mitigation (Hinkel et al., 2014; Bolliger et al., 2026). The Antarctic Ice Sheet (AIS) is the largest body of freshwater on Earth, where small mass change result in large sea level change. Mass loss is dominated by discharge over the grounding line (e.g. The IMBIE team, 2018), while mass gain occurs mainly through surface mass balance or budget (SMB), primarily
 25 snowfall on the grounded AIS. The AIS has contributed to approximately 10% of the increase in sea level since 1991 (Fox-Kemper et al., 2021; Ootosaka et al., 2023), while at the same time, Kolbe et al. (2025a); Wang et al. (2023); Zhang et al. (2024) used satellite data and reanalysis to suggest that increased snowfall has offset the dynamical losses in the years 2020 to 2025.

SMB is the sum of precipitation, runoff from melt, evaporation, sublimation and wind erosion and deposition. Melt and runoff occur rarely on the AIS at present, and the total contribution is negligible to SMB (e.g. Lenaerts et al., 2019), though likely
 30 to increase in the future and a source of disagreement between the current generation of climate models (Hansen et al., 2021; Hofsteenge et al., 2025; Heurgue et al., 2026). In Antarctica, SMB is dominated by precipitation which varies widely both temporally and spatially. Broadly speaking, SMB is highest in the coastal margins and lowest in the interior, a spatial pattern that is likely to intensify under future climate warming (Kittel et al., 2021). Although the accumulation rates on the Antarctic plateau are small, on the order of centimetres per year (Vandecrux et al., 2025), the plateau's sheer size makes the total amount
 35 of snow accumulation in the region large. The accumulation on the grounded AIS is on the order of 2000 Gt year⁻¹ (The IMBIE team, 2018) to 2250 Gt year⁻¹ (Lenaerts et al., 2016).

Evidence from shallow ice cores (Thomas et al., 2015; Morgan et al., 1991), as well as from satellite (Zhang et al., 2024; Rodell et al., 2018) and climate reanalysis (e.g. Kolbe et al., 2025a; Diener et al., 2021; The IMBIE team, 2018) indicates that SMB in Antarctica has been increasing in the last century, primarily through increased precipitation, though increased
 40 melt is also observed especially on ice shelves (Tuckett et al., 2025). The correlation between temperature and precipitation has been projected, as a warmer atmosphere raises the saturation vapour pressure, as described by the Clausius-Clapeyron relationship (Held and Soden, 2006). Recent changes in precipitation have proved difficult to detect beyond uncertainty ranges in observational records even at long and continuously monitored field sites (e.g. Reppert et al., 2025). In general, the Clausius-Clapeyron relationship suggests an average value of 7.5% increase in humidity for every degree of warming (O'Gorman and
 45 Muller, 2010), which in turn brings higher precipitation. Nicola et al. (2023) found values ranging from 0 to 15% additional precipitation per Kelvin, both for different regions of Antarctica and in the projections of different ESMs of the Coupled Model Intercomparison Project for the 6th IPCC assessment report (CMIP6; Eyring et al., 2016) ensemble. Warming also raises the intensity, duration and frequency of extreme precipitation events (Thackeray et al., 2022; Kao and Ganguly, 2011; Payne et al.,



2020), which significantly contribute to snowfall in Antarctica (Turner et al., 2019; Kolbe et al., 2025b). On the other side of the SMB equation, melt has historically been confined to the Antarctic Peninsula, ice shelves and the low elevation grounded ice sheet (Tuckett et al., 2025), but models suggest it will propagate upward on the ice sheet with increased temperatures (Hofsteenge et al., 2025; Zheng et al., 2026). Melt directly affects the SMB only if it does not refreeze and runs off the ice sheet by moving mass off the grounded AIS. Surface melt can also indirectly affect the ice sheet mass balance, for example by contributing to ice shelves break-ups through hydro-fracture (e.g. Kuipers Munneke et al., 2014; Mottram et al., 2025), which buttress ice sheet flow and ice discharge (Cuffey and Paterson, 2010, Sec. 8.9.3).

Numerical climate models are essential tools for projecting future SMB, as in situ observations are necessarily limited to the past. Earth System Models (ESMs; e.g. Döscher et al., 2022; Danabasoglu et al., 2020; Sellar et al., 2020; Mauritsen et al., 2019) are global models that include components covering land, ocean, atmosphere and other parts of the Earth system such as ice sheets, sea ice and carbon budgets. ESMs use only external forcings (e.g. solar or anthropogenic greenhouse gas emissions) and apply them globally. In exercises like CMIP6, ESMs typically follow standardised protocols such that they can be compared. In the Ice Sheet Model Intercomparison for CMIP6 (ISMIP6, Seroussi et al., 2020), ice sheet models are driven by ESMs to, amongst others, make sea level rise predictions. This means that ESMs are a crucial part of the sea level rise predictions.

In previous CMIP exercises, ESM outputs have been used to assess sea level rise contributions and some attempts have been made to assess their accuracy in reproducing Antarctic climate. For example, variables including SMB from CMIP3 ESMs were compared to the reanalysis product ERA-40 by Connolley and Bracegirdle (2007), who found that no ESM performed well on the Antarctic Peninsula. Since, there has been significant technical progress such as added resolution, better physics, new scenarios and experiments, etc (Rummukainen, 2016). Evaluating the latest version of those ESMs against historical and contemporary SMB in situ observations (Wang et al., 2016b; Gorte et al., 2020) or reanalyses (e.g. Dunmire et al., 2022; Agosta et al., 2019) is crucial to understanding their capacity to simulate future climate, though reanalysis have their own biases in the Polar regions. Due to computational constraints, ESMs typically run at resolutions on the order of 1° , which is too coarse to resolve local scale topography and numerous processes accurately, such as orographic uplift, foehn winds, or convection (Rummukainen, 2016, 2010). Additionally, ESMs are not designed to mimic the observed weather but rather to provide a realistic description of the Earth system in response to external forcing (Flato, 2011).

Climate reanalyses are based on high resolution numerical weather prediction models which are continuously updated to minimize the deviation from an extensive set of remotely sensed and in situ observation. Since they rely on observations, reanalyses such as ERA5 (Bell et al., 2021) or ERA-Interim (Dee et al., 2011) are only available for the past, and are not designed to predict future climate. Reanalyses have coarse spatial resolution in order to have global coverage, and because they focus on atmospheric conditions, they also generally do not include all Earth system components, including for example rather poor description of ice sheet surface processes.

To downscale the coarse ESM and global reanalysis at a higher spatial resolution, and to incorporate more realistic atmospheric and surface processes, Regional Climate Models (RCMs) have been developed. At its domain boundary, typically their uppermost atmospheric level, RCMs use as forcing data a selection of atmospheric variables simulated by either ESMs



or reanalyses. The RCMs, usually based on numerical weather prediction models and therefore including full physical and dynamical schemes, produce regional, high-resolution outputs of meteorological and surface variables (e.g. Belušić et al., 2020; Niwano et al., 2018; Rockel et al., 2008). Studies in regions with dense observations and complex topography have demonstrated added value: RCMs outperformed four different ESMs in the Alps on multiple variables (Torma et al., 2015). Orographic uplift is better resolved with higher resolution, resulting in added value of RCMs especially in high relief areas (Rummukainen, 2016). But high relief areas often time do not have a dense enough observation network to observe the added value. For example, Lucas-Picher et al. (2012) were not able to quantify the added value of RCMs due to the lack of meteorological observations on the ice sheet margins. On the Greenland ice sheet and using reanalyses as drivers, Fettweis et al. (2020) found most added value for simpler positive degree day models, and that several RCMs outperformed the ERA-Interim reanalysis. It remains unclear whether the RCMs also have an added value in modelling SMB in Antarctica, given the smooth macro-scale landscape of the AIS plateau and the need for denser observations to assess performance in high relief areas. Previous efforts to assess RCM performance have mostly focused on meteorological variables like temperature, wind speed and pressure (Gilbert et al., 2026; Mottram et al., 2021).

Unlike reanalyses, ESMs evolve freely without assimilating real-world observations, so their inter-annual circulation and weather variability is not synchronous with that of the real world. We can nonetheless extract meaningful information from yearly accumulation when treated as climatology because spatial variability is greater or equivalent to inter-annual variability. Indeed, spatial accumulation spans nearly two orders of magnitude, from a few centimetres on the plateau to over 10 meters on the Antarctic Peninsula, and an order of magnitude at local scale (e.g. Melvold et al., 1998b), while inter-annual variability generally spans an order of magnitude or less (Baiman et al., 2023; Genthon, 2004; Turner et al., 2019). We infer from this that ESMs should still have a reasonable predictive skill for annual to multi-annual SMB, if their spatial distribution of precipitation is close to the observed. Indeed, Lenaerts et al. (2016) found good agreement between the climatic SMB output of CESM2 and ERA-Interim, and other variables than SMB of the CMIP5 and CMIP6 models were in relative agreement to ERA5 (Agosta et al., 2024). The temporal variability of ESM outputs can nevertheless be assessed by examining the impact of the Southern Annular Mode (SAM) on SMB as represented in the models. SAM is the normalised pressure difference between 40° and 65°S, and influences regional SMB (e.g. Kolbe et al., 2025a; Hansen et al., 2021; Kim et al., 2020), and regional melt (Tuckett et al., 2025). There is evidence that reanalyses such as MERRA-2 or ERA5 reliably capture the SAM-SMB relationship (Medley and Thomas, 2019; Kolbe et al., 2025a) since they assimilate variables such as pressure that represent it, but whether ESMs reliably reproduce that relationship, and thus produce credible temporal SMB variability, remains unclear.

The added value of RCMs, and the models biases are poorly known. The number and variety of models available to assess the SMB of the AIS call for a methodical and spatially extensive evaluation of their performance. Compilations of in situ SMB observations provide the observational foundation for such an evaluation (e.g. Wang et al., 2021b; Favier et al., 2013b, SUMup).

In this work, we use 76,003 SMB observations contained in the SUMup dataset to evaluate 4 ESMs, 13 ESM-driven RCMs, 3 reanalyses and 13 reanalysis-driven RCMs. We focus on ESMs that have downscaled RCM simulations as comparison and we answer three research questions:



120 1) What are the biases of the ESMs running with historical (1985-2014) scenarios compared to the observational SMB record?

2) What is the added value of RCMs over ESMs in modelling the SMB of the AIS?

3) Is the current SMB observation network sufficient to assess the predictions of the climate models?

For all research questions, we use reanalyses and reanalysis-driven-RCMs as a performance benchmark.

2 Data

125 We use the simulation output of 4 ESMs, 3 reanalyses and 26 RCM (Tables 1 & 2). We refer to the RCM outputs as either RCM_{forcing}, or RCM (forcing), depending on readability. All models span the time period 1985-2014 (inclusive), with the exception of PARASO_{ECEARTH3}, which spans 1985-2013 inclusive, and COSMO-CLM_{ERA1}², which spans 1987-2014 inclusive.

Table 1. Matrix-style summary of the forcing and RCMs used in this study.

Driven by	ESMs				Reanalyses		
	CESM2	ECEARTH3	MPI	UKESM	ERA5	ERA1	JRA
No RCM	x	x	x	x	x	x	x
COSMO-CLM ²						x	
ERA5-Land					x		
HCLIM	x		x		x		
HIRHAM5	x	x		x	x	x	
MAR 3.11				x			
MAR 3.13			x				
MAR 3.14	x				x		
NHM-SMAP							x
PARASO		x			x		
RACMO 2.3p2						x	
RACMO 2.4p1	x		x		x		
HIRHAM5-SMB	x	x			x	x	
MetUM-SMB						x	

The following sections briefly introduce the models whose key characteristics are summarised in Table 2.



Table 2. Summary of the properties of the ESMs, reanalyses, and RCMs used in this study. SMB estimation acronyms: P: solid precipitation/snowfall depending on model convention; TP: total precipitation; E: sublimation and evaporation; SE: snow evaporation; R: run-off; W: wind erosion or airborne particle deposition. Each model has its own sign convention for mass fluxes, but it is homogenized for readability in this table.

	Model run	Forcing	Years spanned	Resolution	Physics	SMB est.	Citation
ESMs	CESM2 r1i1p1f1	-	1985-2014	1/3°	Unidentified	TP-E	Danabasoglu et al. (2020)
	ECEARTH3 r5i1p1f1	-	1985-2014	0.7°	Unidentified	TP-E	Döscher et al. (2022)
	MPI LR r1i1p1f1	-	1985-2014	0.9735°	Non-hydrostatic	P-E	Mauritsen et al. (2019)
	UKESM 1.0 LL r1i1p1f2	-	1985-2014	~ 1.5°*	Unidentified	P-E	Sellar et al. (2020)
	EM _{ESM} only	-	1985-2014	1/3°	-	-	-
ESM-driven RCMs	HCLIM	CESM2 r1i1p1f1	1985-2014	11 km	Non-hydrostatic	P-E-R	Belušić et al. (2020)
	HCLIM	MPI LR r1i1p1f1	1985-2014	11 km	Non-hydrostatic	P-E-R	Belušić et al. (2020)
	HIRHAM5	CESM2 r1i1p1f1	1985-2014	12 km	Hydrostatic	P-E-R	Boberg et al. (2022)
	HIRHAM5	ECEARTH3 r5i1p1f1	1985-2014	12 km	Hydrostatic	P-E-R	Boberg et al. (2022)
	HIRHAM5	UKESM 1.0 LL r1i1p1f2	1985-2014	12 km	Hydrostatic	P-E-R	Boberg et al. (2022)
	HIRHAM5-SMB	CESM2 r1i1p1f1	1985-2014	12 km	Firm model	TP-E-R-W	Glaude et al. (2024)
	HIRHAM5-SMB	ECEARTH3 r5i1p1f1	1985-2014	12 km	Firm model	TP-E-R-W	Boberg et al. (2022)
	MAR 3.11	UKESM 1.0 LL r1i1p1f2	1985-2014	35 km	Hydrostatic	P-E-R-W	Jourdain et al. (2025)
	MAR 3.13	MPI LR r1i1p1f1	1985-2014	25 km	Hydrostatic	P**	-
	MAR 3.14	CESM2 r1i1p1f1	1985-2014	25 km	Hydrostatic	P-E-R-W	Hofsteenge et al. (2026)
	PARASO	ECEARTH3***	1985-2013	0.25°	Unidentified	TP-E	Sauerland et al. (2025)
	RACMO 2.4p1	CESM2 r1i1p1f1	1985-2014	11 km	Hydrostatic	P-E-R-W	Hofsteenge et al. (2025)
	RACMO 2.4p1	MPI LR r1i1p1f1	1985-2014	11 km	Hydrostatic	P-E-R-W	Hofsteenge et al. (2025)
	EM _{ESM} ∪ RCM	-	1985-2014	11 km	-	-	-
Reanalyses	ERA5	-	1985-2014	31 km	Unidentified	TP-E	Hersbach et al. (2020)
	ERA1	-	1985-2014	0.7°	Unidentified	P-E	Dee et al. (2011)
	JRA (55)	-	1985-2014	0.375°	Unidentified	P-E	Kobayashi et al. (2015)
	EM _{Rea} only	-	1985-2014	31 km	-	-	-
Reanalysis-driven RCMs	COSMO-CLM ²	ERA1	1987-2014	25 km	Non-hydrostatic	P-E	Souvereinjs et al. (2019b)
	ERA5-Land	ERA5	1985-2014	~ 9 km	Downscaling	P-SE-R	Muñoz-Sabater et al. (2021)
	HCLIM	ERA5	1985-2014	11 km	Non-hydrostatic	P-E-R	Belušić et al. (2020)
	HIRHAM5	ERA5	1985-2014	12 km	Hydrostatic	P-E-R	Boberg et al. (2022)
	HIRHAM5	ERA1	1985-2014	12 km	Hydrostatic	P-E-R	Boberg et al. (2022)
	HIRHAM5-SMB	ERA5	1985-2014	12 km	Firm model	TP-E-R-W	Hansen et al. (2021)
	HIRHAM5-SMB	ERA1	1985-2014	12 km	Firm model	TP-E-R-W	Hansen et al. (2021)
	MetUM-SMB	ERA1	1985-2014	13 km	Firm model	TP-E-R-W	Hansen et al. (2024)
	MAR 3.14	ERA5	1985-2014	25 km	Hydrostatic	P-E-R-W	Hofsteenge et al. (2026)
	NHM-SMAP	JRA	1985-2014	12 km	Non-hydrostatic	P-E-W	Niwano et al. (2018)
	PARASO	ERA5	1985-2014	0.25°	Unidentified	TP-E	Sauerland et al. (2025)
	RACMO 2.3p2	ERA1	1985-2014	27 km	Hydrostatic	P-E-R-W	Van Wessem et al. (2018)
	RACMO 2.4p1	ERA5	1985-2014	11 km	Hydrostatic	P-E-R-W	Van Dalum et al. (2025)
	EM _{Rea} ∪ RCM	-	1985-2014	11 km	-	-	-
	EM _{all}	-	1985-2014	11 km	-	-	-

Other forms of precipitation than snowfall come in negligible amount, resulting in negligible differences between the use of total precipitation or snowfall only. *: 1.875° along the longitude; 1.25° along the latitude. **: the sublimation output was corrupted and is therefore unusable. ***: custom run, see Section 2.3.6.

2.1 Earth System Models

130 We used the CMIP6 version of the ESMs. Unless stated otherwise, we used the following realisation number, which nearly maximises consistency between ESM realisation numbers and those of their RCM forcing: CESM2 r1i1p1f1, EC-EARTH3 (ECEARTH3 hereafter) r5i1p1f1, MPI 1.2 LR r1i1p1f1, and UKESM r1i1p1f2. Some mismatches remain, for example HIRHAM5 (ECEARTH3) used r5i1p1f1; and PARASO (ECEARTH3) used a custom run of ECEARTH3. We note that a mismatch in en-



semble member is a minor issue for yearly statistics, using as example that sea ice extent was relatively invariant between
 135 ensemble members of the same ESM, for several of the CMIP6 ESMs (Williams et al., 2024).

Each ESM treated surface processes differently over Antarctica. The CMIP6 version of: CESM2 used a non-evolving land
 ice scheme with CISM2.1 (Danabasoglu et al., 2020; Copernicus Climate Change Service, 2021); ECEARTH3 disabled the
 land ice module for Antarctica but used the HTESSEL surface scheme (Döscher et al., 2022; EC-Earth Consortium, 2019);
 MPI-ESM (LR version, consistent with RCM forcing) used a modified version of the land model in ECHAM5 (Roeckner et al.,
 140 2006; Mauritsen et al., 2019), which incorporates snow processes; UKESM (version 1.0 LL, consistent with RCM forcing) used
 a 10-layer snow module for Antarctica (Sellar et al., 2020).

2.2 Reanalyses

ERA5 is the successor of ERA-Interim (ERA-Interim thereafter), with similar but improved modelling techniques, higher spatial
 resolution and more observations assimilated, while JRA is produced independently by the Japan Meteorological Agency. The
 145 reanalyses therefore differ in their land surface schemes, which govern how SMB is estimated. ERA5 (Copernicus Climate
 Change Service, 2019b; Hersbach et al., 2020) uses an improved version of the land model also used by ERA-Interim (Fasullo, John,
 2022; Dee et al., 2011), incorporating a snowpack scheme (Bromwich et al., 2024). Like ERA5, JRA (downloaded from Japan
 Meteorological Agency, 2023) has a land surface analysis component with a snow module (Kobayashi et al., 2015).

2.3 Regional Climate Models and other downscaling methods

150 We used eight RCMs (rows of Table 1) and the ERA5-Land downscaling. All simulations were collected upon request from the
 original authors, or through open-source access (see data availability statement). ERA5-Land (downloaded from Copernicus
 Climate Change Service, 2019a), a land processes-focused downscaling of ERA5, is included in this category, but is not
 described given its extensive documentation (Muñoz-Sabater et al., 2021).

2.3.1 COSMO-CLM²

155 COSMO-CLM² is a non-hydrostatic RCM developed at the German Weather Service (Rockel et al., 2008). The model was
 applied at a spatial resolution of ~ 25 km and 40 vertical levels in the atmosphere and is forced every 6 h at the boundaries
 by ERA-Interim. The model is coupled to the Community Land Model (version 4.5; Oleson et al., 2013), with adjustments in the
 perennial snow scheme proposed by Van Kampenhout et al. (2017) to better represent the SMB of ice sheets. The model set-up
 and its Antarctic evaluation are described in detail by Souverijns et al. (2019b).

160 2.3.2 HCLIM

We used the daily outputs of the HCLIM model covering the period 1985–2014 when driven by ERA5, and 1984–2015
 when driven by MPI-ESM1.2-LR (Mauritsen et al., 2019) and CESM2 (Danabasoglu et al., 2020). HCLIM is a flexible,
 convection permitting, regional climate modelling framework that allows for different physics configurations. It is based on the



HIRLAM–ALADIN–AROME numerical weather prediction (NWP) system (Belušić et al., 2020). The simulations analysed
 165 here used the mesoscale hydrostatic configuration HCLIM-ALADIN version 43, with a horizontal resolution of 11 km and 65
 vertical levels. Land–atmosphere interactions are represented through the SURFEX surface model, which includes the ISBA-
 ES explicit snow scheme (Masson et al., 2013), while sea-ice processes are simulated using the thermodynamic sea-ice model
 SICE (Batrak et al., 2018). More detailed descriptions of the model setup can be found in Kolbe et al. (2025a), Mottram et al.
 (in preparation), and Torres Alavez et al. (2026). The surface mass balance (SMB) was computed as the difference between
 170 precipitation and the sum of evaporation and surface run-off for the three HCLIM simulations.

2.3.3 HIRHAM5

The RCM HIRHAM5 (Christensen et al., 2006) combines the dynamical core of the HIRLAM7 numerical weather forecasting
 model (Eerola, 2006) with physical schemes taken from the ECHAM5 model (Roeckner et al., 2003). HIRHAM5 was run on
 a horizontal 0.11° by 0.11° rotated-pole grid, corresponding to a 12 km resolution, with 6 h atmospheric model-level fields
 175 of pressure, temperature, humidity and wind speed at the lateral boundaries. Three ESMs (CESM2 r1i1p1f1, UKESM1.0-LL
 r1i1p1f2 and EC-Earth3-LR r5i1p1f1) and two sets of reanalysis data (ERA-Interim and ERA5) were downscaled using HIRHAM5.
 CESM2 and ECEARTH3 were downscaled for the period 1970–2015, UKESM1.0-LL for 1950–2015, ERA-Interim for 1979–2018 and
 ERA5 for 1959–2023. The first year was systematically used for spin-up. We truncated all model runs to the 1985–2014 period.
 HIRHAM's modelling of SMB and other meteorological variables over ice sheets is documented by Boberg et al. (2022).

180 2.3.4 MAR

The Modèle Atmosphérique Régional (MAR) is an RCM representing Antarctic climate using the hydrostatic approximation
 (Gallée and Schayes, 1994), with prognostic evolution of five hydrometeors: snow particles, cloud ice crystals, raindrops, cloud
 droplets, and specific humidity (Gallée, 1995). The Antarctic adaptation is described in Agosta et al. (2019) and Kittel et al.
 (2021). The versions used here are 3.11, 3.13 and 3.14. Compared to 3.11, the later versions included updated Fortran 90 code,
 185 a new radiative scheme (Graillet et al., 2025, in preparation), and corrections in the surface module to conserve water mass.
 For these simulations, MAR was driven at its lateral boundaries by temperature, wind, humidity at each atmospheric level, and
 surface pressure, along with sea ice concentration and SST. The model resolution is run-dependent (Table 2), with topography
 based on BedMachinev3 (Morlighem et al., 2017).

2.3.5 NHM-SMAP

190 NHM-SMAP (Non-Hydrostatic atmospheric Model and Snow Metamorphism and Albedo Process model), is a polar-oriented
 RCM initially developed for Greenland (Niwano et al., 2018), then applied in the AIS at a horizontal resolution of 12 km.
 NHM-SMAP applied in Antarctica uses the ice sheet mask by Slater et al. (2018), employs the same model configuration as
 that developed by Niwano et al. (2018), and is forced at its boundaries every 6 hours by the JRA-55 reanalysis (Kobayashi et al.,
 2015). Daily atmospheric profiles are reinitialised at 00 UTC in the model from JRA-55 to prevent large deviations between



195 synoptic conditions from JRA-55 and NHM-SMAP, while snow and ice physical conditions are not reinitialised throughout the simulation. NHM-SMAP has been applied and evaluated over Antarctica in Sugawara et al. (2026).

2.3.6 PARASO

PARASO (Pelletier et al., 2022) is a fully-coupled regional ice sheet–ocean–sea ice–atmosphere–land model, covering the Antarctic continent as well as its surrounding oceans. It consists of a configuration of the COSMO model for the atmosphere
200 (Rockel et al., 2008) in version 5.0 with the adaptations provided by Souverijns et al. (2019b), coupled via the OASIS3-MCT coupler (Will et al., 2017) to the Community Land Model (CLM) in version 4.5 (Oleson et al., 2013), and the NEMO-LIM model, version 3.6, for the simulation of the open ocean and the sea ice (Madec, 2016; Vancoppenolle et al., 2009; Rousset et al., 2015). NEMO-LIM itself consists of two distinct models with the coupling in between them hard-coded: first, the NEMO model for the open ocean, and second, the Louvain-la-Neuve Sea Ice Model (LIM). Additionally, the Kori (previously known
205 as f.ETISh) ice dynamical model (Pattyn, 2017; Coulon et al., 2021) is used for modelling the AIS, which is coupled offline to NEMO-LIM. The PARASO setup also allows SMB values from COSMO-CLM² to be provided to Kori, though in the runs analysed in this paper, the ice sheet surface is not coupled back to COSMO due to the negligible impact over a 30-year period. The PARASO simulations presented in this paper are described in more detail in Sauerland et al. (2025). We used two PARASO runs: one is initialised by and forced at the lateral boundaries using ERA5 (Hersbach et al., 2020) and ORAS5 (Zuo
210 et al., 2019) reanalysis data, and the other by ECEARTH3 hindcast data (Döscher et al., 2022), a slightly modified version of the r2i1p1f1 member of the CMIP6 historical ensemble. The ECEARTH3-driven run covers 1985–2013; the ERA5-driven run covers 1985–2014.

2.3.7 RACMO

The Regional Atmospheric Climate Model (RACMO) is a hydrostatic model comprising the dynamical core of the HIRLAM
215 model (Undén et al., 2002) and the physics parameterisations of the ECMWF's Integrated Forecast System (IFS). On top of the IFS parameterisations, RACMO includes a separate multilayer snow/ice model representing glaciated surfaces. This sub-model governs the evolution of the snow temperature, density, and grain size as well as water processes in snow, and derives a grain-size-based albedo. Furthermore, it models snow drift over glaciated surfaces. RACMO 2.3p2, described and evaluated in Van Wessem et al. (2018), used IFS cycle CY33R1 (ECMWF, 2009) and employed a horizontal resolution of 27 km over
220 Antarctica. RACMO 2.4p1 (Van Dalum et al., 2024), used IFS cycle CY47R1 (ECMWF, 2020), and incorporated, among other changes, spectral grain-side-based albedo and updated snow drift physics (Gadde and Van De Berg, 2024). Van Dalum et al. (2025) evaluated RACMO 2.4p1 applied over Antarctica at 11 km resolution against observations. An inter-comparison of simulations using different reanalysis and Earth System Model (ESM) realisations is given in Hofsteenge et al. (2025).



2.3.8 DMI SMB model (HIRHAM-SMB and MetUM-SMB)

225 The DMI SMB model is a physically based offline-coupled firn model and was applied to the output of various HIRHAM5 simulations, and MetUM. It is derived from the HIRHAM5 implementation by Langen et al. (2015), updated to include 32 vertical layers extending to 60 m water equivalent (w.e.) depth and incorporates detailed firn physics (Langen et al., 2017; Hansen et al., 2021). It uses a fixed-layer scheme that maintains a constant layer mass and simulates processes such as densification, snow grain growth, hydraulic conductivity, irreducible water content, and ice-layer formation. Meltwater percolation is described by Darcy flow parameterisation, and firn density evolves under overburden pressure using established compaction schemes. The model uses a temperature-dependent albedo: snow albedo varies linearly from 0.85 (below -5°C) to 0.65 (at 0°C), with bare ice albedo fixed at 0.4 (Oerlemans and Knap, 1998). Firn and snow evolution processes—including snowfall, melt, run-off, refreezing, sublimation, and rain—respond to external energy and mass fluxes from HIRHAM5. The DMI SMB model has been used and evaluated in studies for Greenland (Langen et al., 2017; Glaude et al., 2024; Puggaard et al., 2024; Scanlan et al., 2025) and Antarctica (Hansen et al., 2021, 2024; Rajavarathan et al., 2026).

2.4 Ensemble means

Multi-model ensemble means have been shown to consistently outperform any single model (Tebaldi and Knutti, 2007; Flato, 2011). We produce several ensemble means (EM) from different subsets of models. Each EM spans only the years common to all contributing models. All SMB model outputs must be interpolated onto a common grid and we used the nearest-neighbour method to reduce the interpolation bias. We use the grid of HCLIM because it is the highest resolution projected grid available. We produce, 1) $\text{EM}_{\text{ESM only}}$: the four ESM outputs, reprojected to the grid of CESM2; 2) $\text{EM}_{\text{ESM} \cup \text{RCM}}$: the outputs of the four ESMs and the 12 ESM-driven RCMs (PARASO_{ECEARTH3} is excluded because it ends in 2013), reprojected to the grid of HCLIM (identical grid for all HCLIM runs); 3) $\text{EM}_{\text{Rea only}}$: the three reanalyses, reprojected to the grid of ERA5; 4) $\text{EM}_{\text{Rea} \cup \text{RCM}}$: the three reanalyses and the 12 reanalysis-driven RCMs (COSMO-CLM²_{ERA5} is excluded because it starts in 1987), reprojected to the grid of HCLIM (ERA5), and 5) EM_{all} : all 31 model outputs (accounting the exclusions of COSMO-CLM² and PARASO), reprojected to the grid of HCLIM (ERA5).

2.5 In situ measurements of SMB: the SUMup dataset

The SUMup dataset (?) is a compilation of SMB, snow density and firn temperature observations over Antarctica and Greenland from numerous contributors. We extracted the Antarctic SMB observations for this study (Fig. 1). The observations span a wide temporal range thanks to ice core observations going back in time, but we limit our usage to the 1985-2014 period (inclusive). This results in 76,003 SMB observations being available for this study. In situ measurements, such as cores and pits, usually involve weighing a known-volume of a snow/firn sample, with errors of around 5 to 9% (Proksch et al., 2016). The dataset used in this study also includes 60,293 (80.5% of observations) radar observations collected by Konrad et al. (2019b). The radar observations are confined to the Pine Island Glacier in West Antarctica (Fig. 1, panels c and f, and relied on firn cores for dating. The reported mean error for that dataset is about 2.3 cm, or 5.5% of the SMB value. The SUMup dataset mainly



includes multi-year observations (83% of the observations), which would represent climatic SMB if ranging long enough. All measurements used in this study span one year or more, and are expressed in m w.e. year^{-1} . The sources of the data used here, and their respective number of measurements and temporal coverage are listed in Table A1.

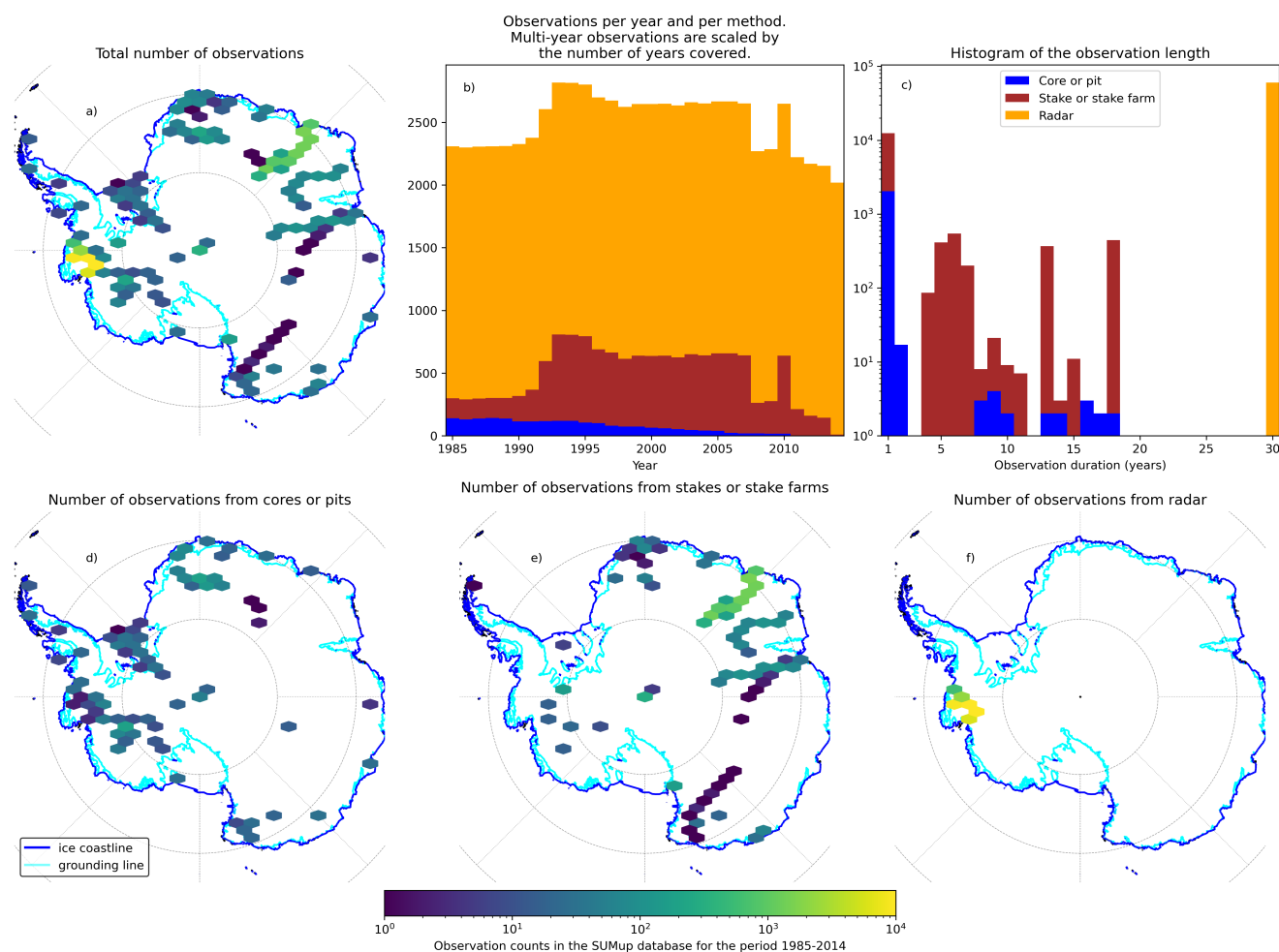


Figure 1. SMB observations from the SUMup dataset, showing a) the spatial distribution of observations; b) the years covered by such observations; c) the duration of the observations; the spatial distribution of observations from d) cores or pits; e) stakes or stake farms; and f) from radar profiles.



3 Methods

260 3.1 Model evaluation

For each model output, we extracted the SMB observations that strictly fall within the model time period. We then extracted the model output from the nearest grid cell (Euclidean distance) to the observation location for comparison. ESMs have coarser resolution, and therefore often have several observations assigned to one grid cell, meaning worsened statistics. Multi-year observations were compared to the matching period from the model, scaled to an accumulation per year unit (m w.e. year⁻¹).
 265 Although the total number of observations available is 76,003, the models COSMO-CLM_{ERA1}² and PARASO_{ECEARTH3} have fewer overlapping observations because they were run for a shorter time period. Because of their shorter temporal records, datasets including that from Konrad et al. (2019b) are out of range of COSMO-CLM_{ERA1}² and PARASO_{ECEARTH3}, which were assessed using 14,019 and 14,595 observations, respectively. This large difference prevented fair comparison to other models, but is used to assess the impact of observational coverage on model evaluation. For a fair performance comparison of these two
 270 RCMs with that of their drivers (ERA1 and ECEARTH3, respectively), we reduced the temporal extent of the drivers to match that of the RCMs.

3.1.1 Performance metrics

The performance of each model against matched modelled-observed SMB pairs using: 1) the correlation coefficient r ; 2) the Perkins Skill Score (PSS, described further below); 3) the Mean Error (ME), or bias, along with its significance using the
 275 t-statistics with null hypothesis $H_0 : \widehat{ME} = 0$; and 4) the Root-Mean-Square-Error (RMSE). The significance of the ME is assessed via a t-test, reported as a p-value. We only report numbers with a p-value < 0.05.

The PSS, described by Perkins et al. (2007), is a metric of the overlap of modelled and observed distributions. We bin the data into 100 equal-width bins spanning the combined minimum and maximum of all modelled and observed values. Perkins et al. (2007) used on the order of 50 to 100 bins, and we found high correlation scores between all models' PSS when ranging
 280 from 50 to 200. We conclude that 100 bins is a reasonable number. A perfect overlap in distributions results in a PSS of 1; a complete non-overlap gives a PSS of 0. Higher bin number will result in higher PSS on average.

3.2 Total accumulation on the grounded ice sheet

To further highlight the differences between models, we derived for each model the total accumulation on the grounded AIS. Following Hansen et al. (2022), we used the Zwally ice mask (Zwally et al., 2012) to remove the floating ice shelves, which
 285 would otherwise differ in the models' native mask. We multiplied the accumulation in each cell by the cell area and summed all cells within the mask. Different grids (e.g. geographic, projected, regular or irregular; Cherblanc et al., 2025) introduce distortion around the pole; we therefore systematically approximated the cell area for all models. We used the two-dimensional Riemann sum using right-bottom endpoints, which differed by less than 0.1% from the native cell-area fields from the ESM. With higher resolution and reprojected grids (which have less distortion by the poles), errors are expected to be smaller for the



RCMs. We included all cells within the ice sheet mask, meaning that the effective ice sheet area differs by about 1 % between the models, from 11.86×10^6 to 12.02×10^6 km², because each model's grid differs.

3.3 Relationship between Southern Annular Mode and regional accumulation anomalies

The Southern Annular Mode (SAM) is an index representing the pressure difference between the Antarctic convergence zone and the edge of the circumpolar winds. SAM influences local weather and climate variability on a basin scale in Antarctica (e.g. Marshall and Bracegirdle, 2015; Hansen et al., 2021). Due to the stochastic nature of SAM variability, the ESMs cannot reproduce the observed SAM, but Gerber et al. (2008) found that idealised global circulation models simulate SAM variations which have amplitudes and frequencies comparable to the observed SAM, and so do the CMIP5 ESMs (Marshall and Bracegirdle, 2015). The critical property therefore resides in each ESM being able to reproduce internally the impact of SAM on the spatial variability of SMB, and if RCMs make any difference in this modelling.

We estimate SAM as the normalised mean pressure difference between -40° and -65° . For ERA5, four ESMs, and all ESM-driven RCMs, for the period 1985-2014, we use all model cells within 1° of latitude of the two specified reference latitudes to accommodate for varying resolutions (Eq. 1).

$$\text{SAM}_{\text{model}} = \frac{P_{39.5-40.5^\circ} - \overline{P_{39.5-40.5^\circ}}}{\sigma(P_{39.5-40.5^\circ})} - \frac{P_{64.5-65.5^\circ} - \overline{P_{64.5-65.5^\circ}}}{\sigma(P_{64.5-65.5^\circ})} \quad (1)$$

For a given model, with $P_{l_1-l_2}$ being the sea level pressure between latitudes l_1 and l_2 , $\sigma()$ being the standard deviation of the time series in parentheses, and the overbars denote the temporal mean. The domain of the RCMs does not cover the latitudes needed, so we systematically used the ESMs to compute SAM. We therefore retrieved the exactly matching ESM ensemble member to compute SAM, which are CESM2 r11i1p1f1 for the Polar CORDEX runs (Gilbert et al., 2025), and ECEARTH3 FC01 for PARASO (PARASO; Sauerland et al., 2025).

For each basin from Zwally et al. (2012) and for each model run, we normalize monthly SMB by the month-of-year mean to take into account uneven seasonal and regional accumulation (Wang et al., 2016b), yielding the SMB anomaly (SMBa). We fitted a simple linear model of the form $\widehat{\text{SMBa}} = \widehat{\beta}_0 + \widehat{\beta}_1 \text{SAM}$, where the $\widehat{\beta}_i$ are model parameters, and referred to $\widehat{\beta}_1$ as the "slope" of the SAM-SMBa relationship for a given model and basin. We then compared the slopes of the ESMs and ESM-driven RCMs to that of the reference, ERA5.

3.4 Maps of spatial heterogeneity of SMB

The observations do not cover the Antarctic continent evenly, impacting the results differently across regions. We identify areas of high spatial heterogeneity in EM_{all} using a Laplacian filter, then relate these to the distribution of available observations. A Laplacian filter is computed by applying a convolution operation using a kernel (Eq. 2) on the temporal mean of EM_{all} . This kernel approximates the discrete Laplacian (∇^2 , where $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right)$; Arfken et al., 2012), a second-order 2D spatial derivative that identifies inflexion points in the SMB field. Cells that have a similar pattern to the filter will return numbers ~ 0 , but dissimilar cells may return numbers that are either $\ll 0$ or $\gg 0$, where the sign carries no physical meaning for our



purposes. We therefore take the absolute value of the output of the convolution, retaining only the magnitude of the spatial heterogeneity.

$$\mathcal{L} = \begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix} \quad (2)$$

4 Results

325 4.1 Overall model performance

4.1.1 ESMs and ESM-driven RCMs

The four ESMs generally perform worst of all models considered with an average R of 0.71, and average PSS of 0.38, an average ME of 0.26 cm (although with compensating bias with opposite signs) and an average RMSE of 17.88 cm. Occasionally, metrics of individual ESMs can approach those of reanalyses, for example ECEARTH3 has an R close to that of ERAI (Fig. 2 and Table 3). ESM performance is also more variable than that of reanalyses. The mean errors of CESM2 and UKESM are -2.28 and -1.31 cm, respectively, which is close to those of reanalyses, while other ESMs have absolute mean errors that are further from 0.

The R and PSS are systematically higher for ESM-driven RCMs than for their driving ESM with R increases from 0.71 to 0.86, PSS increases from 0.38 to 0.67, and RMSE decreases from 17.90 cm to 15.60 cm (Fig. 2, panels **a**, **d**, **g**, and **j**, and Table 3). One of the most notable improvements are a 2-fold increase in PSS from 0.37 for CESM2 to 0.79 for HIRHAM5_{CESM2} respectively (Table 3), and an increase in R from 0.56 for MPI to 0.89 and 0.91 for HCLIM_{MPI} and RACMO 2.4p1_{MPI} respectively. The RMSE of ESM-driven RCMs is lower than that of their driver for 9 out of 11 models (excluding the ensemble means). In contrast, the mean error of ESM-driven RCMs is closer to 0 for only 3 out of 11 models.

4.1.2 Reanalyses and reanalysis-forced RCMs

340 The reanalyses almost systematically have higher R and PSS, and lower RMSE, than ESMs, leaving only a little room for RCMs to add value. As a result, R improves for 7 out of 11 models (excluding the ensemble means), PSS increases for 8 models, RMSE decreases for 5 models; mean errors are further from 0 for all runs. On average, from reanalyses to reanalysis-driven RCMs, R increases from 0.88 to 0.90, PSS increases from 0.58 to 0.69, and RMSE decreases from 11.45 cm to 11.23 cm.

345 The use of offline firn modelling brings only minor changes in performance: we see a decrease in 6 out of the 8 metrics across the two ESM-driven firn model runs. The same applies for reanalysis-driven runs (HIRHAM5-SMB_{ERA5} and HIRHAM5-SMB_{ERA1} in panels **b**, **e**, **h**, and **k** of Fig. 2), where only the PSS increases for firn models relative to RCMs.

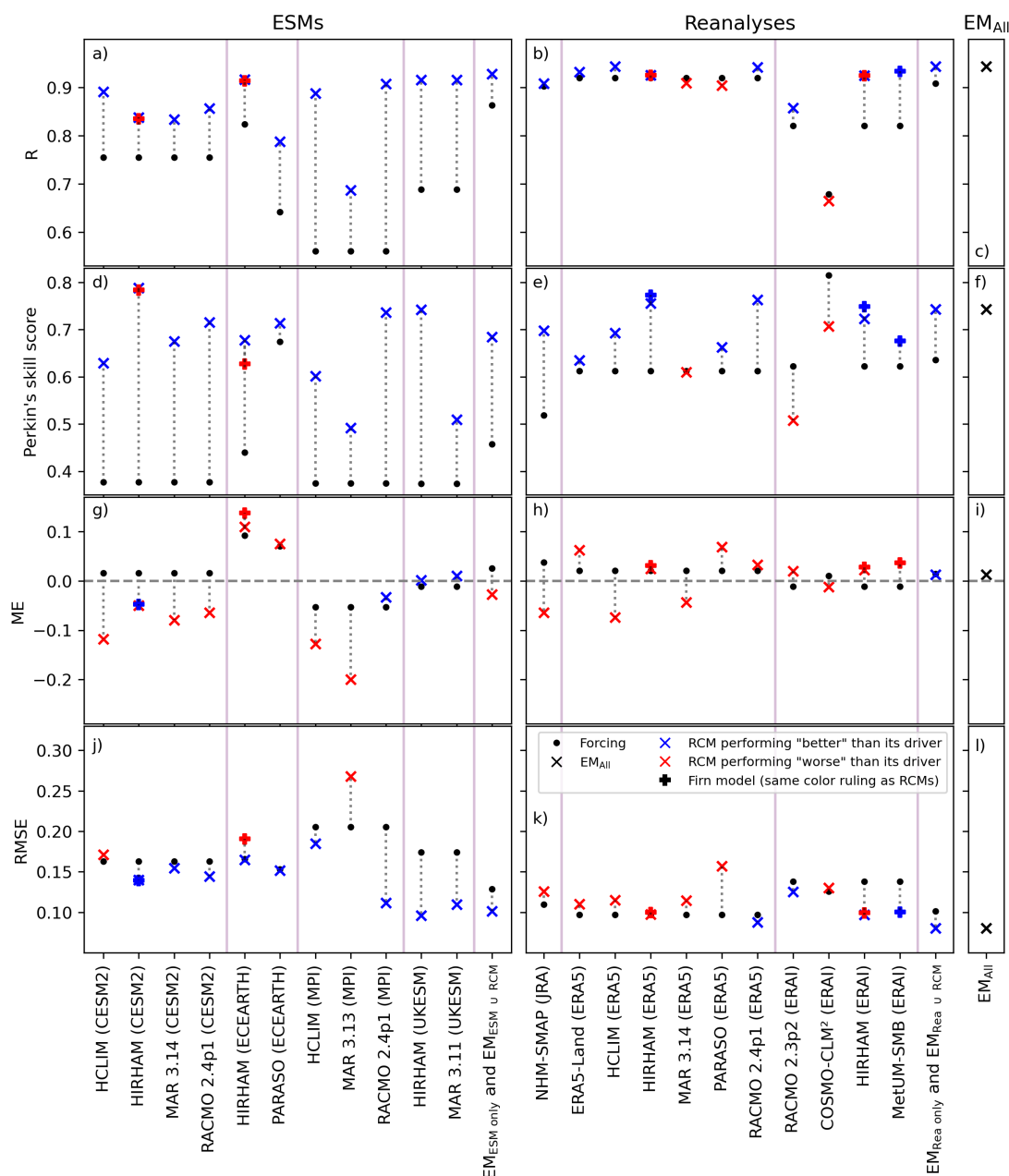


Figure 2. Between modelled and observed SMB: correlation coefficient (R; panels a, b, and c), Perkins Skill Score (PSS; d, e, and f), Mean Error (ME; g, h, and i), and Root Mean Squared Error (RMSE; j, k, and l) for ESMs (a, d, g, and j), reanalyses (b, e, h, and k), and the ensemble mean of all (c, f, i, l). The performance of RCMs relative to their forcing is indicated in color, and that of firm models relative to RCMs identically. The purple vertical lines separate different drivers.



Table 3. Model statistics with respect to the SUMup observations. See Figure 2 for the definition of the abbreviations. Numbers in bold indicate the lowest and highest values for each column, where ESM and ESM-driven RCMs are qualified independently of reanalyses and reanalysis-driven RCMs.

	model	# obs	R	PSS	ME (cm)	RMSE (cm)
ESMs	CESM2	74914	0.76	0.37	-2.10	16.56
	ECEARTH3	74914	0.82	0.39	9.57	17.01
	MPI	74914	0.56	0.37	-5.30	20.54
	UKESM	74914	0.69	0.37	-1.15	17.41
	EM _{ESM only}	74914	0.86	0.46	2.53	12.88
ESM-driven RCMs	HCLIM (CESM2)	74914	0.89	0.63	-11.84	17.10
	HCLIM (MPI)	74914	0.89	0.60	-12.78	18.49
	HIRHAM (CESM2)	74914	0.84	0.79	-5.02	13.99
	HIRHAM (ECEARTH3)	74914	0.92	0.68	11.00	16.50
	HIRHAM (UKESM)	74914	0.92	0.74	0.16	9.61
	MAR 3.11 (UKESM)	74914	0.92	0.51	1.03	10.98
	MAR 3.13 (MPI)*	74914	0.69	0.49	-20.02	26.78
	MAR 3.14 (CESM2)	74914	0.83	0.68	-7.91	15.48
	PARASO (ECEARTH3)	14612	0.79	0.71	7.56	15.16
	RACMO 2.4p1 (CESM2)	74914	0.86	0.72	-6.39	14.43
	RACMO 2.4p1 (MPI)	74914	0.91	0.74	-3.32	11.19
	HIRHAM-SMB (CESM2)	74914	0.84	0.78	-4.71	13.97
	HIRHAM-SMB (ECEARTH3)	74914	0.91	0.63	13.80	19.09
	EM _{ESM ∪ RCM}	74914	0.93	0.68	-2.70	10.15
Reanalyses	ERA5	74914	0.92	0.61	2.11	9.71
	ERA1	74914	0.82	0.62	-1.16	13.78
	JRA	74914	0.90	0.52	3.74	10.96
	EM _{Rea only}	74914	0.91	0.64	1.42	10.16
Reanalysis-driven RCMs	COSMO-CLM ² (ERA1)	14032	0.66	0.71	-1.19	13.04
	ERA5-land	74914	0.93	0.64	6.28	11.03
	HCLIM (ERA5)	74914	0.94	0.69	-7.41	11.51
	HIRHAM (ERA5)	74914	0.93	0.76	2.49	9.76
	HIRHAM (ERA1)	74914	0.92	0.72	2.20	9.69
	MAR 3.14 (ERA5)	74914	0.91	0.61	-4.34	11.44
	NHMSMAP (JRA)	74914	0.91	0.70	-6.41	12.59
	PARASO (ERA5)	74914	0.90	0.66	6.88	15.70
	RACMO 2.3p2 (ERA1)	74914	0.86	0.51	1.98	12.54
	RACMO 2.4p1 (ERA5)	74914	0.94	0.76	3.24	8.77
	HIRHAM-SMB (ERA5)	74914	0.93	0.77	3.09	10.00
	HIRHAM-SMB (ERA1)	74914	0.92	0.75	2.82	9.93
	MetUM-SMB (ERA1)	74914	0.93	0.68	3.65	10.04
	EM _{Rea ∪ RCM}	74914	0.94	0.74	1.30	8.06
	EM _{all}	74914	0.94	0.67	-0.76	8.51
	mean of the column	71725	0.87	0.63	-0.46	13.28

*: SMB from MAR 3.13 (MPI) is only from precipitation, the evapo-sublimation was not available.



4.1.3 Ensemble means

Ensemble means produce good estimates of SMB. The performance of $EM_{ESM \cup RCM}$ in all metrics is even comparable to those
 350 of $EM_{Rea \text{ only}}$ and $EM_{Rea \cup RCM}$ (Fig. 2 and Table 3). Although $EM_{ESM \text{ only}}$ underperforms in R, PSS, and RMSE relative to the
 other ensemble means, it still outperforms ESMs in all but one statistic (UKESM's ME of -1.31 cm).

4.1.4 Impact of observations used

The observations used for the model evaluation are identical for all models except $PARASO_{ECEARTH3}$ and $COSMO-CLM^2_{ERA1}$,
 where about only one-fifth of all the observations was available during the shorter temporal range of the two models. The
 355 impact of using a different subset of observations is visible when compared with their driving model. For both ECEARTH3
 and ERAI over the shorter temporal record, there is minimal change in ME and RMSE, but larger changes in R and PSS,
 relative to the full record models. The most sensitive metric appears to be PSS, with a factor of 2 increase from the full to
 short record ECEARTH3, and a 30% increase for ERAI. Comparisons between these RCMs and their respective drivers are
 therefore valid, but cross-model comparisons with full-record runs are not.

360 4.2 Maps of residuals

Maps of residuals between modelled and observed SMB show a consistent pattern: the absolute errors are smallest inland and
 highest near the coast, in particular on the Antarctic Peninsula (Fig. 3 and 4). However, the large errors on the coast reflect the
 high accumulation in those regions. Relative error maps (Fig. A1 and A2) are consequently more uniform, as errors scale with
 local SMB magnitude, except for some observations at the plateau's margins. Six models forced by either CESM2 or MPI are
 365 too dry in West Antarctica, with biases reaching 30 centimetres w.e. per year or about 20% of the annual SMB, and too wet in
 Dronning Maud Land, with up to 50 centimetres w.e. per year or up to 100% of the annual SMB. These two frequent biases
 are also reflected in the ensemble mean maps.

4.3 Grounded ice sheet accumulation

Some of the biases found in a previous section expand on the Antarctic continent. In some cases, the RCMs inherit the bias
 370 of their driver (Fig. 5). For example, the ESM ECEARTH3 produces too much accumulation, and this bias is carried to all the
 ECEARTH3-driven RCMs which almost systematically have the highest accumulation. This accumulation bias is positively
 correlated with the ME of the models. More generally, the RCMs tend to moderate the biases of their drivers, pulling accumu-
 lation values toward the mean. ECEARTH3 is the highest-accumulation global model, but all the ECEARTH3-driven RCMs
 are closer to the mean. The same principle applies for CESM2, UKESM, ERAI, and four out of seven ERA5-driven RCMs.
 375 The only notable exceptions are two out of three MPI-driven RCMs are drier than the already-dry MPI.

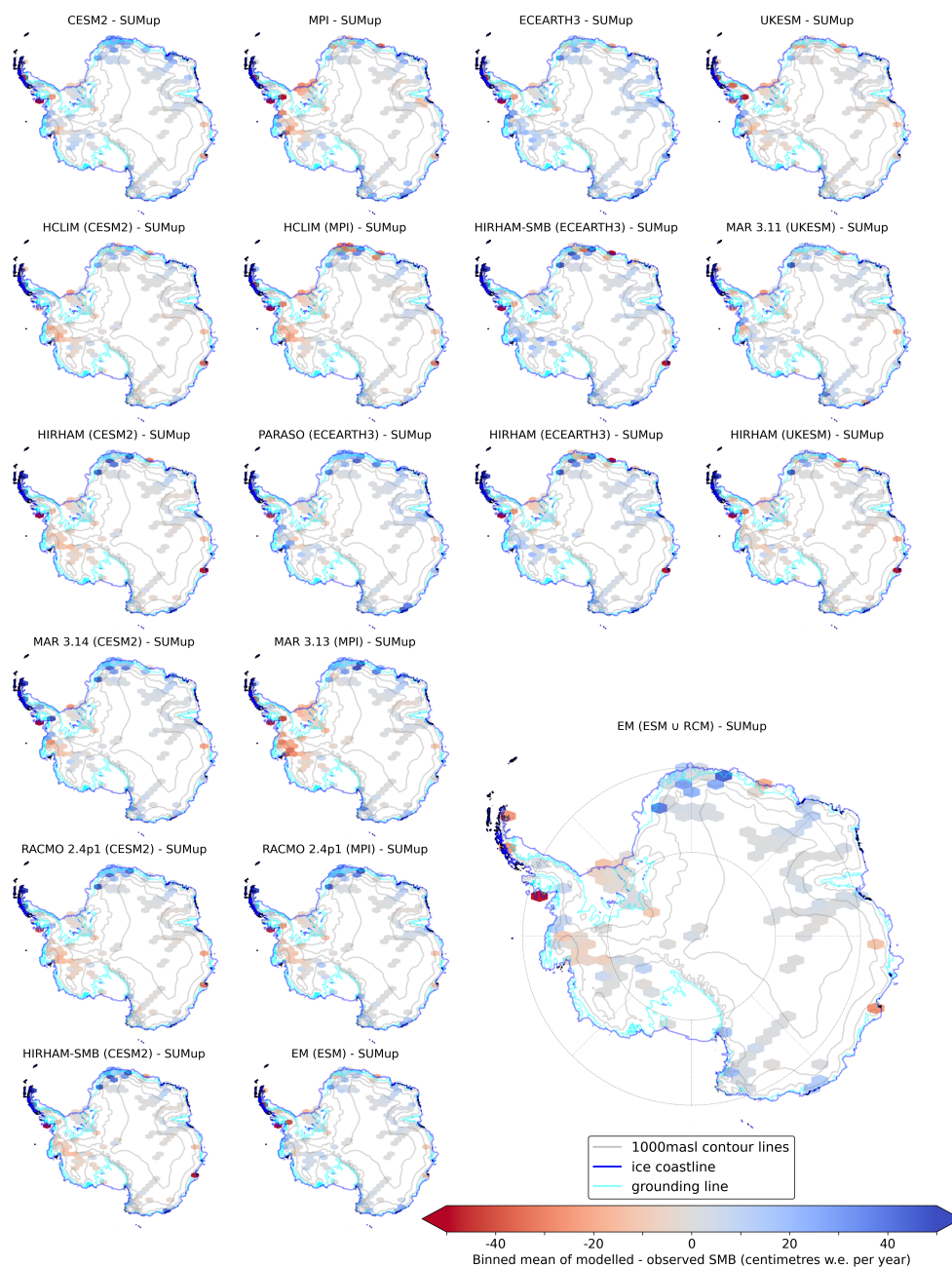


Figure 3. Maps of residuals, where multiple residuals in a bin are averaged out, for ESM products. We attempted to keep similar models nearby, with ESMs on columns and RCMs on rows. All maps use the British Antarctic Survey Antarctic Digital Dataset for the coastline and ice coastline (Gerrish et al., 2025).

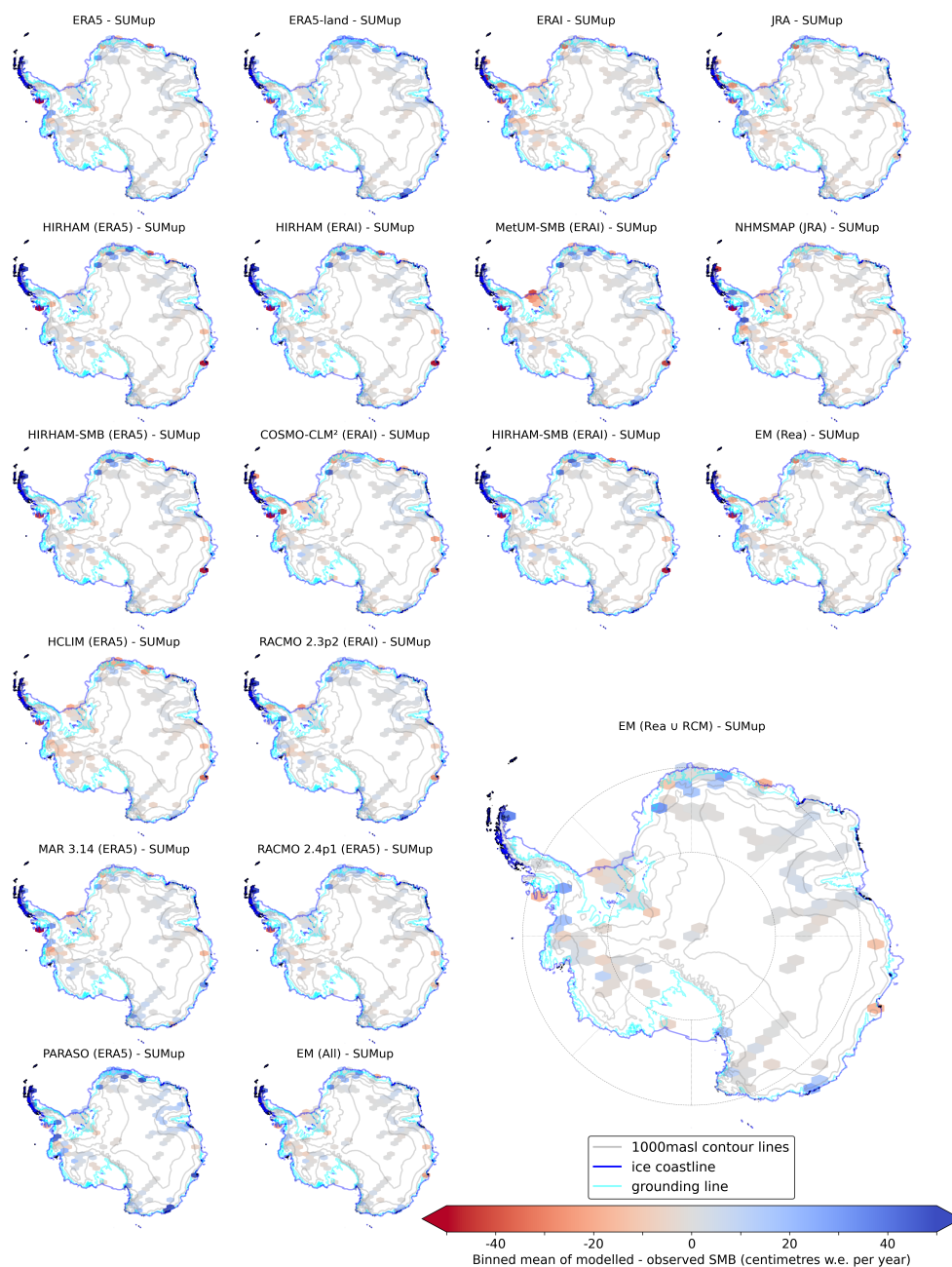


Figure 4. Binned time mean of all modelled-observed pairs, for reanalysis products and the ensemble mean of all models (ESM+reanalyses). We attempted to keep similar models nearby, with reanalyses on columns and RCMs on rows.

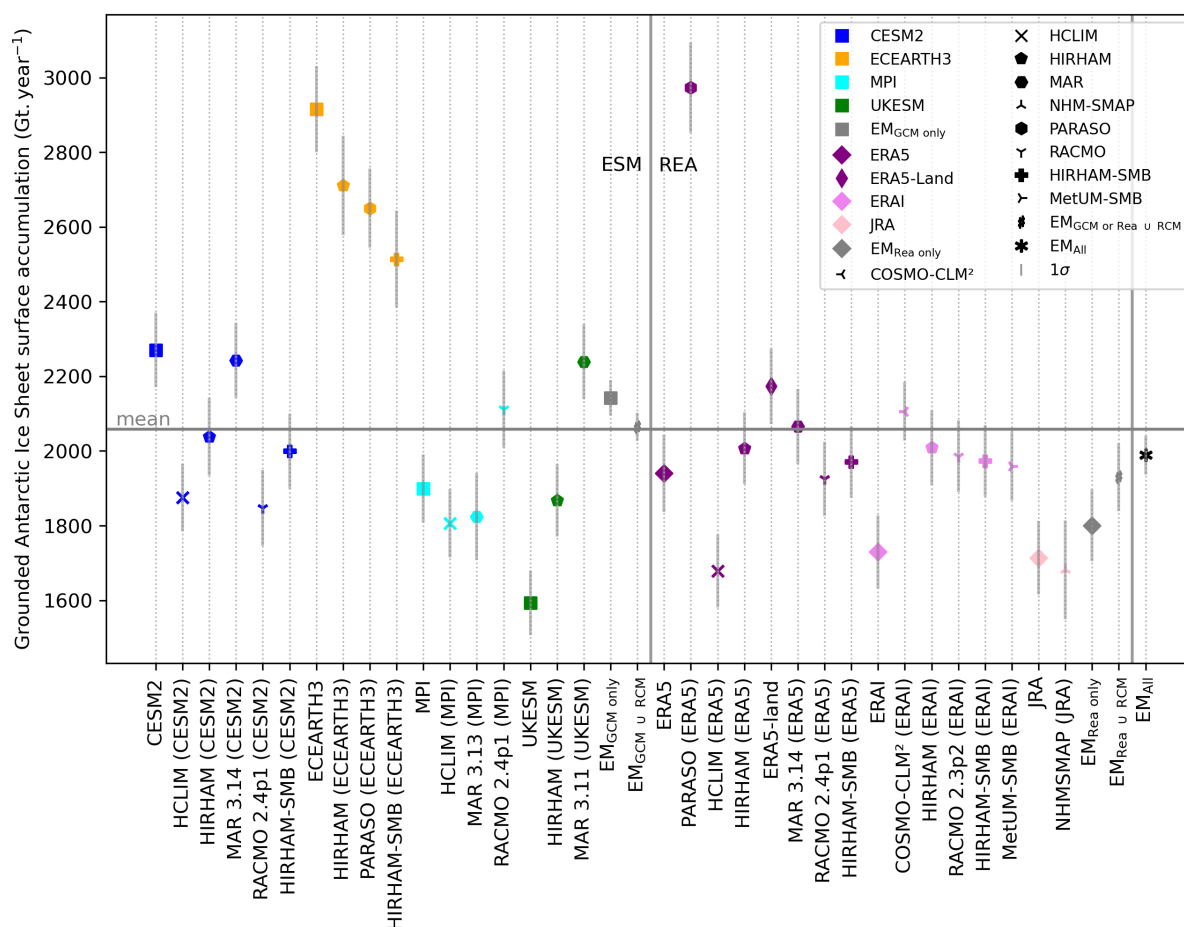


Figure 5. Integrated SMB over the grounded AIS using the mask from Zwally et al. (2012), with 1σ bars to represent the inter-annual variability. The rasterization of a single polygonal mask onto the different grids of the different models results in effective area that varies by less than 1.2 % between the models.

4.4 Relationship between SAM and SMBa in the ESMs

There are strong regional relationships between the SAM index and SMBa (Fig. 6, panels **a** and **g**). The areas of Pine Island Glacier, the Peninsula, and western Dronning Maud Land have a positive correlation between SAM index and SMBa, while an opposite correlation is observed from Marie Byrd Land to the Amery Ice Shelf. The regional slopes sum up to nearly zero across Antarctica according to the reference ERA5 (Fig. 6, panel **d**). The ESMs and the ESM-driven RCMs show similar but weaker patterns than ERA5 (Fig. 6, panels **b**, **c**, and **h**), with basin-wise relationships being generally closer to 0. The extremes are not well modelled by the ESMs. According to ERA5, Coastal Marie Byrd Land (Basin 20) experiences a $13.3 \text{ Gt year}^{-1}$ SMB reduction per unit increase in the SAM index, corresponding to a 7.1% drop relative to the average $187.6 \text{ Gt year}^{-1}$,



but most ESMs and ESM-driven RCMs predict losses that can be an order magnitude smaller. On the other hand, the 13.6 Gt
 385 year⁻¹ from the South-west Peninsula (Basin 24), an 8.6 Gt year⁻¹ per unit increase in SAM index, is better resolved by most
 ESMs and ESM-driven runs. Although the relationship in some ESM or ESM-driven models, no model perfectly reproduces
 the ERA5 SAM-SMBa relationship.

4.5 Relating the spatial heterogeneity of model output to the density of observations

We applied the Laplacian filter to EM_{all} and took the absolute value of the output (Fig. 7). The continent's margins and high
 390 relief areas have a high spatial heterogeneity, while the plateau is very homogeneous. The observations do not span the continent
 evenly, and leave most of East Antarctica void of measurements. West Antarctica has a few key areas with dense observations,
 mainly from Konrad et al. (2019b). Several transects in East Antarctica have been repeated over the years; they are very valuable
 because they are along elevation gradients, and are complemented by spatially diverse observations in Dronning Maud Land,
 but Victoria and Wilkes Lands have very few observations. The Peninsula has widespread spatial heterogeneity, but close to no
 395 observations.

5 Discussion

5.1 Limitations

In the following section we discuss our results and their implications in detail. However, it is important to be aware of some
 common limitations that necessarily affect studies of this type due to the nature of the datasets.

400 Evaluating gridded models with observational point data is complex and requires a number of choices during analysis that
 may also affect interpretation. For example, point observations are typically located within a single grid cell, which necessarily
 covers an area, rather than representing the exact point of the observation. No model output is available at the exact location
 of observations, we therefore use the nearest valid value. This is effectively a nearest-neighbour interpolation which typically
 penalises coarser-resolution models, since more observations are associated with one model cell of 1000 km² than one of
 405 100 km². As a result, performance changes may stem from either better model physics or from increased resolution, or a
 combination of both. We disentangled model resolution and physics by estimating the performance of the RCMs reprojected
 onto their driving model grid (Fig. A3), and found that most of the time, the reprojected RCMs had performances between that
 of their driver and that of the RCM. An alternative way of handling variable model resolution is to interpolate all models to a
 common grid using a bilinear or bicubic method. In a comparable study over the Greenland Ice Sheet, Fettweis et al. (2020)
 410 interpolated all models using a bilinear interpolation. Interpolation introduces a bias that depends on the method chosen, for
 example bilinear assumes a smooth continuity between cell centres.

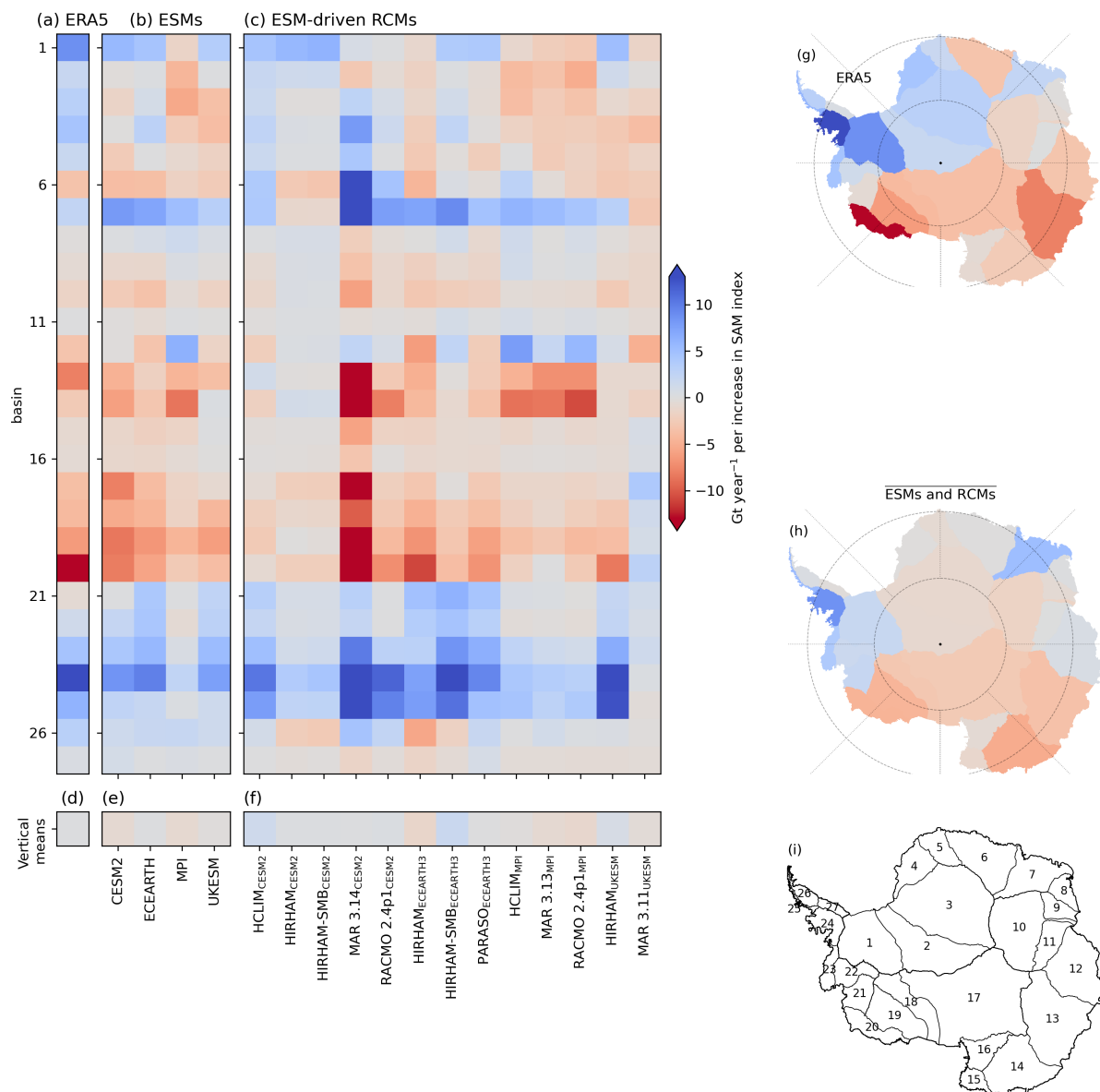


Figure 6. Slope of the linear regression of SMBa versus SAM index, for **a)** ERA5, **b)** ESMs, and **c)** ESM-driven RCMs. We compute the vertical means, or AIS-wide statistic for a given model, of **a)**, **b)** and **c)** in **d)**, **e)** and **f)** respectively, and the horizontal means, or per-basin statistic, of **a)** and on **g)** (per-basin means for ERA5), and **b)** and **c)** on **h)** (per-basin mean of all ESM and ESM-driven RCMs). Basins locations are shown on **i)**. We refer to the basins 24 through 27 as the Peninsula, the Plateau as most of basins 2, 3, 10, and 17, and Dronning Maud Land as basins 4 through 6, and most of 7.

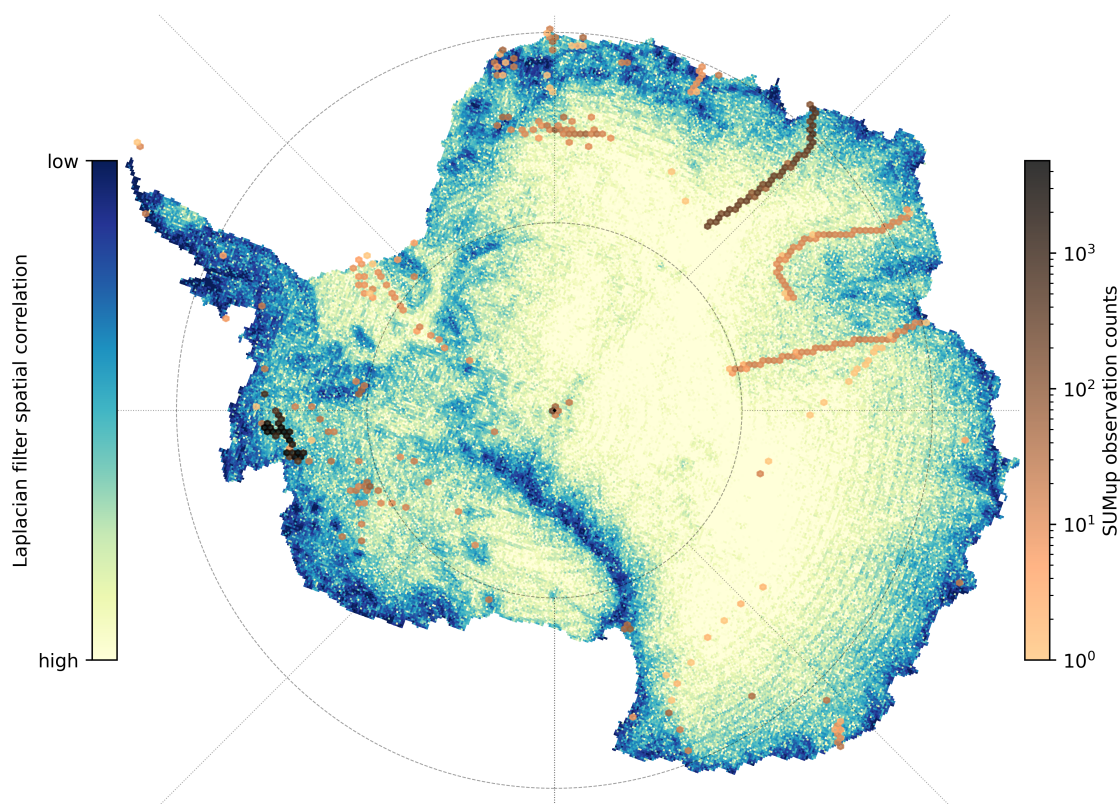


Figure 7. Spatial heterogeneity of mean SMB from EM_{all} , overlaid with SUMup observation density.

5.2 SMB from ESMs

As noted above, our study focuses on ESMs as they are the only available forcing data for future projections of SMB and sea level rise. Our results show that ESMs in this study, which likely represent the CMIP6 ensemble due to the storyline approach laid out in Williams et al. (2024), have reasonable performance over the historical record, but suffer from spatial biases. Antarctic-wide biases, such as over-estimated accumulation in ECEARTH3 and under-estimated accumulation in MPI (Figs. 3, 5, and Table 3), coexist with regional biases such as over-estimated accumulation in western Dronning Maud Land and under-estimated accumulation in West Antarctica for MPI and UKESM runs (Fig. 3). The Antarctic-wide biases extend beyond the observational network, as shown when SMB is integrated over the grounded ice sheet (Fig. 5). The mean grounded ice sheet accumulation of $2059 \pm 318 \text{ Gt year}^{-1}$ is close to the 1950-2000 CMIP6 ensemble mean of $2039 \pm 333 \text{ Gt year}^{-1}$ (Gorte et al., 2020), and about 3% greater than the mean of reanalyses, consistent with the findings of The IMBIE team (2018). We suggest that the strong continent-wide biases in precipitation are related to the models' temperature biases, which in turn likely results from the representation of the atmospheric circulation (Williams et al., 2024). Indeed, MPI and ECEARTH3 have similar temperature-precipitation sensitivities, but opposite temperature biases (Nicola et al., 2023). ECEARTH3 is the



425 warmest model and display an over-accumulation of snow, while MPI is the coldest and driest model, both consistent with the ME reported here.

5.2.1 The SAM-SMB relationship

Although Nicola et al. (2023) report a linear temperature-precipitation relationship from historical records to future scenarios, SMB is further modulated by 1) increasing melt (Hofsteenge et al., 2025), 2) changes in synoptic conditions and in extreme
 430 event distributions (e.g. Maclennan et al., 2025), and 3) the impact of the positive trend in SAM.

We found that the modulation of regional SMB patterns explained by the SAM index resembles between ESMs and the ERA5 reference simulation, with some divergences. An observed increase in SAM has been attributed to anthropogenic causes (King et al., 2023), driving corresponding changes in accumulation and melt (e.g. Kolbe et al., 2025a; Hansen et al., 2021). Unless synoptic circulation changes substantially, the intensification in the SAM will amplify the biases reported here for
 435 each ESM. The continent-wide biases reported in this study are on the order of 1 Gt year^{-1} , which is the same order of magnitude as the trend in SMB from the CMIP5 and CMIP6 ensemble for the period 1900-2000 (Gorte et al., 2020). RCMs are not systematically closer to ERA5 than their drivers, for example outputs from the MPI-driven RCMs are closer to ERA5 simulated SMB than MPI simulated SMB, while ECEARTH3-driven RCMs diverge more from ERA5 than the ECEARTH3 driving model. Given that the anthropogenic cause of the SAM will maintain this increase (King et al., 2023), ESMs that
 440 poorly reproduce the SAM-SMBa relationship will display an increasing divergence in regional SMB projections, unless this relationship is explicitly improved in future model versions.

5.3 Added value of RCMs

Our analysis does show that RCMs greatly improve modelling of SMB relative to the driving ESMs, but only marginally improve SMB relative to the reanalyses. The systematic increase in statistical measures of R and PSS for RCMs relative to
 445 ESMs, and the quasi-systematic drop in RMSE, clearly demonstrates the added value of RCMs over raw ESM output. This is partly driven by higher resolution as also found in other regions of the globe. For example, in the European Alps and for precipitation, RMSE also decreased and R also increased for RCMs relative to ESMs (Torma et al., 2015), even for RCMs of low spatial resolution. Although the ESMs may have a land ice and snowpack component, most RCMs have polar-specific schemes – such as estimating wind transport of snow particles, improved albedo, finer cloud representation – which explains
 450 some of the improvement reported here. RCMs do not consistently improve upon their drivers in reproducing the regional SAM-SMBa patterns, even though they have the ability to distribute precipitation in a more realistic way. We also attempted to partition the improvements of RCMs between higher resolution and improved physics by upsampling the RCMs to their driver's grid, but found no conclusive results (not reported here). The regional biases on the margin of Antarctica are not systematically closer to 0 for the RCMs than for the ESMs (Figs. 3 and 4). For example, HCLIM_{CESM2} reduces the over-accumulation bias of
 455 CESM2 in Dronning Maud Land, while HIRHAM5_{CESM2} increases it. Conversely, the latter performs better in West Antarctica than the former. We find that the improvement in performance of RCMs over ESMs often stems from improvements in specific regions and not from continent-wide improvement.



When interpreting the results, one has to keep in mind that the evaluation is done using matched model-observed SMB pairs, implying that these pairs samples vary both in location and in time. Even though ESMs appear to be able to capture the right spatial patterns, the temporal evolution does not necessarily match that of the observations. Indeed, the phase of the natural variability can differ from reality in the ESMs because they are not constrained by observations. Therefore, the correlation coefficient and the root mean square error should be treated with some care. However, since the correlations of the GCM-driven RCMs go up to 0.9, it is likely that the correlation found here is dominated by the spatial correlation.

Reanalyses, especially ERA5, have high R, PSS, near-zero ME, low RMSE, and little to no regional bias, making it difficult for RCMs to add further value. Wang et al. (2016b) similarly found high performance of ERAI and JRA in modelling AIS SMB, using a longer time record and more observations, but our analysis finds that ERA5 outperforms ERAI on most metrics. Moreover, When evaluating RCMs against their driving reanalysis, an increase in temporal RMSE is expected, particularly in the absence of spectral nudging, because the RCMs are less constrained by observations than the reanalysis. However, we found that the RCMs do outperform the reanalysis in the Perkins skill score. This implies that RCMs add value compared to their driving reanalyses when the application depends on the spatiotemporal distribution of SMB. However, if the timing of the events is key for the application, then RCMs adds little value, compared to the reanalyses with full data assimilation.

Large-scale intercomparison projects have not always been able to use RCMs, mostly because of time and computational resource constraints (e.g. Seroussi et al., 2020), but we show that RCMs add most value when downscaling ESMs for AIS SMB. We emphasize that there is not one single RCM that outperforms all others for all forcings. Generally, we urge users not to disentangle the behaviour of an RCM from its driver; each pair has its own distinct behaviour.

5.4 Limited observations restrict a generalised evaluation of the models

Understanding model output diversity may contribute to better relating distributed model output to heterogeneously distributed observations. The statistics used in this study show added value in bulk, similar to previous findings (e.g., Torma et al., 2015; Giorgi, 2019). However, RCMs are expected to add value in high relief area (Rummukainen, 2016), and lack of observations in these areas can preclude quantifying the added value (Lucas-Picher et al., 2012). For example, only 73 observations were available on the Peninsula (basins 24 through 27 on Fig. 6), which is insufficient to get a generalised quantified added value of RCMs. Alternatively, transects can be used to measure the ability of climate models to resolve orographic processes locally (e.g. Wang et al., 2016b), but this method does not ensure generalisability. Although we did not solve this problem of generalisable model evaluation, we used a novel approach to identify areas of high model output spatial heterogeneity that would benefit from additional observations (Fig. 7).

High spatial heterogeneity is found in high relief areas, but observations are sparse in precisely these areas. Two key areas are densely covered however (Figs. 1 and 7): West Antarctica and Dronning Maud Land; allowing us to reliably identify the biases between these two regions throughout this study. The remaining of high spatial heterogeneity areas, such as East Antarctica and the Peninsula, lack sufficient observations to allow us to confidently ascribe biases correctly between models and observations made from in situ techniques. Although methods exist to optimise the location of observations (e.g., Amorim et al., 2012; Parajuli and Feng, 2025; Lorenz and Emanuel, 1998; Pelucchi et al., 2025), the distribution of in situ SMB



observations in Antarctica is mainly determined by logistics. Inevitably this means existing published data is usually centred around research stations, other project sites, and along traverse lines. Some of these datasets are continuous and relatively long-lived observational programmes, but many of the published datasets, particularly away from research stations, cover only relatively short time periods. Model outputs must be assessed by accurate ground-truth observations, especially in high spatial heterogeneity areas, but while our analysis highlights under-observed regions, it also shows that the density of observations may not need to be as high in some very large and inaccessible regions such as on the plateau compared to coastal or high-relief areas. In other words, if new, and long-term observation sites can be installed, then for model evaluation and optimisation purposes, they should maximise the distance to pre-existing observations, but should not over-populate areas of low modelled diversity.

Our analysis also demonstrates the importance of statistical rigour and physical insights in model evaluation. Assessing models on different observational datasets can drastically change performance statistics. For example, fair quantification of the added value for the two RCMs with shorter temporal extent ($\text{PARASO}_{\text{ECEARTH3}}$ and $\text{COSMO-CLM}_{\text{ERA1}}^2$) required that we match the RCMs with their driver's temporal extent. A large drop in R and a large increase in PSS are observed when the study period is truncated, such that the Konrad et al. (2019b) dataset is not included as part of the observations, as is the case for ECEARTH3 and ERAI. More generally, the use of climatic SMB (long term averages) smooths out inter-annual variability, reducing RMSE; which likely explains the lower RMSE reported by Mottram et al. (2021).

6 Conclusions

We assessed and compared the performance of ESMs, reanalyses, ESM-driven RCMs and reanalysis-driven RCMs in their ability to model the SMB of the AIS using 76,003 in situ observations.

Research question 1 aimed to quantify the performance of ESM and ESM-driven RCMs on modelling SMB on the historical period. We found that ESMs and ESM-driven RCMs underperform relative to their reanalysis equivalents, but still produce climatologically realistic estimates. The ESMs have Antarctic-wide and regional biases. For example, MPI is too dry over the AIS, especially over West Antarctica, while ECEARTH3 displays a positive accumulation bias. In addition, we found that the SAM-SMB relationship is poorly resolved by all ESMs, with consequences that will grow as the intensification of the positive SAM continues.

Research question 2 aimed to quantify the added value of RCMs on modelling AIS SMB. ESM-driven RCMs show systematically higher R and PSS, and lower RMSE, than their driving ESM. However, improvements from RCMs relative to reanalyses are highly inconsistent, as reanalyses already perform well across all metrics.

Research question 3 aimed to ensure that the observation network is sufficient for the above. We note that our findings are limited by uneven observational coverage, but sufficient to show the contrasting biases between West Antarctica and Dronning Maud Land. The high spatial homogeneity in modelled SMB over the plateau suggests that new observations in those areas would be of lower priority than in margin regions, where local processes occur and higher model resolution are most critical.



These findings provide a basis for more informed selections of climate model products for Antarctic SMB estimation and downstream ice sheet modelling for sea level projections. In spite of regional and Antarctic-wide biases, our analysis does show that ESMs and especially dynamically downscaled ESMs can represent the SMB of the AIS. The ensemble means generally outperform any single model, suggesting that the development of machine learning based climate and SMB emulators offer a promising step forward in production of large ensembles of SMB and runoff.

Code availability. All code to process the model output is available at <https://doi.org/10.5281/zenodo.17734052>.

Data availability. Model output download links or source can be found in Table 4, the list of original publications in the SUMup dataset can be found on Table A1.



	Model run	Download link or data responsible person	Complementary citation
ESMs	CESM2 r1i1p1f1 CESM2 r1i1p1f1 ECCARTH3 r1i1p1f1 ECCARTH3 r5i1p1f1 MPI 1.2 LR r1i1p1f1 UKESM 1.0 LL r1i1p1f2	https://data.ceda.ac.uk/badc/cmip6/data/CMIP6/CMIP/CNAR/CESM2/historical/r1i1p1f1 https://data.ceda.ac.uk/badc/cmip6/data/CMIP6/CMIP/CNAR/CESM2/historical/r1i1p1f1 https://cds.climate.copernicus.eu/datasets/projections-cmip6 https://esg-dn1.nci.lln.as/search/cmip6-lln/ https://cds.climate.copernicus.eu/datasets/projections-cmip6 https://cds.climate.copernicus.eu/datasets/projections-cmip6	for Atmospheric Research (2019) for Atmospheric Research (2019) Copernicus Climate Change Service (2021) Copernicus Climate Change Service (2021) Copernicus Climate Change Service (2021)
	HCLIM (CESM2 r1i1p1f1) HCLIM (MPI 1.2 LR r1i1p1f1) HIRHAM5 (CESM2 r1i1p1f1) HIRHAM5 (ECCARTH3 r5i1p1f1) HIRHAM5 (UKESM 1.0 LL r1i1p1f2) HIRHAM5-SMB (CESM2 r1i1p1f1) HIRHAM5-SMB (ECCARTH3 r5i1p1f1) MAR 3.11 (UKESM 1.0 LL r1i1p1f2) MAR 3.13 (MPI 1.2 LR r1i1p1f1) MAR 3.14 (CESM2 r1i1p1f1) PARASO (ECCARTH3 FC01) RACMO 2.4p1 (CESM2 r1i1p1f1) RACMO 2.4p1 (MPI 1.2 LR r1i1p1f1)	https://cordex.dmi.dk/thredds/fileServer/seg_cordex/PolarRes/ANT-12/HCLIMcom-DMI/ https://cordex.dmi.dk/thredds/fileServer/seg_cordex/PolarRes/ANT-12/HCLIMcom-DMI/ Fredrik Boberg Fredrik Boberg Fredrik Boberg https://doi.org/10.5281/zenodo.13270554 http://ftp.climato.be/ http://ftp.climato.be/ http://ftp.climato.be/ Florian Sauerland https://cordex.dmi.dk/thredds/fileServer/seg_cordex/PolarRes/ANT-12/UU-IMAU/ https://cordex.dmi.dk/thredds/fileServer/seg_cordex/PolarRes/ANT-12/UU-IMAU/	- - Boberg et al. (2022) Boberg et al. (2022) Boberg et al. (2022) Claude (2024) Boberg et al. (2022) - - - Sauerland et al. (2025) -
Reanalyses	ERA5 ERA5 JRA	https://doi.org/10.24381/cds.11705047 https://zenodo.org/records/15501697 https://gdx.ucar.edu/datasets/d640000/dataaccess/	Copernicus Climate Change Service (2019b); Hersbach et al. (2020) Fisaulin, John (2022) Japan Meteorological Agency (2023)
Reanalysis-driven RCMs	COSMO-CLM ² (ERA5) ERA5-Land (ERA5) HCLIM (ERA5) HIRHAM5 (ERA5) HIRHAM5 (ERA5) HIRHAM5-SMB (ERA5) HIRHAM5-SMB (ERA5) MetUM-SMB (ERA5) MAR 3.14 (ERA5) NHM-SMAP (JRA) PARASO (ERA5) RACMO 2.3p2 (ERA5) RACMO 2.4p1 (ERA5)	https://doi.org/10.5281/zenodo.2539146 https://doi.org/10.24381/cds.682b830 https://cordex.dmi.dk/thredds/fileServer/seg_cordex/PolarRes/ANT-12/HCLIMcom-DMI/ Fredrik Boberg Fredrik Boberg Nicolaj Hansen (parts at https://doi.org/10.5281/zenodo.5005264) Nicolaj Hansen (parts at https://doi.org/10.5281/zenodo.5005264) Nicolaj Hansen (parts at https://doi.org/10.5281/zenodo.5005264) http://ftp.climato.be/ Masashi Niwano Florian Sauerland https://www.projects.science.uu.nl/iceclimate/publications/data/2018/index.php https://cordex.dmi.dk/thredds/fileServer/seg_cordex/PolarRes/ANT-12/UU-IMAU/	Souwerijns et al. (2019a) Copernicus Climate Change Service (2019b); Muñoz-Salazar et al. (2021) - Boberg et al. (2022) Boberg et al. (2022) Hansen et al. (2021) Hansen et al. (2021) Hansen et al. (2021) - - Sauerland et al. (2025) Van Wessem et al. (2018) -

Table 4. Data availability per the statement of authors and/or original papers.



Appendix A: Maps of relative differences between modelled and observed SMB

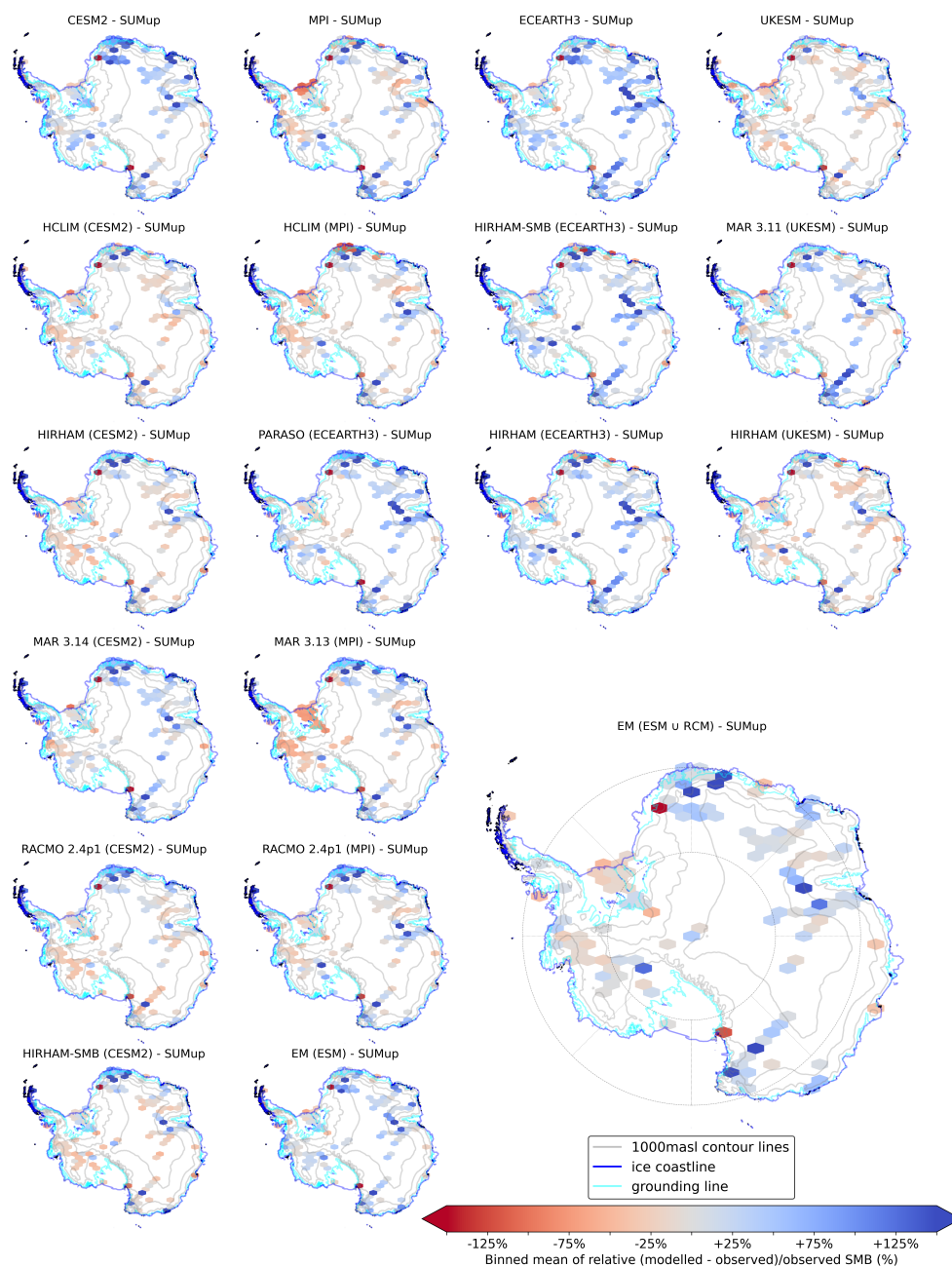


Figure A1. Binned time mean of all (modelled-observed)/observed pairs, for ESM products. We attempted to keep similar models nearby, with ESMs on columns and RCMs on rows. All maps use the British Antarctic Survey Antarctic Digital Dataset for the coastline and ice coastline (Gerrish et al., 2025).

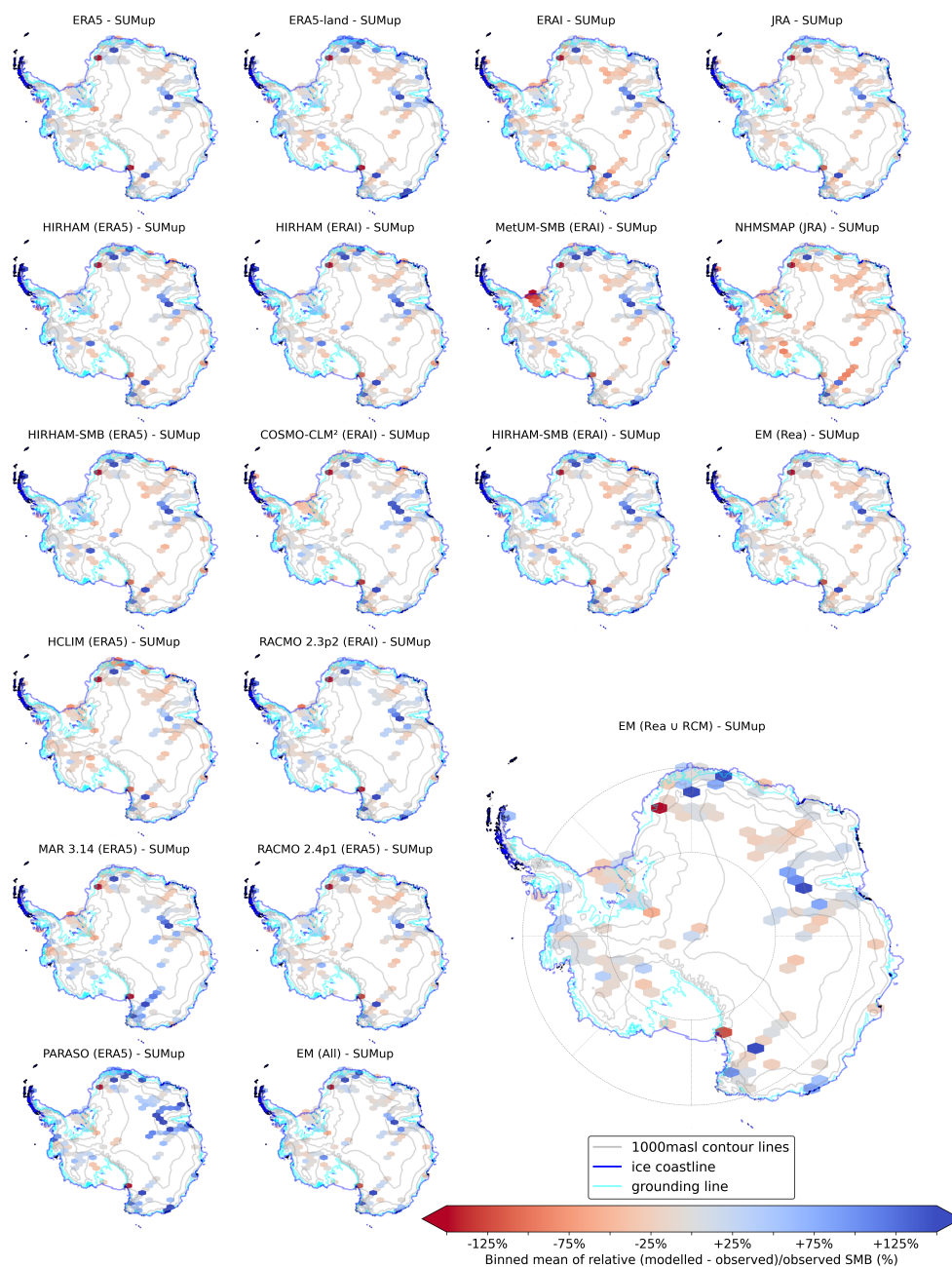


Figure A2. Binned time mean of all (modelled-observed)/observed pairs, for reanalysis products and the ensemble mean of all models (ESM+reanalyses). We attempted to keep similar models nearby, with reanalyses on columns and RCMs on rows.

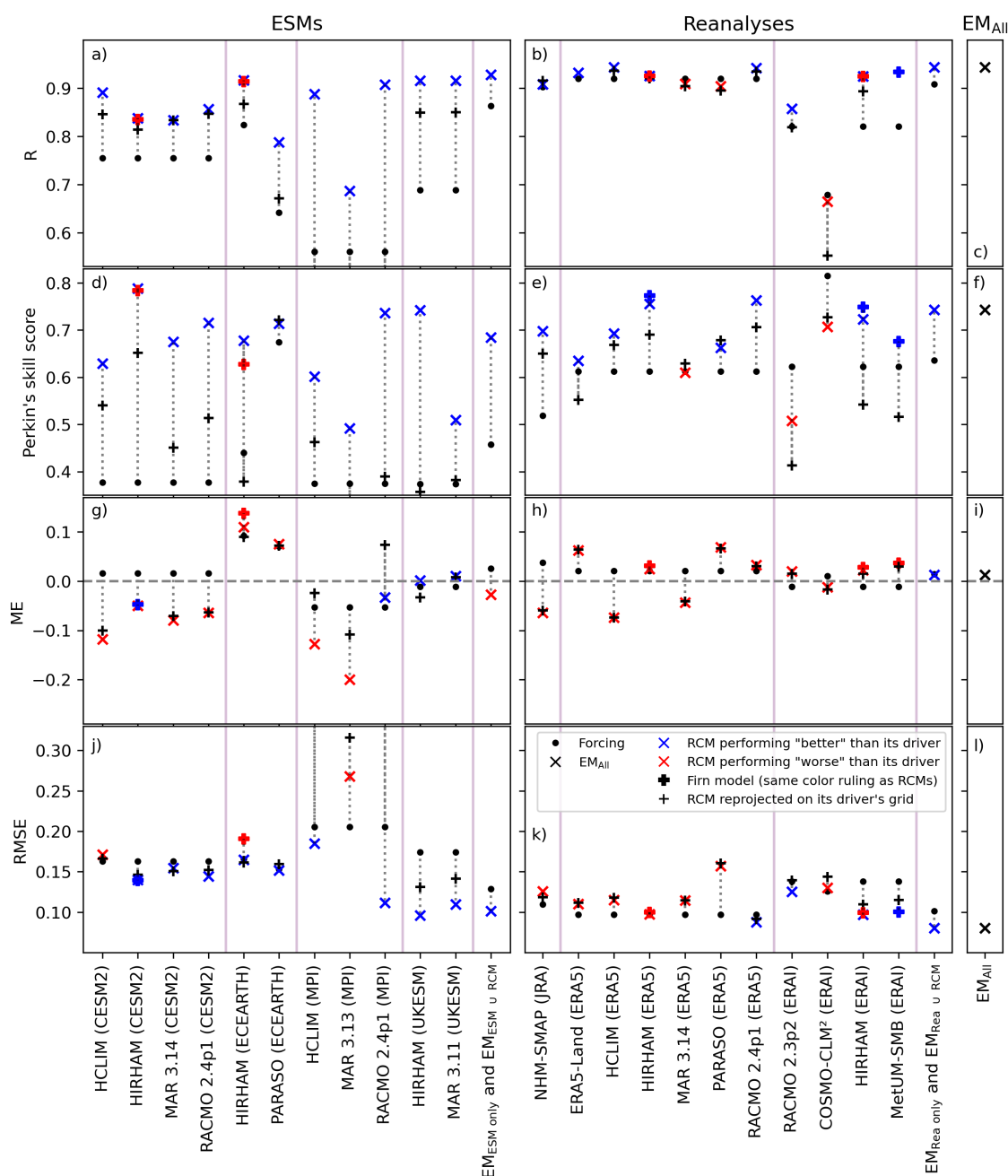


Figure A3. Similar to Fig. 2, but also including the RCMs reprojected on their driver's grid.



Appendix B: Sources of SMB observations



Table A1. Sources of SMB observations used in this study.

Reference	N measurements	Temporal coverage
Konrad et al. (2019a)	60293	1985-2014
Wang et al. (2015) as in Wang et al. (2021a)	9829	1985-2014
Wang et al. (2016a) as in Wang et al. (2021a)	581	1994-2011
Higham et al. (1997) as in Wang et al. (2021a)	526	1990-1995
Motoyama and many coauthors (2015) as in Wang et al. (2021a)	374	1993-2010
Mayewski (2013)	340	1985-2002
Mosley-Thompson et al. (1999) as in Wang et al. (2021a)	236	1992-1997
Thomas et al. (2017)	214	1985-2010
Oerter (2008)	204	1990-2005
Oerter et al. (2000)	174	1985-1996
Bliss (2011) as in Wang et al. (2021a)	164	2002-2011
Hoffmann et al. (2020) as in Wang et al. (2021a)	158	1985-2014
Burgener et al. (2013)	130	1985-2010
Graf et al. (1999)	123	1985-1994
Fernandoy et al. (2010)	118	1985-2006
Anschütz et al. (2007)	101	1985-2003
Schlosser et al. (2012) as in Wang et al. (2021a)	92	1985-2009
Agosta et al. (2011) as in Wang et al. (2021a)	91	2004-2010
Graf and Oerter (2006)	88	1985-1990
Medley et al. (2013)	78	1985-2010
Favier et al. (2013a) as in Wang et al. (2021a)	59	2009-2012
Schlosser et al. (2014) as in Wang et al. (2021a)	52	1991-2009
Frezzotti et al. (2004) as in Thomas et al. (2017)	40	1985-2004
Banta et al. (2008)	40	1985-2004
Oerter et al. (1999) as in Wang et al. (2021a)	34	1985-1997
Oerter (2008) as in Wang et al. (2021a)	34	1985-1994
Kaspari et al. (2004) as in Wang et al. (2021a)	33	1985-2001
Frezzotti et al. (2013) as in Thomas et al. (2017)	31	1985-2003
Winski et al. (2019) as in Wang et al. (2021a)	30	1985-2014
Sinisalo et al. (2003) as in Wang et al. (2021a)	26	1988-2002
Roberts et al. (2015) as in Thomas et al. (2017)	26	1985-2010

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Reference	N measurements	Temporal coverage
Philippe et al. (2016) as in Thomas et al. (2017)	26	1985-2010
Stenni et al. (2000) as in Wang et al. (2021a)	26	1985-2010
Bertler et al. (2018) as in Thomas et al. (2017)	26	1985-2010
Graf et al. (2002) as in Thomas et al. (2017)	26	1985-2010
Goodwin et al. (2016) as in Thomas et al. (2017)	25	1985-2009
? as in Wang et al. (2021a)	23	1985-2014
Mayewski (2013) as in Wang et al. (2021a)	22	1985-2001
Thomas et al. (2008) as in Thomas et al. (2017)	22	1985-2006
Fudge et al. (2016) as in Wang et al. (2021a)	22	1985-2006
Fudge et al. (2016) as in Thomas et al. (2017)	21	1985-2005
Morris et al. (2017)	21	1985-2013
Xiao et al. (2004) as in Thomas et al. (2017)	19	1985-2003
Ferris et al. (2011)	19	1985-2003
Frezzotti et al. (2013) as in Wang et al. (2021a)	19	1985-2003
Schlosser and Oerter (2002b)	17	1985-1998
Schlosser and Oerter (2002a)	17	1985-1997
Ding et al. (2017) as in Wang et al. (2021a)	17	1985-2001
Mayewski (2013) as in Thomas et al. (2017)	16	1985-2000
Eka (2014) as in Thomas et al. (2017)	15	1985-1999
Kaczmarek et al. (2004) as in Thomas et al. (2017)	15	1985-1999
Khodzher et al. (2014) as in Wang et al. (2021a)	13	2006-2010
Aristarain et al. (2004) as in Thomas et al. (2017)	13	1985-1997
Isaksson et al. (1999) as in Thomas et al. (2017)	12	1985-1996
Wen et al. (2006) as in Wang et al. (2021a)	12	1985-1996
Wagenhach et al. (1994)	10	1985-1989
Mulvaney et al. (2002)	10	1985-1994
Reusch et al. (1999) as in Wang et al. (2021a)	9	1985-1993
Stenni et al. (2000) as in Thomas et al. (2017)	8	1985-1992
Jiawen et al. (1999) as in Wang et al. (2021a)	8	1985-1992
Graf et al. (1988)	8	1985-1985
Sinisalo et al. (2013) as in Wang et al. (2021a)	8	2009-2012
Goodwin (1995) as in Wang et al. (2021a)	8	1985-1992
Isaksson et al. (1996) as in Wang et al. (2021a)	7	1985-1991



Reference	N measurements	Temporal coverage
Pasteur and Mulvaney (2000) as in Thomas et al. (2017)	7	1985-1991
Frezzotti et al. (2005) as in Wang et al. (2021a)	7	1993-2002
? as in Thomas et al. (2017)	7	1985-1991
Ding et al. (2011) as in Wang et al. (2021a)	7	1998-2009
Frezzotti et al. (2007) as in Wang et al. (2021a)	6	1996-2005
Thompson et al. (1994) as in Thomas et al. (2017)	5	1985-1989
Ekaykin et al. (2016) as in Thomas et al. (2017)	4	1985-1988
Melvold et al. (1998a) as in Wang et al. (2021a)	3	1994-1998
Fujita et al. (2011) as in Wang et al. (2021a)	3	1993-2008
Kameda et al. (2008) as in Wang et al. (2021a)	1	1995-2006
Skvarca et al. (2004) as in Wang et al. (2021a)	1	2001-2010
Igarashi et al. (2011) as in Wang et al. (2021a)	1	1994-2001
Meyerson et al. (2002) as in Wang et al. (2021a)	1	1986-1986
McConnell et al. (1997) as in Wang et al. (2021a)	1	1988-1995
Frezzotti et al. (2004) as in Wang et al. (2021a)	1	1998-2002

Author contributions. Conceptualisation: CC, NH, CSH, and RM; Data Curation: CC, FB, FS, JAT, MGH, BV, and NH; Methodology: CC, NH, CSH, and RM; Formal analysis: CC; Model development: CvD, WJvdB, and MN; Model simulations: AG, CA, CvD, FB, JAT, KV, MvT, NH, NS, PVH, SM, WJvdB, and MN; Writing - original manuscript: CC; Writing - review and editing: all authors contributed.

Competing interests. At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

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