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Consistent evidence of increasing Antarctic accumulation with warming

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Projections of changes in Antarctic Ice Sheet (AIS) surface mass balance indicate a negative contribution to sea level because of the expected increase in precipitation due to the higher moisture holding capacity of warmer air[1]. Observations over the past decades, however, are unable to constrain the relation between temperature and accumulation changes because both are dominated by strong natural variability[2–5]. Here we derive a consistent continental-scale increase in accumulation of approximately 5 ± 1% K^{-1}, through the assessment of ice-core data (spanning the large temperature change during the last deglaciation, 21,000 to 10,000 years ago), in combination with palaeo-simulations, future projections by 35 general circulation models (GCMs), and one high-resolution future simulation. The ice-core data and modelling results for the last deglaciation agree, showing uniform local sensitivities of ∼6% K^{-1}. The palaeo-simulation allows for a continental-scale aggregation of accumulation changes reaching 4.3% K^{-1}. Despite the different timescales, these sensitivities agree with the multi-model mean of 6.1 ± 2.6% K^{-1} (GCM projections) and the continental-scale sensitivity of 4.9% K^{-1} (high-resolution future simulation). Because some of the mass gain of the AIS is offset by dynamical losses induced by accumulation[6,7], we provide a response function allowing projections of sea-level fall in terms of continental-scale accumulation changes that compete with surface melting and dynamical losses induced by other mechanisms[6,8,9].

General Circulation Models and high-resolution atmospheric regional climate models (RCMs) consistently project increasing AIS accumulation (herein defined as precipitation–sublimation) over the twenty-first century[5,10–14]. Continental-scale increases are mainly attributed to increasing precipitation due to higher atmospheric moisture concentrations in a warmer atmosphere, whereas regional patterns result mainly from the interaction between ice-sheet topography and circulation-driven changes in meridional moisture transport[14–16]. The surface topography of the AIS leads to a spatially variable distribution of precipitation, with low precipitation rates (<50 mm yr^{-1}) over the high-elevation inner plateau and a rapid increase in precipitation towards the lower elevation coastal regions[4,11,17,18]. The projected continental-scale change in precipitation is also dominated by an increase in the coastal regions. Based on a GCM with regional zoom capacity, the mean absolute increase in precipitation over coastal areas (surface elevation < 2,250 m) is projected to be three times larger than the mean increase over the inner ice sheet[10]. In contrast, the projected relative increase in precipitation over the twenty-first century is much more uniformly distributed and even tends to be slightly higher in the interior than in the coastal regions[10,13,19].

Despite model simulations consistently showing an increase in continental-scale accumulation with regional warming, individual estimates of the sensitivities (herein accumulation sensitivity) have a wide range, from 3.7% K^{-1} estimated from one GCM over the twenty-first century[20], to 5.5% K^{-1} derived from simulations of the historical period provided by five GCMs (ref. 5) within the Coupled Model Intercomparison Project phase 3 (CMIP3), 7% K^{-1} based on high-resolution model simulations by the end of the twenty-first century[11], and 13% K^{-1} based on simulations from 15 CMIP3 GCMs through the twenty-first century[10], although the high sensitivity in the latter study may be largely due to the empirical correction factor used to adjust for resolution effects. Moreover, because high-resolution RCMs better resolve the steep coastal topography and uplift of air masses, adiabatic cooling and associated precipitation than lower-resolution global models, they often result in higher projected continental-scale precipitation changes for the same amount of warming[10,12].

There are few observational data to evaluate these model simulations. Linear regression analysis of present-day observations[21] suggests a sensitivity of 4% K^{-1} for the Antarctic continent. However, because of the large inter-annual variability of snowfall on a continental scale[4], long-term records are required to infer significant accumulation trends[3]. The analysis of a current 50-year benchmark data set has not shown a significant trend in Antarctic accumulation with time[3]. In combination with temperature observations, the accumulation sensitivity reaches 4.9 ± 4.9% K^{-1}, in close agreement with a GCM-derived value of 5.5 ± 0.8% K^{-1} (ref. 5) and the early estimate by Fortuin and Oerlemans[21]. However, the simulated sensitivities are based on significant increases in accumulation rates (17 ± 4 mm century^{-1}) and temperatures that are not seen in the observational data.

Ice cores provide information about accumulation changes during the period of warming associated with the last deglaciation (∼21–10 ka; Fig. 1), thus providing a unique opportunity to evaluate accumulation sensitivities independent of model simulations. At the same time, however, these records identify only local changes, and thus do not allow an assessment of the continental-scale relationship between integrated accumulation changes across the AIS and continental-mean temperatures that is critical for estimates of sea-level rise. We thus use results from a transient simulation with the coupled atmosphere–ocean Community Climate System Model version 3 (CCSM3) that spans much of the last deglaciation (22.0–14.3 ka; refs 22,23) to derive associated

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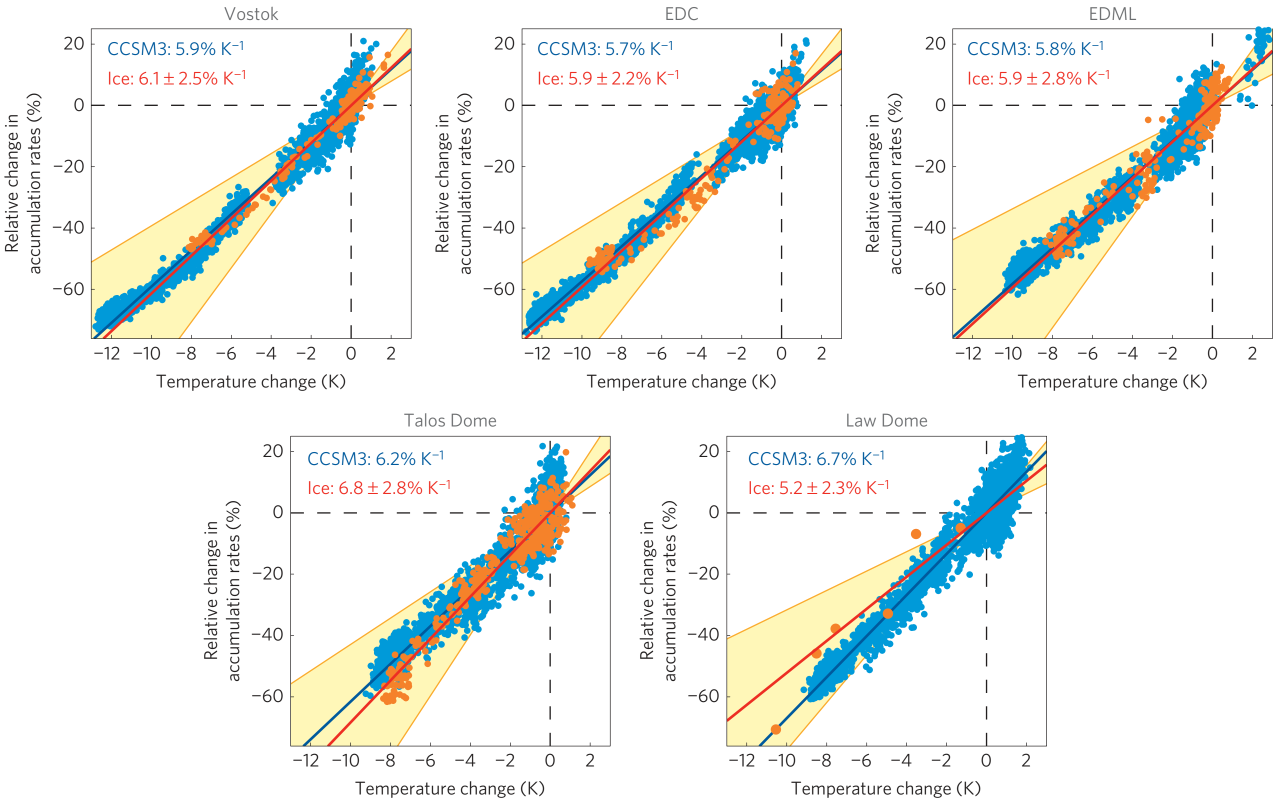

Figure 1 | Changes in local accumulation rates and temperatures derived from ice cores (orange) and CCSM3 palaeo-simulations (blue, decadal averages) at the ice-core sites. Changes in accumulation and temperature are described in comparison to a core-specific pre-industrial reference level (see Supplementary Information). Thick solid lines are derived by linear regression assuming that the intercept is zero (orange lines for ice-core data and blue lines for simulations, sensitivities are given in each panel including the 2σ uncertainty range of the sensitivities derived from the ice cores). The shaded area describes the uncertainty range of the ice-core sensitivities.

continental-scale sensitivities. These results are then compared to sensitivities derived from future simulations generated by the latest generation of GCMs that contributed data to the Coupled Model Intercomparison Project phase 5 (CMIP5) based on the four Representative Concentration Pathways (RCPs) and a high-resolution future simulation by the Regional Atmospheric Climate Model 2 (RACMO2; ref. 24).

We consider three ice-core sites that are located in the interior of the East Antarctic Ice Sheet (EPICA Dronning Maud Land (EDML, 75° S 0°), EPICA Dome C (EDC, 75° S 123° E) and Vostok (78° S 106° E)), two that are more proximal to the coast (Talos Dome (72° S 159° E) and Law Dome (66° S 112° E)), and one from the West Antarctic Ice Sheet (WAIS Divide, 79° S 112° W). For the Law Dome and WAIS Divide cores, accumulation changes were derived independent of an assumption about the relationship between temperature and accumulation. For the other four cores, such an assumption is initially used but then fully evaluated and revised based on an assessment with independent age-control markers (see Supplementary Information).

Each of the six sites shows a linear relationship between local accumulation and temperature changes, with the accumulation sensitivity derived from the six cores ranging from $5.2\pm2.3\%\,K^{-1}$ to $6.8\pm2.8\%\,K^{-1}$ (Fig. 1 and Table 1). Relative accumulation changes are described in comparison to ice-core-specific reference data and the uncertainty ranges represent the 2σ uncertainty due to uncertainties in the temperature and accumulation profiles (see Supplementary Information).

The palaeo-simulation by CCSM3 shows similar accumulation sensitivities at the six ice-core sites ($4.4\%\,K^{-1}$ to $6.7\%\,K^{-1}$; Fig. 1 and Table 1), where we derived reference levels in the same way as the ice-core reference levels (see Supplementary Information). There are periods of rapid AIS surface lowering where local warming is strongly amplified by the elevation feedback, but we find that the relationship between warming and accumulation changes remains robust across these periods (see Supplementary Information). Sensitivities agree with the sensitivities from the ice cores within their 2σ uncertainty ranges (the simulated sensitivities deviate by less than 10% from the sensitivities derived from the ice-core data, except for Law Dome and WAIS Divide).

Using present-day (1890–1980) reference periods has only a minor effect on the simulated sensitivities (Table 1). Based on this present-day reference period, we derive a continental-scale sensitivity from the palaeo-simulations that reaches $4.3\%\,K^{-1}$ (Fig. 2), which is in agreement with the multi-model mean value of $6.1\%\,K^{-1}$ (inter-model standard deviation of $\sigma_{mod}=2.6\%\,K^{-1}$, see Methods) derived from the future simulations of 35 CMIP5 GCMs (Fig. 3). The continental integrals of accumulation rates and temperature averages include ice shelves (Fig. 4). Similar to CCSM3, all CMIP5 models consistently show a quasi-linear increase in Antarctic accumulation rate with regional warming up to a global mean warming of 6 K (Fig. 3). For higher levels of regional warming, the relationship becomes nonlinear in some of the models (Supplementary Fig. 4). In comparison with the dependence on the specific GCM, the dependence of the scaling coefficients on the four RCP scenarios is particularly low (standard deviation of the inter-scenario spread of scaling coefficients $\sigma_{scen}=0.4\%\,K^{-1}$, see Methods), indicating that the sensitivities derived here for the RCP scenarios can be used to estimate accumulation changes for other regional temperature scenarios.

We next use high-resolution simulations with RACMO2 to evaluate the potential effects of smaller-scale processes on the GCM-derived results. The model provides a more detailed

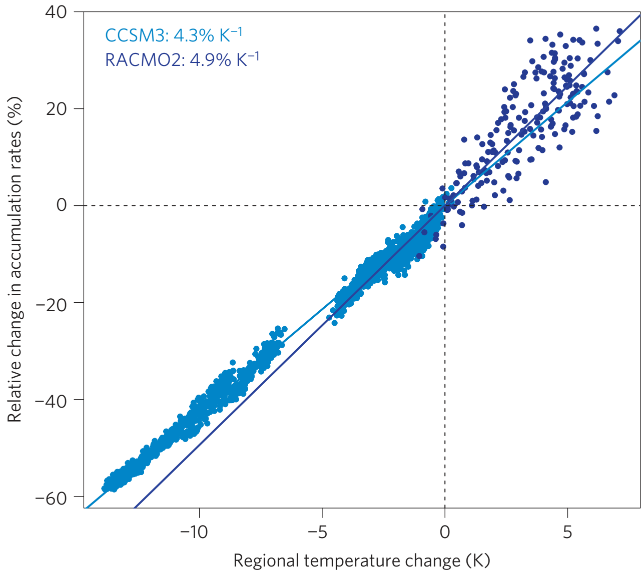

Figure 2 | Accumulation sensitivities on continental scale. Light blue: relative changes in integrated accumulation across the Antarctic Ice Sheet (including ice shelves) in terms of regionally averaged temperature changes based on palaeo-simulations by CCSM3 (decadal data). Dark blue: associated annual data from high-resolution future simulations (SRES A1B emission scenario) by RACMO2. Solid lines are derived by linear regression, assuming that the intercept is zero (light blue line from CCSM3 data and dark blue line from RACMO2 data, corresponding sensitivities are given in the panel). All changes are described in comparison to the present-day reference.

Table 1 | Summary of accumulation sensitivities.

	Scaling coefficient (% K^{-1})	2σ uncertainty (% K^{-1})
Continental-scale sensitivities		
Palaeo-simulations (CCSM3)	4.3	<0.1
CMIP5 GCMs/ESMs future simulations	6.1	0.9
High-resolution future simulations (RACMO2)	4.9	0.2
Local sensitivities		
Ice-core data		
EDC	5.9	2.2
EDML	5.9	2.8
Talos Dome	6.8	2.8
Law Dome	5.2	2.3
Vostok	6.1	2.5
WAIS Divide	5.5	1.2
Palaeo-simulations, reference time of the ice-core data (based on present-day reference)		
EDC	5.7 (5.8)	<0.1 (<0.1)
EDML	5.8 (5.1)	<0.1 (<0.1)
Talos Dome	6.2 (6.0)	<0.1 (<0.1)
Law Dome	6.7 (6.2)	<0.1 (<0.1)
Vostok	5.9 (5.8)	<0.1 (<0.1)
WAIS Divide	4.4 (4.3)	<0.1 (<0.1)

For the model simulations, the uncertainty estimate represents two times the standard error of the estimated scaling coefficient. For the ice-core data, the range includes the uncertainties in the temperature and accumulation profiles (see Supplementary Information).

representation of Antarctic topography (∼55-km horizontal resolution) and includes a sophisticated snow pack model[25]. Forced with ERA-Interim re-analysis data, it has proved to yield results that compare well with *in-situ* observations of Antarctic surface mass balance (SMB; ref. 4). We report local- and continental-scale accumulation changes relative to the reference period 1980–1999. Based on future projections for the SRES A1B scenario, the continental-scale accumulation sensitivity in RACMO2 is 4.9% K^{-1} (Fig. 2), which falls well within the range derived from the GCMs. Local accumulation sensitivities from CCSM3 are much more uniformly distributed than the local accumulation rates simulated by RACMO2 (Fig. 4). Although local sensitivities vary between 0 and 7.4% K^{-1} for CCSM3, they reach values up to 15% K^{-1} in RACMO2. In general, both models show lower sensitivities in coastal regions and higher sensitivities in interior regions, whereas absolute accumulation rates are significantly higher at the coast (Fig. 4c for RACMO2). RACMO2 shows greater spatial variability of sensitivities along the coast than CCSM3 that may be related to topographic features, which cause precipitation changes that are related to the interaction between ice-sheet topography and circulation changes. Furthermore, lower accumulation sensitivities in coastal regions may be explained by higher sublimation increases as compared to regions further inland. The inner parts of Antarctica with very high sensitivities simulated by RACMO2 are particularly dry. Because the SMB is so small, even a small absolute increase in SMB means a large relative increase. The high simulated sensitivities may reflect the fact that the applied version of RACMO2 tends to underestimate precipitation in the interior of Antarctica[26].

To estimate the sea-level fall associated with projected snowfall increases, it is necessary to account for the self-induced dynamical loss occurring with a certain delay. Here we provide a means to translate continental-scale accumulation changes into mass gain that accounts for this effect by emulating the response of the Parallel Ice-Sheet Model (PISM; ref. 6). The model was forced by step increases in relative accumulation assuming the regional pattern provided by RACMO2 (Fig. 4b) to derive a response function R describing the model's response to a peak forcing in continental-scale accumulation changes (see Supplementary Information for a more detailed description of the fitting). This function can then be applied to estimate the mass gain for an arbitrary temporal evolution of accumulation changes:

$$\Delta M(t) = \int_0^t \Delta A(t')R(t-t')\mathrm{d}t'$$

where $\Delta A(t')$ = relative change in continental-scale accumulation rates and $R(t) = \gamma(\frac{t}{t_0})^{\alpha}$, with $t_0 = 1\,\mathrm{yr}$, $\gamma = 7.95\,\mathrm{mm\,yr^{-1}}$ and $\alpha = -0.1$.

Based on this approach and the continental-scale sensitivities provided above, it is now possible to estimate the snowfall-induced mass gain for any new scenario of regional or global mean temperature change (given a close quasi-linear relationship between regional warming and global mean temperature changes) without requiring additional GCM or RCM simulations and the associated runs of a complex ice-sheet model.

In summary, local- as well as continental-scale changes in Antarctic accumulation rates show a remarkably linear relationship with local or continental average warming, respectively. Sensitivities from all four sources used here (ice-core data, palaeo-simulations, CMIP5 GCM future simulations and RCM future simulations) are positive. Palaeo-simulations as well as high-resolution future projections fall into the multi-GCM range of 6.1% K^{-1} ± 2.6% K^{-1} derived from 35 CMIP5 models. Additional agreement with the sensitivities derived from the ice-core data provides confidence in

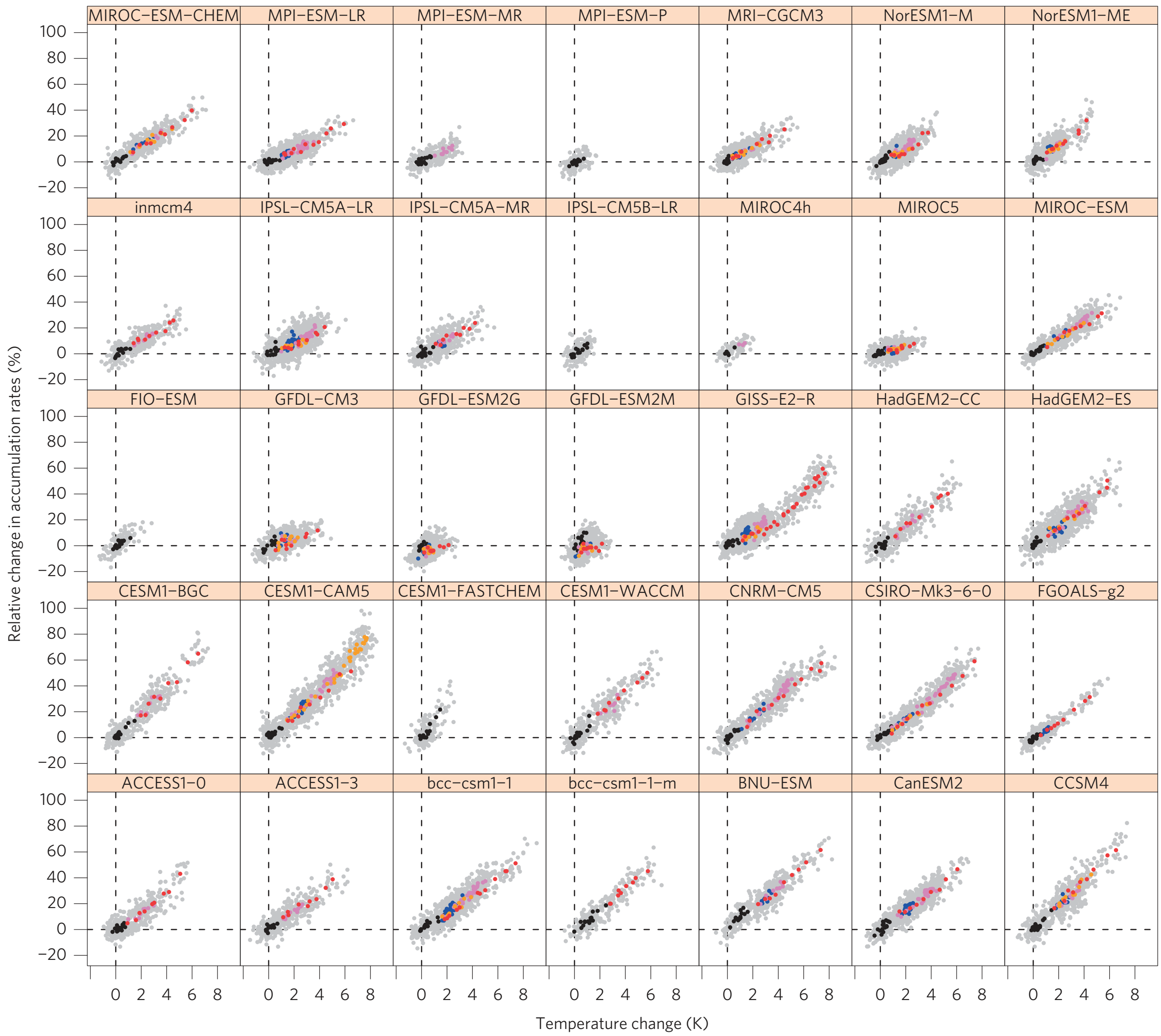

Figure 3 | Continental-scale accumulation change versus continental average temperature changes as derived from the CMIP5 GCM ensemble up to a global mean warming of 6 K. Black: Decadal data from historical simulations. Blue, RCP2.6; violet, RCP4.5; orange, RCP6.0; red, RCP8.5; grey, annual data.

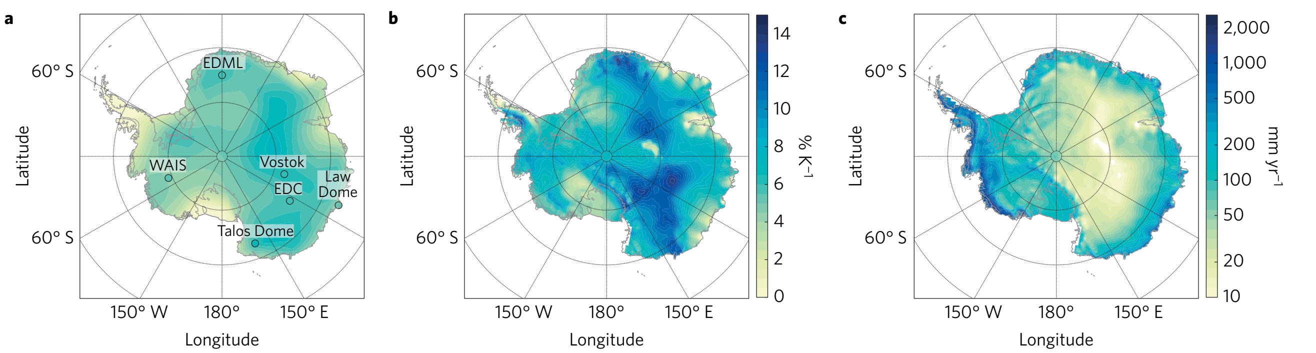

Figure 4 | Spatial distribution of relative changes in accumulation rates in terms of local warming. **a**, Based on low-resolution palaeo-simulations by CCSM3. **b**, Based on high-resolution future simulations by RACMO. In both cases, sensitivities are based on present-day reference periods. **c**, Associated absolute reference accumulation rates for RACMO2. Panel **a** also includes the accumulation sensitivities derived from the six ice cores (Fig. 1).

projections of enhanced snowfall over Antarctica in offsetting the ice sheet's dynamical contribution to future sea-level rise[1].

Methods

Ice-core data. Accumulation rate data from four ice cores (EDC, EDML, Talos Dome, Vostok) are derived using the Datice methodology[27,28]. Accumulation rates for Law Dome are from age tie-points and an ice-flow model that simulates ice thinning from vertical strain[29]. Accumulation rates for the WAIS Divide ice core are from annual layer counting[30]. Temperature reconstructions are derived from isotope (δD, δ^{18}O) records (see Supplementary Information).

CCSM3 palaeo-simulations. The CCSM3 palaeo-simulations are described as 'all-forcing experiment' in ref. 22, which was driven by transient variations of orbital configurations, greenhouse gas concentrations, Atlantic meridional overturning circulation as well as quasi-transient variations of continental ice sheets since the Last Glacial Maximum.

Changes in accumulation rates derived from CMIP5 GCM data. Relative changes in annual accumulation and absolute changes in annual near-surface air temperature are calculated with respect to a smoothed version (linear trend line) of the parallel pre-industrial control data. As data are grouped in different GCMs and scenarios, they cannot be considered as independent random variations around one single trend line. However, Fig. 3 suggests that they are well described as random variations around individual model and scenario specific trend lines. Therefore the following random effects model is fit to the data:

$$\Delta A_{i,j}(t) = (c + r^{\text{mod}}{}_i + r^{\text{scen}}{}_{i,j})^* \Delta T_{i,j}(t) + \varepsilon_{i,j}(t)$$

where $\Delta A_{i,j}$ is the relative change in integrated accumulation across the AIS (including ice shelves), $\Delta T_{i,j}$ is the absolute change in regional temperatures, $\varepsilon_{i,j}$ describes the residual variation, and t represents the time period. Within this modelling framework, there is a multi-model mean scaling coefficient c where individual GCMs (i) and scenarios (j) specific scaling coefficients are assumed to deviate randomly from the multi-model mean. Each scenario run provides one realization of these deviations (the so called 'random effects'), which are described by r^{mod} (inter-GCM deviations) and r^{scen} (inter-scenario deviations). All random effects are assumed to follow a normal distribution centred at zero and with standard deviations σ_{mod} and σ_{scen}, respectively.

Regional climate simulations. To provide accumulation rates under warming conditions, we use RACMO2 simulations where lateral boundaries were prescribed by the output of the coupled global climate model HadCM3 (CMIP3 database) driven by the A1B emissions scenario. Beyond 2100, the scenario was extended to 2199 assuming constant forcing. A more detailed description of these RACMO2 model simulations is given in ref. 13.

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Author contributions

K.F., P.U.C. and A.L. conceived the study; F.H. contributed the palaeo-simulations; M.R.v.d.B. and S.R.M.L. provided the RCM simulations; P.U.C. and C.B. contributed the analysis of the ice-core data; R.R. and R.W. added the PISM simulations and the associated response functions. All authors contributed to analysis and writing the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to K.F.

Competing financial interests

The authors declare no competing financial interests.