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Future Antarctic snow accumulation trend is dominated by atmospheric synoptic-scale events

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Over the last century, the increase in snow accumulation has partly mitigated the total dynamic Antarctic Ice Sheet mass loss. However, the mechanisms behind this increase are poorly understood. Here we analyze the Antarctic Ice Sheet atmospheric moisture budget based on climate reanalysis and model simulations to reveal that the interannual variability of regional snow accumulation is controlled by both the large-scale atmospheric circulation and short-lived synoptic-scale events (i.e. storm systems). Yet, when considering the entire continent at the multi-decadal scale, only the synoptic-scale events can explain the recent and expected future snow accumulation increase. In a warmer climate induced by climate change, these synoptic-scale events transport air that can contain more humidity due to the increasing temperatures leading to more precipitation on the continent. Our findings highlight that the multi-decadal and interannual snow accumulation variability is governed by different processes, and that we thus cannot rely directly on the mechanisms driving interannual variations to predict long-term changes in snow accumulation in the future.

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The Antarctic Ice Sheet (AIS) is currently losing mass at an accelerated pace at its margins of the West Antarctic Ice Sheet, driven by oceanic warming that induces ice shelf melting, subsequent grounding line retreat, and enhanced ice discharge[1–3]. Partly opposing this mass loss, snowfall has increased over much of the AIS since the early 19th century, as shown in a recent AIS-wide reconstruction based on ice core compilation[4]. This positive trend in snow accumulation, i.e. the difference between total precipitation and losses from the evaporation/sublimation, wind snow redistribution, and meltwater runoff, is estimated to have led to the mitigation of sea-level rise[4]. Both ice core records and climate models suggest an increase in snow accumulation over the last century, in concert with and driven by the warming of the AIS near-surface atmosphere[4,5]. Accordingly, climate model projections predict that the Antarctic snow accumulation will continue to increase and partially offset dynamic AIS mass loss by the end of the 21st century[6,7].

However, the regional variations in the trends suggest that the processes driving this snow accumulation increase are more subtle than a simple temperature-snow accumulation relationship. Additionally, ice cores reveal that the snow accumulation over the Holocene period might not be systematically related to changes in air temperature[8,9]. In this regard, some areas over the West Antarctic Ice Sheet have witnessed warming over 1950–2010 CE without a snow accumulation increase[10,11], pointing out the role of the interaction between orography and atmospheric circulation in the temperature-accumulation relationship[12].

Our limited understanding of those processes governing the snow accumulation variations has two important consequences. First, it restrains our ability to assess future Antarctic contribution to global sea-level rise[13]. Second, it introduces uncertainties in the information inferred from interpretation of ice core records such as snow accumulation or the isotopic ratio of oxygen, that are notably used to reconstruct past near-surface air temperature, sea ice extent, and atmospheric circulation[14,15]. Nevertheless, without a thorough understanding of the atmospheric processes that control AIS snow accumulation, inferring the past climate beyond the instrumental period from these records may be hazardous.

Snow accumulation variability is mainly controlled by three mechanisms: thermodynamic processes, large-scale dynamics, and synoptic-scale dynamics[4,12,13,16,17]. Thermodynamic processes refer to snow accumulation changes attributed to a change in air temperature. Following the Clausius-Clapeyron relation, the maximum atmospheric moisture content increases with increasing air temperature, and potentially leads to more AIS continental snow accumulation in a warming climate[4,5,9,18]. In contrast to thermodynamic processes that have a pervasive impact on snow accumulation changes, large-scale atmospheric dynamics, which bring moisture from lower latitudes, lead to more regional variability as topography largely controls precipitation changes in response to modification in atmospheric circulation[12]. Finally, recent studies[19,20] have pointed out the large contribution of short-lived synoptic-scale events, such as atmospheric rivers, to the interannual variability of snow accumulation. Some Antarctic regions receive more than 50% of their annual snowfall in just a few days, such as the Amery Ice Shelf[20], but the net contribution of these short-lived synoptic-scale events in the long-term snow accumulation changes for Antarctica as a whole is unknown. It is worth noting that these three mechanisms are difficult to disentangle because they are not mutually exclusive.

To better understand the individual contributions of these three mechanisms on past, present, and future AIS snow accumulation, we calculate a moisture budget for the AIS atmosphere, analogous to that of previous studies[21,22] (see Methods section for more details). From this budget, we can separate the contributions of the moisture transported by large-scale atmospheric dynamics from the moisture transported by synoptic-scale events (see Methods section for more details). The proposed methodology makes the distinction between the two by assuming that synoptic-scale events mainly influence day-to-day variations, while the influence of large-scale circulation is obtained as the result when monthly means are used. Separating these two mechanisms across temporal scales also corresponds to a separation in the spatial scales, as synoptic-scale events are typically 100–2000 km scale systems embedded within the large-scale flow characterized by scales larger than 2000 km. The analysis uses the European Centre for Medium-Range Weather Forecasts Interim reanalysis, the latter which is ERA-Interim, the best reanalysis to study the Antarctic climate over the last few decades[23,24], and Global Climate Model (GCM) simulations covering the 20th and 21st centuries, including ozone depletion experiments. The goal is to investigate all the known mechanisms that explain the snow accumulation variability from the interannual to multi-decadal scale, at both regional and continental scales, in a common framework.

Although it is not possible to estimate the errors introduced by the moisture budget calculation on each term of the budget, it is worth noting that the moisture budget calculation underestimates the Antarctic snow accumulation, which most likely originates from an underestimation of the contribution of the moisture brought by the synoptic-scale transport (around 18% when integrating over the entire continent over 1985–2014 CE). However, both the spatial and temporal variability of the snow accumulation are well reproduced (see Supplementary Methods for the discussion of the errors related to the moisture budget calculations).

Results

Despite those uncertainties in the moisture budget calculation, the main contributor to the mean Antarctic snow accumulation averaged over the 1985–2014 CE period for each of the seven geographical regions defined here (see Methods section for more details) is the synoptic-scale transport, with an average contribution slightly exceeding 100% (105 ± 4% for Antarctica as a whole (Fig. 1). This is consistent with previous studies[21,25]. While the synoptic-scale transport positively contributes to the mean snow accumulation for each of the seven regions, the contribution of the large-scale transport is only positive for the Antarctic Peninsula and the West Antarctic Ice Sheet (WAIS) (18 ± 9% and 32 ± 6%, respectively). For East Antarctica, the contribution of the large-scale transport is negative (−34 ± 7%), which implies that the mean atmospheric circulation tends to transport the moisture brought by the synoptic-scale transport away from the region. This finally adds up to a quasi-null contribution of large-scale transport for the continent as a whole (−5 ± 4%). The net contribution of the mean atmospheric circulation to the Antarctic snow accumulation averaged over the 1985–2014 CE period is, therefore, a net atmospheric moisture transport, and associated snowfall, from West to East Antarctica.

Although the contribution of the large-scale transport to the mean snow accumulation integrated over the entire AIS is small compared to the synoptic-scale transport, it provides a large contribution to the interannual variability of the snow accumulation on the regional scale. Except for the Antarctic Plateau, the role of the large-scale transport in the interannual variability is larger than 29% and is similar to or higher than the role of the synoptic-scale transport (Fig. 1). For instance, for the Antarctic Peninsula, year-to-year variations in the large-scale transport explain almost 80% of interannual variability in snow

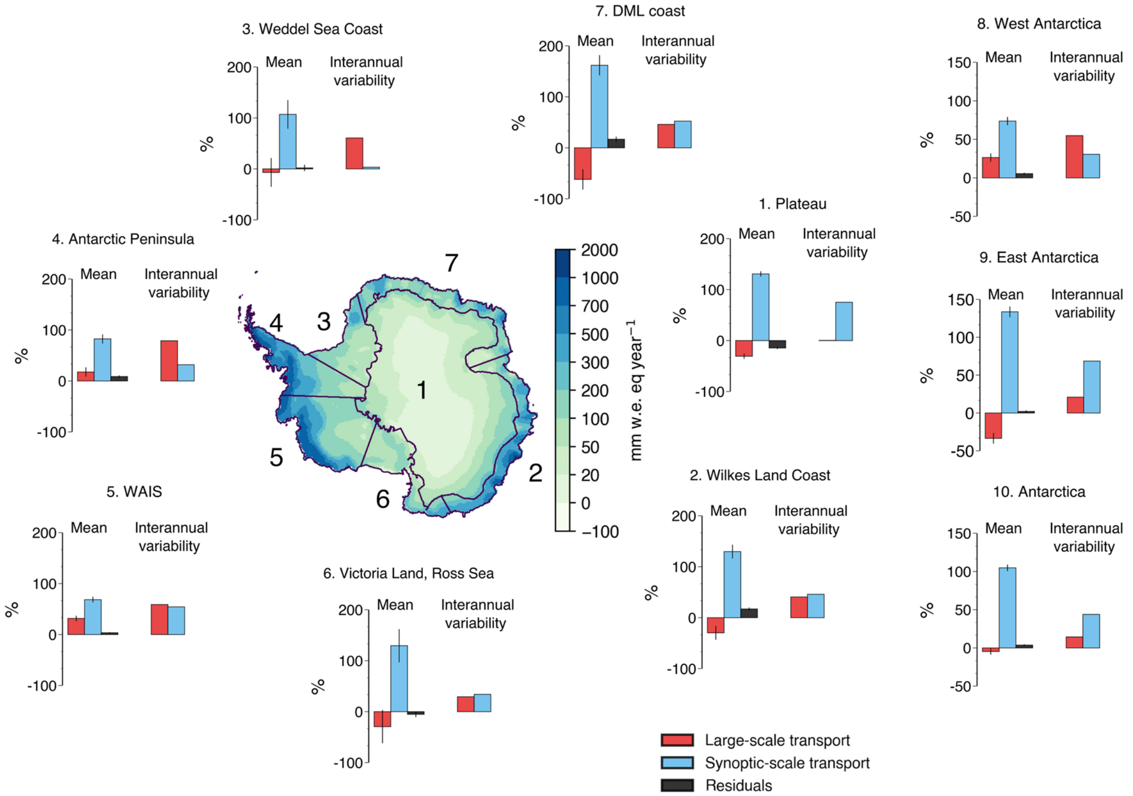

Fig. 1 Relative contributions of the large-scale and synoptic-scale transports to Antarctic snow accumulation. The bar plots show the contributions of the large-scale transport (red) and synoptic-scale transport (blue) to the mean and interannual variability of snow accumulation for the seven Antarctic regions based on ERA-Interim over the 1985–2014 CE period. The residuals (black; i.e., the error related to the moisture budget calculation) are defined as the difference between the mean snow accumulation from model outputs and the one from the moisture budget (see Methods for more details). In the center, the Antarctic snow accumulation climatology over the 1985–2014 CE period (in mm w.e. year^{-1}) with the regional boundaries defined. The error bars are calculated as the standard deviation of the annual contribution to the snow accumulation mean. Antarctic regions are defined as in ref. [17]: the Plateau where the altitude is higher than 2000 m, Wilkes Land Coast (70–150°E), Weddell Sea Coast (60–15°W), Victoria Land and Ross Sea (150–170°E), and Dronning Maud Land (DML) Coast (15°W–70°E). All these regions together is considered as East Antarctica. West Antarctica is divided into two regions with a division at 88°W: the Antarctic Peninsula and the West Antarctic Ice Sheet (WAIS).

accumulation, while it only contributes to 18% of the long-term mean. However, the synoptic-scale transport still dominates the interannual variability of snow accumulation at the continental scale (Fig. 1, Antarctica as whole).

Contributions of large-scale and synoptic-scale transports in multi-decadal trends. To analyze snow accumulation changes over longer timescales, including the last century, we calculate the moisture budget for the AIS using Earth System Model (ESM) outputs over the 1850–2014 CE period. For this purpose, we use the most recent version of the Community Earth System Model, CESM2[26]. The use of CESM2 is justified by large similarities between the calculated CESM2 moisture budget and the one from ERA-Interim for the 1985–2014 CE period (Supplementary Fig. 1 and Supplementary Table 1). Both ERA-Interim and CESM2 indicate the synoptic-scale transport as the main contributor to the mean of snow accumulation for all the regions, with for instance a total contribution of 100% for Antarctica as a whole for CESM2 against 105% for ERA-Interim. Additionally, in accordance with ERA-Interim, CESM2 highlights the role of the large-scale circulation on the interannual variability of the regional snow accumulation (on average over the seven regions without the Plateau, this contribution reaches 58% against 53% for ERA-Interim), but the interannual variability at the continental scale is dominated by the synoptic-scale transport (63% for CESM2 against 44% for ERA-Interim).

On the continental scale, we obtain a modeled snow accumulation increase of 211 Gt year^{-1} (relative increase: +8%) between the 1850–1879 CE and 1985–2014 CE periods, with the largest relative increase for Dronning Maud Land (+17%: +62 Gt year^{-1}; Fig. 2). This large increase over recent years over Dronning Maud Land is consistent with several other data and model studies[27–29]. CESM2 shows a positive snow accumulation change for all seven regions. Analogously, CESM2 under the SSP5-85 scenario (see Methods section for more details) predicts that Antarctic snow accumulation over the 2071–2100 CE period will be 1200 Gt year^{-1} higher compared to the 1985–2014 CE period (relative increase of 42%; Supplementary Fig. 2). CESM2-shows an increase for all seven regions, with the Weddell region displaying the highest relative increase (+54%), closely followed by the Dronning Maud Land region (+52%; Supplementary Fig. 2).

According to our results, it turns out that the snow accumulation increase for the 1985–2014 CE period at the continental scale is mainly explained by an increase in the synoptic-scale transport (+95%) as the change in the large-scale transport leads to almost no change in snow accumulation (+5%; Fig. 2). However, on the regional scale, changes in the large-scale transport do contribute to snow accumulation changes for WAIS

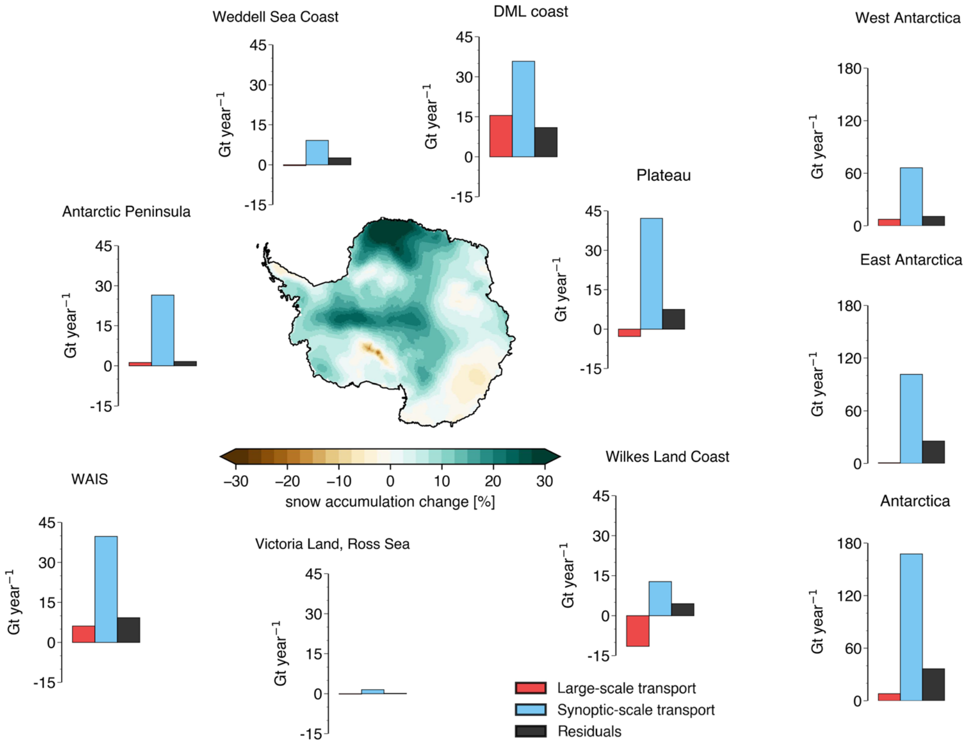

Fig. 2 Snow accumulation changes in the CESM2 simulation between the 1985–2014 CE and 1850–1879 CE periods. The bar plots represent the absolute contributions of the large-scale transport (red) and synoptic-scale transport (blue) to the snow accumulation change per region (in Gt year^{-1}). The change in the residuals (black; i.e. the error related to the moisture budget calculation) is defined as the change in the difference between the snow accumulation from model outputs and the one from the moisture budget (in Gt year^{-1}; see Methods for more details). Regional boundaries are as in Fig. 1.

(13%) and Dronning Maud Land (30%). Separating the contribution of the large-scale transport into dynamic and thermodynamic components (i.e., due to changes in the winds or humidity, respectively; see Methods section for more details) indicates that for the Wilkes Land Coast and Dronning Maud Land regions, the snow accumulation increase is driven by an atmospheric circulation change and not a specific humidity change (Supplementary Fig. 3). Similarly to these changes described over the past decades, future snow accumulation increases at the continental scale are dominated by an increase in the contribution of the synoptic-scale transport (96%; Supplementary Fig. 2). The change in the large-scale transport leads to no change in snow accumulation at this continental scale (4%), but at the regional scale, changes in the large-scale transport are important for almost all regions with its highest relative positive contribution for Victoria Land (+89%) followed by WAIS (+55%) and the Antarctic Peninsula (+41%).

Physical mechanisms behind snow accumulation changes. The ESM-based results allow us to also assess the mechanisms (i.e., thermodynamic processes, large-scale and synoptic-scale dynamics) behind recent and future AIS snow accumulation changes. At first, given that the water vapor pressure of the air depends directly on the air temperature following the Clausius-Clapeyron relation (i.e., the concentration of water in the atmosphere is potentially higher in a warmer atmosphere), we assume that snow accumulation changes are proportional to air temperature changes (i.e., the CC approximation; see Methods section for more details. If applying the CC approximation shows a good match of the changes observed in air temperatures and snow accumulation rates, thermodynamic changes can explain the modeled snow accumulation changes. On the other hand, a non-matching CC approximation potentially indicates that the origin of snow accumulation changes arise from a dynamic change (changing atmospheric circulation, bringing more or less humidity) rather than a thermodynamic change (change in air temperature).

The CC approximation largely underestimates the modeled snow accumulation interannual variability at the regional scale over the 1985–2014 CE period (Supplementary Fig. 4). It better explains the long-term changes in snow accumulation between the 1985–2014 CE and 1850–1879 CE periods, obtaining a relative underestimation of 16% of the total AIS snow accumulation change (Fig. 3a), with large regional disparities. This suggests that the interannual changes are more directly influenced by local changes such as a change in the winds (i.e., atmospheric dynamics), while long-term changes are well approximated by large-scale temperature changes. This result confirms that the large-scale circulation largely explains the interannual variability of regional snow accumulation. Similarly, the CC approximation overestimates the total future AIS change by 1% (i.e., between the 2071–2100 CE and 1985–2014 CE periods), albeit with less regional differences than for recent changes (Fig. 3b).

The trend in AIS snow accumulation not explained by the thermodynamic effect but rather attributed to changes in atmospheric dynamics might be linked to the Southern Annular Mode (hereafter SAM), the main mode of atmospheric variability in the Southern Hemisphere[30]. The SAM is related to changes in the strength and position of Westerlies around the Antarctic. A recent study[4] has shown that the SAM is the dominant contributor for the interannual variations of snow accumulation at the regional scale, explaining more than 80% of the spatial snow accumulation variability in trends over the 1957–2000 CE period. The increase in SAM index between the 1985–2014 CE

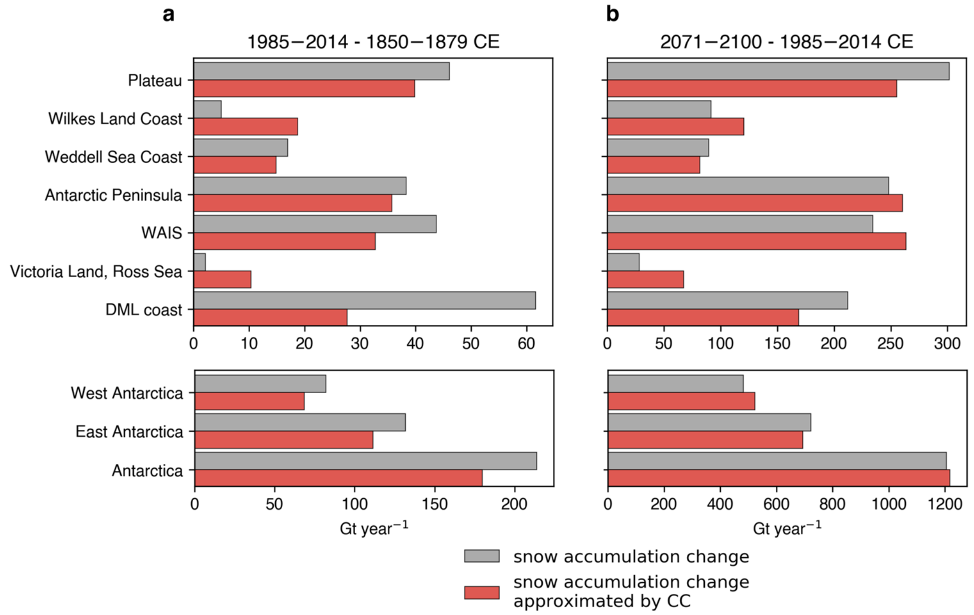

Fig. 3 Snow accumulation changes approximated by the Clausius-Clapeyron relation. Regional snow accumulation changes (gray) with their estimations by the Clausius-Clapeyron approximation (red) for the CESM2 simulations between the 1985–2014 CE and 1850–1879 CE periods (**a**) and between the 2071–2100 CE and 1985–2014 CE periods (**b;** in Gt year^{-1}). Regional boundaries are as in Fig. 1. Note that for readability, limits of the x-axis are different for the two plots.

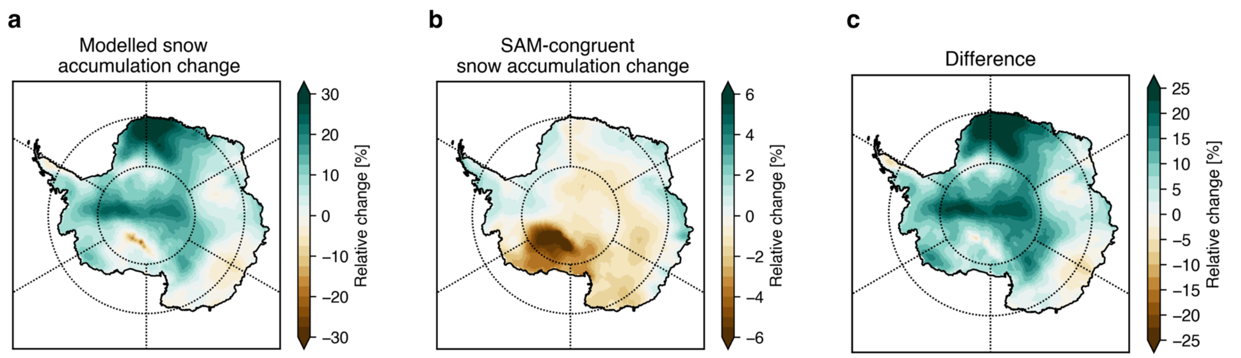

Fig. 4 Snow accumulation changes and their relationship with the Southern Annular Mode (SAM). a Relative snow accumulation changes in the CESM2 simulation between the 1985–2014 CE and 1850–1879 CE periods. **b** relative SAM-congruent snow accumulation changes in the CESM2 simulation between the 1985–2014 CE and 1850–1879 CE periods. **c** The difference between **a** and **b**.

and 1850–1879 CE periods (+0.32 standard deviation of the SAM index in the model) induces a contraction and poleward shift of the Westerlies over the Southern Ocean, which leads to less snowfall around the Ross Ice Shelf and more over the Peninsula[31]. Comparing the modeled snow accumulation changes with the SAM-congruent changes over the 1985–2014 CE period, we notice that the strongest regional impact of the SAM is observed for Victoria Land (Fig. 4; −2.31 Gt year^{-1} against 1.45 Gt year^{-1} for the modeled change; see Methods section for more details). When integrating the SAM-congruent AIS-wide snow accumulation change over the 1985–2014 CE period relative to the 1850–1879 CE period, the SAM has only caused a 6 Gt year^{-1} total AIS snow accumulation decrease (equivalent to less than 3%). This implies that the SAM is not the driver of the AIS-wide snow accumulation increase over the recent decades in the simulations analyzed here, in agreement with other studies[4,32]. Additionally, the Antarctic climate is also influenced by tropical large-scale modes of variability[33]. In this regard, the Interdecadal Pacific Oscillation (IPO) displays a negative trend over the last decades and may partially explain the recent Antarctic snow accumulation increase[34]. However, similar to the SAM, the IPO only contributes to 4% of the Antarctic snow accumulation increase over the 1985–2014 CE period according to CESM2 (see Supplementary Methods).

Along with the SAM and IPO variations, stratospheric ozone depletion over the last decades might have played a role in the snow accumulation changes at both regional and continental scales[35]. In addition to constituting one of the likely drivers of the SAM increase over the last decades[36], based on sensitivity experiments, the ozone depletion accounts for 31 ± 19% of the AIS snow accumulation increase over the 1986–2005 CE period in model simulations (see Supplementary Methods and ref. [35]). As ozone depletion leads to increased snow accumulation without a near-surface air temperature increase (Supplementary Fig. 5b),

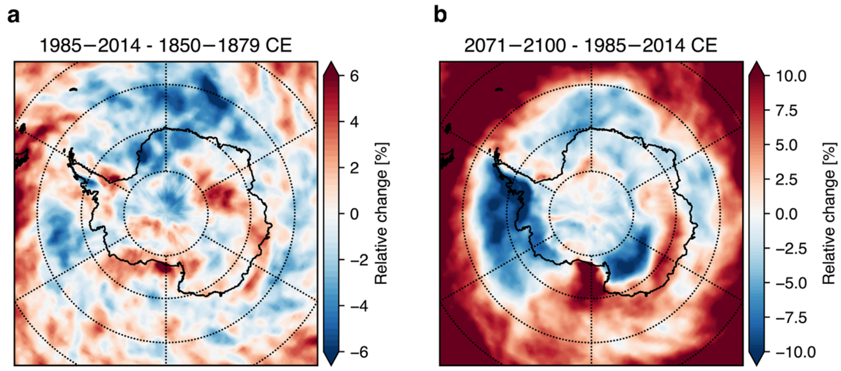

Fig. 5 Changes in the contributions of extreme precipitations events. Relative differences in the contribution of extreme precipitation events (EPEs) to the total precipitation in CESM2 between the 1985–2014 CE and 1850–1879 CE periods (**a**), and between the 2071–2100 CE and 1985–2014 CE periods (**b**). Here, EPEs follow the definition of ref. [20]: they correspond to the events for which the total daily precipitation is higher than the 90th percentile of the entire time series. The computation of the contribution of EPEs is done by calculating the 90th percentiles for each of the three periods (i.e., 1850–1879 CE, 1985–2014 CE and 2071–2100 CE periods) and used to determine the contribution of the EPEs to the total precipitation. See Supplementary Fig. 6 for the same diagnostic using the 95th percentile as threshold.

its contribution is considered here as a dynamic input. Since the CC approximation explains 58% of the AIS snow accumulation increase over the 1985–2005 CE period, the total AIS snow accumulation change is predominantly explained by thermodynamic processes, and, to a lesser degree, by dynamic processes, likely largely driven by stratospheric ozone depletion.

In addition to the thermodynamic effect and impact of large-scale atmospheric variations, other mechanisms might explain why the synoptic-scale events lead to more Antarctic snow accumulation over the past decades and in the future. In particular, changes in the intensity or frequency of cyclones that bring snowfall to the AIS coastal areas could have contributed to this snow accumulation increase. In order to characterize the cyclone activity associated with high-precipitation events, we calculate the difference in contribution of the extreme precipitations events (EPEs, ref. [20]) to total snowfall between the 1985–2014 CE and 1850–1879 CE periods. We assume that if this contribution has not changed between the two periods, the frequency or/and relative intensity of the cyclones is unchanged as well. In such a case, only an air temperature change can explain a snow accumulation increase from these synoptic-scale events. In many regions, the EPE contribution has changed between the two periods (Fig. 5a). On the continental scale, however, the EPE contribution to AIS precipitation has not significantly changed between the two periods (57.2% and 57.3%, respectively for the 1985–2014 CE and 1850–1879 CE periods). Similar results are obtained for future changes (Fig. 5b) with a contribution of EPEs slightly lower for the 2071–2100 CE period (55.8%; statistically significant). Consequently, as their relative influence of EPEs is nearly unchanged, the Antarctic-wide snow accumulation increase linked to the synoptic-scale events is likely related to a thermodynamic effect.

Discussion

Although CESM2 is an Earth System Model (ESM) from the latest generation (i.e., the Climate Model Intercomparison Project Phase 6, CMIP6) and displays a good performance at simulating the Antarctic Climate (see ref. [7] for the evaluation of the previous version of the model and Supplementary Methods), a comparison of the results derived from the CESM2 with the ones from other climate models allows for more robust conclusions. For this, two CMIP5 models, among the ones that simulate best the atmospheric dynamics above the Antarctic (ACCESS1-3 and NorESM1-M)[37], and the large ensemble of CESM1 (CESM1-LE) are analyzed (see their evaluations in Supplementary Methods). Under present-day conditions, as for ERA-Interim and CESM2, all these models show that the synoptic-scale transport is the main contributor to the mean of the snow accumulation at the continental scale (100% on average) while the contribution of the large-scale transport to Antarctic snow accumulation on average is close to zero (Supplementary Figs. 7–9). When analyzing the interannual variability of the snow accumulation, the large-scale transport plays a large role since it explains on average 49% over all regions except the Plateau. Additionally, the three models show a negative contribution (−2%) of the SAM to the Antarctic snow accumulation increase over the last decades. This confirms that the SAM is not responsible for the observed increase at the continental scale even though it contributes to regional changes, in particular over the Peninsula with a contribution of 51% on average for the three models (Supplementary Figs. 10–12). For the snow accumulation changes expected for the end of the century, the absolute AIS-integrated snow accumulation increase is different between all the models but, all indicate that the synoptic-transport remains the main driver of the snow accumulation increase for Antarctica as a whole (104%; Supplementary Figs. 13–15). The large-scale transport explains some snow accumulation increase such the Antarctic Peninsula with a relative contribution of 47% on average over the three models but, as highlighted by CESM2, this corresponds mainly to a snow redistribution between the regions. Finally, the additional models show that using the classical Clausius-Clapeyron relationship and the near-surface air temperature increase over the 21st century provides a good approximation of the future snow accumulation increase at the continental scale with an underestimation of 1% for the two CMIP5 models (Supplementary Figs. 16 and 17) and an overestimation of 2% for CESM1-LE (Supplementary Fig. 18). This implies that all the major conclusions derived from CESM2 results are confirmed by the analysis of outputs of several other, independent climate models.

Implication for the future AIS contribution to sea-level rise. Our study shows that the mechanisms behind AIS snow accumulation change as a function of the spatial and temporal scales. According to our results, the SAM, i.e., the main Antarctic mode of atmospheric circulation variability, plays a minor role in the AIS-wide snow accumulation changes over long periods compared to changes in short-lived synoptic-scale events. We argue that the recent and expected (i.e., for the 21st century) snow accumulation increase arise from global air warming that leads to more continental snowfall, carried by these synoptic-scale events. As a direct implication, the drivers of the observed year-to-year changes in snow accumulation cannot be directly used to infer future snow accumulation changes, and therefore predict the future contribution of the AIS to global sea-level rise.

Methods

Moisture budget calculation. The moisture budget calculation is fully described in ref. [38]. Therefore, only a short description is given here. The column-integrated moisture budget in pressure coordinates can be expressed as:

$$P - E = -\frac{1}{g\rho_w}\nabla\cdot\int_0^{p_s}\mathbf{u}\,q dp \quad (1)$$

where P stands for total precipitation, E for total evaporation, $\mathbf{u}$ for the horizontal wind, q for the specific humidity, ρ_w for the water density, g for the gravitational acceleration and p_s for the surface pressure. Over the Antarctic Ice Sheet, snow accumulation is estimated by calculating the precipitation-minus-evaporation ($P - E$)[13]. This definition of the snow accumulation does not include the runoff coming from the melt, mass change due to wind (snow deposition/erosion) and the sublimation of the snow particles induced by the drifting snow. At the continental scale, the contribution of this later term to the total Antarctic snow accumulation is about 15–20%[39,40]. In contrast, the runoff under present-day conditions represents less than 0.1% of the total Antarctic snow accumulation[40,41]. Although the melt is expected to increase in the current century with climate warming, a large part of the melt will refreeze in the firn[13], which implies this increase in the melt will not be thus necessarily converted into a runoff contribution. Consequently, the use of snow accumulation resulting from the difference between precipitation and evaporation is adequate since $P - E$ is the largest component of snow accumulation[40,41].

Considering monthly means, we can rewrite Eq. (1):

$$\overline{P} - \overline{E} = -\frac{1}{g\rho_w}\nabla\cdot\int_0^{p_s}\overline{\mathbf{u}}\overline{q}dp - \frac{1}{g\rho_w}\nabla\cdot\int_0^{p_s}\overline{\mathbf{u}'\mathbf{q}'}dp \quad (2)$$

where the first term represents the monthly mean moisture convergence and the second term represents the sub-monthly transient eddy moisture convergence. To facilitate the reading, we use "large-scale transport" when referring to the moisture convergence due to the mean atmospheric circulation and we use "synoptic-scale transport" to refer to the moisture convergence due to the transient eddies. The overbar indicates a monthly mean while the prime indicates a departure from the monthly mean (i.e., $\mathbf{u}' = \mathbf{u} - \overline{\mathbf{u}}$). The change in large-scale transport (the first term of the right hand side of Eq. (2)) between two periods p2 and p1 can be further separated into humidity- and circulation-induced change components as follows:

$$\delta\left(\frac{1}{g\rho_w}\nabla\cdot\int_0^{p_s}\overline{\mathbf{u}}\,\overline{q}\,dp\right)_{p2-p1} \simeq \frac{1}{g\rho_w}\overline{\nabla\cdot\int_0^{p_s}\overline{\boldsymbol{\delta}\mathbf{u}_{p2-p1}}\,\overline{q_{p1}}dp} + \frac{1}{g\rho_w}\overline{\nabla\cdot\int_0^{p_s}\overline{\mathbf{u}_{p1}}\delta\overline{q_{p2-p1}}dp} = \delta\overline{\mathrm{DYN}} + \delta\overline{\mathrm{TH}} \quad (3)$$

where $\delta\overline{\mathbf{u}_{p2-p1}} = \overline{\mathbf{u}_{p2}} - \overline{\mathbf{u}_{p1}}$ and $\delta\overline{q_{p2-p1}} = \overline{q_{p2}} - \overline{q_{p1}}$ represent the changes in horizontal wind and humidity, respectively, between the periods p2 and p1. This breakdown allows us to gain insight into the origin of the changes in $P - E$. However, the part of the $P - E$ change resulting from a change in specific humidity combined to a change in winds (given by $\nabla\cdot\int_0^{p_s}\overline{\boldsymbol{\delta}\mathbf{u}_{p2-p1}\delta q_{p2-p1}}dp$), the so-called quadratic term is neglected in Eq. (3). See Supplementary Methods for the evaluation of the moisture budget calculation.

Atmospheric reanalysis and climate model simulations. We have selected the ERA-Interim reanalysis from the ECMWF[42] as input for the moisture budget calculation over the last decades (1985–2014 CE period). ERA-Interim, which has a spatial resolution of 0.75°[42], is considered as one of the best reanalysis products in reproducing the present-day Antarctic climate and, more specifically in the present framework, to analyze Antarctic snow accumulation[23,24,43]. Nonetheless, ERA-Interim suffers from some biases, such as a large underestimation of the snow accumulation over the Antarctic Plateau where the snow accumulation values are lower than 10 mm;w.e. eq. year^{-1} [23,24]. Biases in ERA-Interim mainly come from the weak observational network and because of processes that are not included in ERA-Interim such as drifting snow and diamond dust[23,24], which are the main contributors to the mass gain over the dry Antarctic Plateau[44]. We also use the ERA-Interim results to assess the climate models' simulated moisture budgets. Since ERA-Interim displays a strong dry bias over the Antarctic Plateau, the model evaluation based on ERA-Interim has to be taken with caution for this region.

For the historical period (1850–2014 CE period) and for the end of the 21st century, we calculate the moisture budget from simulations performed by the National Centre For Atmospheric Research (NCAR) with the Community Earth System Model (CESM). CESM is a fully coupled global climate model simulating the interactions between the atmosphere, ocean and land at a horizontal spatial resolution of approximately 1°. Numerous studies have shown the good performance of CESM in simulating the Antarctic climate[7,12,35,37]. In particular, CESM1 provides a reasonable representation of the climatology and interannual variability of the Antarctic snow accumulation when comparing to observations and regional climate models[7,12]. Albeit the evaluation of the latest version of CESM (CESM2.1, hereafter CESM2) is as detailed for CESM1, this new version seems to simulate more accurately the Antarctic climate[26]. First, we calculate the moisture budget using this latest version of CESM (i.e., CESM2) that participates in the Coupled Model Intercomparison Project (CMIP) phase 6 (CMIP6). We analyze the historical simulation (1850–2014 CE period) and the future projection simulation (2015–2100 CE period) under the Societal Development Pathway (SSP) 5-85 (hereafter SSP5-85; high energy imbalance), which is at the upper end of available scenarios and is the nearest equivalent to the RCP8.5 applied in CMIP phase 5 (CMIP5)). We use 6-hourly data on atmospheric model levels (33 atmospheric levels expressed in hybrid coordinates) for the computation of the moisture budget[38]. Unfortunately, data at this temporal and spatial resolution is only available for one simulation. In addition to the CESM2 simulation, we also calculate the moisture budget using the Large Ensemble (LE) of the CESM version 1 (CESM1-CAM5; hereafter CESM1-LE) spanning 1920–2100 CE[45]. After 2005 CE, the representative concentration pathway 8.5 (RCP8.5) is used as a forcing in CESM1-LE. This large ensemble, which includes 35 members, allows us to quantify the role played by the internal variability on the moisture budget, something that cannot be done with the other CMIP5 models or with CESM2. The high temporal resolution requirements are only met for the 1990–2005 CE, 2031–2040 CE, and 2071–2080 CE periods, but for all CESM1-LE members.

In addition to the CESM simulations, we also use two other climate models from the CMIP5 database to support our results (Supplementary Figs. 7–18). Among all the climate models which can provide the required data for the moisture budget available for the historical and future (under the RCP8.5 scenario) simulations, the selection of the CMIP5 models is based on data availability and a model evaluation[37] which ranked CMIP5 models in the aim of using them for regional climate modeling over the Antarctic Ice Sheet. We selected the models that are the best ranked in the evaluation of the ref. [40]. This evaluation is adequate in the present framework as it analyses the performance of models in representing the atmospheric mechanisms behind snow accumulation changes, although it does assess model behavior in simulating Antarctic climate itself. Therefore, according to this evaluation, we selected ACCESS1-3 and NorESM1-M. However, given that the CMIP5 model simulations are only available from 1950 CE, we mainly use CESM2 to describe the mechanisms involved in the snow accumulation.

Clausius-Clapeyron approximation. To determine to what extent the near-surface air temperature change can explain the $P - E$ change, we estimate the snow accumulation changes that can be related to a change in near-surface air temperature—the so-called Clausius-Clapeyron (hereafter CC) approximation as in ref. [46]:

$$\delta\left[(P - E)_{CC}\right]_{p2-p1} = \alpha\delta T_{p2-p1}(P - E)_{p1} \quad (4)$$

where T is the near-surface air temperature and α is the sensitivity of the saturation vapor pressure to temperature ($dlne_s dT^{-1}$), equal to 0.07 K^{-1} for typical temperatures in the lower troposphere[9,46]. This means that for each degree of warming, the saturation vapor pressure is 7% higher. This value is consistent with the snow accumulation sensitivity to air temperature found in multi-GCM-based estimations of 6.1 ± 2.6% K^{-1} for Antarctica[9].

SAM-congruent change. To establish the SAM-congruent snow accumulation changes, we first need to calculate the SAM index. It is defined as the annual mean of the normalized zonal-average of the difference between 40°S and 65°S geopotential heights at 500 hPa[47]. Then, we compute the snow accumulation sensitivity to deviations in the SAM index by performing a linear regression between the two variables for each grid cell after removing linear trends over the 1850–2014 period for CESM2 and over the 1920–2005 period for CESM1. We then multiply the snow accumulation sensitivities obtained from this regression (in mm w.e. eq. year^{-1}) by the change in the SAM index between the two time periods (or between the evolving and fixed ozone member ensembles for the ozone case) to obtain the SAM-congruent snow accumulation changes between those two periods. The methodology applied here is identical as in ref. [4]

Antarctic regions. The Antarctic continent is divided into seven regions, which are further grouped into two bigger regions: East Antarctica and West Antarctica, as defined in ref. [17]. The five regions that form East Antarctica are: the Plateau where the altitude is higher than 2000 m and four coastal regions, namely Wilkes Land Coast (70–150°E), Weddell Sea Coast (60–15°W), Victoria Land and Ross Sea (150–170°E), and Dronning Maud Land (DML) Coast (15°W–70°E). West Antarctica is split into two regions with a division at 88°W: the West Antarctic Ice Sheet (WAIS) and the Antarctic Peninsula.

Data availability

The ECMWF ERA-Interim reanalysis can be freely downloaded from the website (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim). The CMIP5 (ACCESS1-3 and NorESM1-M) and CMIP6 (CESM2) model outputs can be obtained at the esgf website (https://esgf-node.llnl.gov), while the large ensemble of CESM1 (CESM1-LE) is distributed via the Earth System Grid Federation (https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.CESM_CAM5_BGC_LE.html).

Code availability

The python (version 3.6) scripts used for producing the figures can be made available upon request to the corresponding author.

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Author contributions

Q.D. and H.G. designed the study. Q.D. performed the analysis and made the figures. J.T.M.L. provided CESM outputs. N.H. provided the source code for the moisture budget calculation. H.G., J.T.M.L., and M.G.P.C. provided enriching content discussion and Q.D. wrote the manuscript with the contributions of all authors.

Competing interests

The authors declare no competing interests. Jan Lenaerts is an Editorial Board Member for *Communications Earth & Environment*, but was not involved in the editorial review of, or the decision to publish this article.

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