Response the Editor regarding the submitted paper *Reconciling the surface temperature–surface mass balance relationship in models and ice cores in Antarctica over the last two centuries*

We thank the Editor for their positive comments and constructive suggestions. We have responded to all Editor and reviewer comments, and have modified the paper accordingly. And we would like to thank the Editor and the two anonymous reviewers for their helpful and constructive comments which have strongly improved the quality of this manuscript. Our point-by-point answers follow, as well as the marked up manuscript and supplement.

Response to RC1 comments on the submitted paper *Reconciling the surface temperature–surface mass balance relationship in models and ice cores in Antarctica over the last two centuries*

We thank the reviewer for their constructive comments. We have responded to all of them and have modified the paper accordingly. Our point-by-point answers follow.

Please note that review comments are in grey italics while our answers are not. Changes/additions to the original manuscript are indicated in blue.

Answers to RC1

In this article, Cavitte and co-authors analyse the link between surface mass balance (SMB) and surface air temperature (SAT) over the Antarctic ice sheet, at annual resolution. They focus on the last 200 years (1871–2000).
They use a series of climate model simulations: four global climate models including water stable isotopes (iGCMs) and a regional climate model (RCM) without isotopes. They also use observation-based results : the temperature reconstruction of Nicolas and Bromwich, 2014 (NB14) and ice-core annual to 5-year-mean $\delta^{18}O$ (Stenni et al., 2017) and SMB (Thomas et al., 2017).
SAT is supposed to be recorded by the $\delta^{18}O$ signal of ice cores. But $\delta^{18}O$ and SAT are generally correlated with SMB, as they both result of large scale advection of warm and moist air from lower latitudes. The aim of the authors is to understand how much SMB and SAT are correlated based on climate simulations and ice core records, and what can explain the strength of correlations at the regional and local scale. They also want to understand what is lacking in our current understanding to explain the observed lower correlation of $\delta^{18}O$-SMB in ice cores than SAT-SMB in models.
It is a very interesting study that I recommend for publication in The Cryosphere.
However, I pointed out major issues that need to be answered before publication.

Major (method)
This is a minor remark, but important for improving the readability of the article. In the article, the main assumption is that $\delta^{18}O$ is a proxy of SAT. However, you show 'SMB-SAT' and '$\delta^{18}O$-SMB' correlations. I suggest to write it the same order for both, e.g. 'SMB-SAT' and 'SMB-$\delta^{18}O$', even if it has no effect on correlations.
Answer: This has been changed everywhere in the manuscript.

iGCM members averaging
P5L121 *'we average over their ensemble of simulations to obtain a mean representation of SMB, SAT and 18O for each iGCM.' I think this might be a major issue, as when averaging each variable across different simulation, the interannual variability is dampened. The correlation of average is not the average of correlations. It might not change dramatically your results but it should be corrected.*
Answer: We are sorry that the wording of this sentence was confusing. What we did was: (1) we calculated the correlation of the two variables (SMB-SAT or SMB-δ^{18}O) for every grid point for each model member (3 members for iCESM1 and 7 members for iHadCM3). (2) We calculated the mean of the correlation values obtained per grid point over all the model members that belong to iCESM1 or iHadCM3 to get the mean SMB-SAT and SMB-δ^{18}O correlation for each model. (3) We interpolated then all four iGCM correlation results (ensemble means for iCESM1 and iHadCM3, ECHAM5-MPI/OM and ECHAM5-wiso correlation results) onto the RACMO27 grid, for both the SMB-SAT annual correlations and the SMB-δ^{18}O 5-yearly correlations. (4) We then calculated the mean over all four iGCMs to get the resulting iGCM plots shown in Fig.1. The sentence has now been changed to: "For the iCESM1 and iHadCM3 GCMs ensembles that include three and seven simulations, respectively (each has slightly different initial conditions), we first calculate the correlation of the two variables (SMB-SAT or SMB-δ^{18}O) for every grid point for each ensemble member (3 for iCESM1 and 7 for iHadCM3). Then we obtain the mean of the correlation values per grid point over each ensemble of simulations for both iCESM1 or iHadCM3. These ensemble means can then be compared to the correlations calculated for ECHAM5-MPI/OM and ECHAM5-wiso."

iGCMs evaluation

P5L123 'Dalaiden et al. (2019) provide an evaluation of the iGCMs used here'. Model evaluation is too weak. You should show in supplementary key evaluations for the 4 models.
You should add all Dalaiden et al. 2019's evaluations related to the 3 iGCMs you use in your article, and add evaluation of iCESM1, that is not provided in Dalaiden et al. 2019.
As SMB-SAT relationship is driven by atmospheric circulation, it would be good to see how large-scale circulation of these models compare with reanalyses for the satellite era. Showing at least an evaluation of sea level pressure patterns on average for the common period is needed to understand how large the models' biases can be.
Answer: As suggested, we now provide an evaluation of the SMB, SAT and SLP (Sea-Level Pressure) for the 4 iGCMs, described at length in supplement S2. SMB and SAT are evaluated against RACMO27, while SLP is evaluated against ERA-Interim as its grid does extends further north. The evaluation is done over the 1979–2000 AD time period, the longest period of overlap for all the models examined. In addition to the evaluation in S2, we add the following short paragraph page 5 of the manuscript after the description of the models: "Dalaiden et al. (2020) provide an evaluation of first three iGCMs used, and we provide an evaluation of the SMB, SAT and the atmospheric circulation (we use sea-level pressure) for all four iGCMs in Supplement S2. SMB and SAT are evaluated against RACMO27, while sea-level pressure is evaluated against ERA-Interim as the ERA-Interim grid extends further north. The evaluation is done over the 1979–2000 AD time period, the longest period of overlap for all the models examined. We show that all four models produce realistic SMB, SAT and sea-level pressure outputs, with biases likely linked to differences in their physics as well as their spatial resolutions (supplement S2)."
Note that the Dalaiden et al. (2019) The Cryosphere Discussions paper has now been published in The Cryosphere and all references have been changed to Dalaiden et al. (2020), here and in the manuscript.

Model selection and averaging
P5L122 *'all four iGCMs show similar spatial variations of the correlation between SMB-SAT and δ^{18}O-SMB on the continent scale [...] To compare the iGCM continent-wide correlations to the RCM-derived correlations, we interpolate the iGCM results onto the RCM grid and average over all four iGCMs.' From Fig. S1 we can see that ECHAM5-MIP-OM gives significantly different results than the other 3 iGCMS at the ice sheet margins for δ^{18}O-SMB. From Dalaiden et al. 2019 Fig. S7 and S8, we can see that ECHAM5/MPI-OM have a major issue for modelling SMB. It is of major importance for this article, because as you average the 4 isotopic global climate models (iGCMs) correlations into one single map of correlation, it suppose that you consider equal skills of the 4 models. Consequently, you should consider disregarding ECHAM5-MIP-OM simulations, or at least giving it less weight in the average.*
Answer: We agree that ECHAM5-MPI/OM differs from the other 3 iGCMs in representing SMB, based on Dalaiden et al. (2020) Fig. S7 and S8 and our new supplementary material S2. Nevertheless, selecting a criteria to keep or remove a model from our analyses may be difficult to justify objectively as all models have strengths and weaknesses. We propose to keep all 4 iGCMs in this study, but we have moved figures S1 and S3 (that display the SMB-SAT and SMB-δ^{18}O correlations over the 1871–2000 AD time interval) to the main manuscript. We now discuss the similarities and differences between the models more explicitly in the manuscript Section 3.1.1 (P7-8) and in the supplement S2. We show in supplement S2 that although differences are clearly visible for ECHAM5-MPI/OM in terms of SMB representation, its SAT and SLP fields do not seem to differ much more than the other models' compared to the reference models (RACMO27 and ERA-Interim).

Major (results and interpretation)
Consistencies between models and time scales
P6L183 *'Moreover, the maximum and minimum correlations obtained are consistent between iGCMs, in*

magnitude and spatial distribution (see supplementary Fig.S1-S4).'
Can you develop the area you think are consistent? Because I see more differences that analogy between the 4 models. ECHAM5-MPI-OM is the only iGCM with a clear loss of correlation at the ice sheet margins in East Antarctica (for both SAT and $\delta^{18}O$). If you exclude ECHAM5-MPI-OM, I see some consistencies between the 3 models left, but still, it's not very clear given the patchy patterns.
Answer: We have now expanded the description of the similarities and differences in this paragraph by defining several regions (specific boxes) over the continent where we observe consistently positive and negative correlations. These areas are shown on Fig. 1 and 2 and include: central West Antarctica, the eastern Antarctic Peninsula, the Plateau, the Amery Embayment and Adélie Land. For each of these five regions, we calculate the average correlation and percentage of significant grid cells for each iGCM and now compare the iGCM correlation results quantitatively in our description. We have modified section 3.1.1 as: "We calculate the annual correlation between SMB and SAT at the regional scale over 1871–2000 AD, the time interval shared by all iGCMs. We obtain a positive annual relationship between SMB and SAT at the regional scale with a continent-wide average value of 0.57 and a spatial standard deviation of ±0.10 (hereafter referred to as ±0.10) over the four iGCMs (the individual iGCMs continent averages range from 0.54-0.60) with a p-value $< p_{FDR}$ for more than 96% of each iGCM's surface area (Fig. 1), and > 99% on average. We note some spatial differences between models, in particular we focus on five distinct regions of the ice sheet: (1) the AP (also "AP" on Fig. 1) shows weak correlations for iCESM1 and ECHAM5-wiso (0.22-0.24, 57-76% significant grid cells) and positive correlations for ECHAM/MPI-OM and iHadCM3 (0.51-0.60, 100% significant), (2) central West Antarctica ("CWA") which shows the same contrast between iCESM1 and ECHAM5-wiso versus ECHAM/MPI-OM and iHadCM3 (0.31-0.48, 78-91% significant versus 0.63 and 100% significant), (3) the East Antarctic Plateau ("EAP") which shows positive and 100 % significant correlations (0.58-0.70); the Amery Embayment ("AE") and Adelie Land ("AL") which show positive correlations (0.49-0.57 and 0.49-0.69, 100% significant). Areas of weaker SMB-SAT correlations are only observed in iCESM1 and ECHAM5-wiso, which could arise from the models' finer spatial resolution compared to iHadCM3 and ECHAM5-MPI/OM. The SMB-SAT correlation remains positive overall for all models. We obtain the same result if we take non-overlapping 5-year averages of the SMB and SAT variables to calculate their 5-yearly correlation (supplementary Fig. S5)."

P7L190 *'This implies that the correlation of SMB and SAT is similar over the 1871–2000 AD and the 1979–2016 AD time intervals, and from a spatial resolution of >1 down to 5.5 km.' Please clarify what you think is similar between the resolutions and the time periods. I see many differences, so if you want to highlight the consistencies, you should detail them (e.g. high correlations for West AIS?).* ***Generally, I am concerned about the too optimistic way of presenting consistencies between simulations.***
Answer: We agree that we were too vague in our description and now describe the similarities and dissimilarities in more details in that paragraph, the same way that we have done it for the iGCMs (see comment above). We use the same 5 Antarctic regions, shown on the corresponding figure (now Fig. 1, panel f) to quantify the average correlation and the percentage of significant grid cells per region. Section 3.1.1. L224-236 has now been changed to: "We repeat the annual correlation of SAT and SMB using the RACMO27 simulations over 1979–2016 AD (Fig. 1, panel f). At this spatial scale, the annual correlation is also positive in the large majority of the ice sheet with a similar range of correlation values and a continent-wide average value of 0.54±0.22, which is within the range of the iGCM average (0.57±0.10). For the same five distinct regions, we can see that the EAP and AL are also positive and 100% significant. For AP and CWA that had a lower correlation for iCESM1 and ECHAM5-wiso, we see a stronger weakening down to 0.27 with a lower percentage of significant grid cells (48%). The AE area is most distinct with a correlation average of 0.22 and ∼30% significant grid cells. The much higher spa-

tial resolution of RACMO27 with respect to the iGCMs is likely behind these differences and the higher percentage of areas with a weaker correlation value, if we compare to what we observed for the iGCMs."

Wind effect

P7L196 *'There are a few areas, spatially consistent between the RACMO27, RACMO5 simulations and the iGCMs, where the SMB-SAT correlation is not as strong.' Again, I am not sure to agree with the authors. If you look at SMB-SAT correlation on Fig.S4 compared to Fig.2, it is not clear that there is a loss of correlation in the iGCMs at the "same areas" than in the RCM. It seems that combining the 4 iGCMs gives by chance the same pattern as in RACMO2?*

Answer: We expect that the SMB-SAT correlations won't be identical. We agree with the reviewer that we were too general and optimistic in our description. In light of having changed Figs. 1 and 2 to show the individual iGCM correlation results (see a few comments above), and having defined the 5 regions of fous, we now discuss the similarities and differences in light of these regions specifically between the iGCMs and RACMO2.3 (see comment above). Also, we stress that the increased percentage of non-significant grid cells is likely linked to the finer spatial resolution of RACMO27 with respect to the iGCMs. This is already seen in the different SMB-SAT correlation patterns of iCESM1 and ECHAM5-wiso versus iHadCM3 and ECHAM5-MPI/OM, iCESM1 and ECHAM5-wiso having finest spatial resolution of the iGCMs used here. We have added at the end of the paragraph (P8 L230-232): "The much higher spatial resolution of RACMO27 with respect to the iGCMs is likely behind these differences and the higher percentage of areas with a weaker correlation value, if we compare to what we observed for the iGCMs."

P7L204 *(1) 'Large-scale air masses, originating over the Southern Ocean and further north, bring warm moist air towards the interior as they flow up-slope, thus inducing a strong and negative correlation': You suggest that at the interannual time scale, when you have upslope winds (so more negative) you have higher temperature and SMB, and the more positive is mean slope in mean wind direction (MSWD) the colder and the dryer. It seems reasonable, but it would be really good to explicit this, because I had trouble trying understanding the positive/negative correlations with wind.*

(2) Can you show time series of MSWD together with time series of SAT and SMB at some specific locations, so that we can understand what the correlation means? E.g. at locations where it's significantly positively/negatively correlated to SAT/SMB, and on the coast/on the plateau, or at least examples for your cases (1) and (2), and for Adelie Land vs. Amery Embayment.

(3) In addition, I am wondering how much annual MSWD is a good indicator of the mechanism you want to highlight. Advection of warm and moist air by cyclones are punctual whereas surface winds generally flow downslope all year long. Consequently I am not sure how much you capture the cyclone activity with MSWD.

(4) You discuss this with cases (1) and (2), but it seems very speculative. Basing your statement on time series will help developing more robust analyses. I was lost reading the wind considerations, but after re-reading it a couple of times, I think I agree with most of your conclusions. It would be better to re-write this part before I can give a better feedback. ***I do think it is very interesting to analyse the strong correlations between MSWD, SMB and SAT at the interannual time scale.*** *You should use the different components of SMB available in RACMO to analyse the effect of wind on this components (precipitation, drifting snow fluxes, sublimation, etc.), instead of trying to guess why it works this way.*

Answer: Point #1 - We agree that the sign of the positive/negative correlations is perhaps unclear, we have now added a sketch (now Fig. 4 in the manuscript) to help with the sign of MSWD with respect to slope and wind direction, for the different scenarios that we describe (synoptic air masses and katabatic wind interactions). The following sentence is also added just below the description of Eq (1) for clarity: ”Since we define a positive MSWD as a wind pointing down-slope, we expect winds coming from the coast up into the interior to have a negative MSWD, and winds flowing from the interior to the coast to have a positive MSWD (Fig. 4, and supplementary Fig. S8).” and (P9-10 L272-279): ”Large-scale air masses, originating over the Southern Ocean and further north, bring warm moist air towards the interior as they flow up-slope. At the annual time scale, these up-slope winds (negative MSWD) will therefore bring a higher temperature and SMB (positive anomaly), and thus induce a strong and negative annual MSWD-SAT and MSWD-SMB correlation (Fig. 4, scenario 1a). Similarly, winds flowing down-slope (positive MSWD) will bring drier and colder air (negative anomaly) from the interior to the coast, and will also induce a strong and negative annual correlation of MSWD with SAT and SMB (Fig. 4, scenario 2a). Any area of the AIS that does not show this negative annual correlation between wind and SAT or SMB implies that the changes cannot be interpreted simply in terms of large-scale circulation at the annual scale or descending cold air from the interior (so in that case, scenarios 1b and 2b).”

Point #2 - We have plotted time series of MSWD with time series of SAT and SMB (Fig. 1 at the end of this document). We have chosen, as asked, four locations where MSWD is significantly positively or negatively correlated to SAT/SMB. We show one location on the Amery Embayment (first row of Fig. 1) and one on the eastern side of the Antarctic Peninsula (2nd row of Fig. 1) where MSWD and SAT/SMB are positively/weakly correlated. We show one location in the middle of the plateau region and one in Adélie land where the MSWD-SMB/SAT correlation is strong and negative (third and last rows of Fig. 1). The black cross on the inset maps show the exact position of the location chosen. These plots clearly show that for the negative MSWD-SAT/SMB correlations described in Figs. 5 and 6 of the manuscript (case of Adélie Land and the Plateau), MSWD and SAT/SMB are out of phase. While for the locations where MSWD-SAT is positive and MSWD-SMB is weak, MSWD are clearly in phase with SAT and almost in phase with SMB (case of the Antarctic Peninsula and Amery Embayment locations). However, we do not find that these curves add much information to the information already present in the correlation figures (Figs. 5 and 6 of the manuscript) and so do not include them in our revised submission.

Point #3 - The hypothesis in this paper is that, even if cyclone activity is punctual, by correlating MSWD to SMB/SAT over 1979–2016 AD, we will be capturing the variations of cyclonic activity at interannual timescales, i.e. the variability in the path or intensity of cyclones, and therefore the variability in the sources of heat and moisture. It would be interesting to compare to the SMB and MSWD at the daily timescale, to look at individual cyclonic events more reliably. However, at present, daily RACMO2.3p2 simulations are not freely available, and in any case this could not be done for the ice core records. We have added a short sentence to this effect in the manuscript in this paragraph: ”We are aware that such cyclonic activity is punctual in time. However, by correlating MSWD to SMB and SAT over 1979–2016 AD, we make the hypothesis that we capture the first order variations of cyclonic activity at interannual timescales, and therefore the variability in the sources of heat and moisture.”

Point #4 - Although not shown, we had looked at the influence of the various SMB components on the total SMB and observed that SMB variability is strongly dominated by precipitation at the annual timescale. Correlating SMB with its precipitation component over 1979–2016 AD gives an average correlation over the whole continent of 0.96. We have now calculated the correlation of MSWD with the various components of SMB (sublimation, snowdrift, snowfall, snowmelt and snowdrift sublimation), however there is no one to one relationship with any of these components. The global effects of the wind are not clear at the annual timescale. It would certainly be insightful to look at their influence at the daily timescale, however, the focus of this study is the annual timescale as we want to be able to compare results with ice core data. We include the results of these correlations at the end of this document (Fig. 2). Note that for the correlation of MSWD and snowmelt, the p_{FDR} value used implies that none of the map is significant (the Bonferroni threshold has to be used for this correlation, Wilkes et al. (2016)).

Related minor comments:
Eq. (1) *You must remove the arrow on MSWD as it is a scalar.*
Answer: It has been removed.

Fig.S9 *Can you show MSWD too? To see where it's negative and positive?*
Answer: Yes, it has been added as Fig. S8.

P7L215 *'We then remove areas of the AIS with a negligible slope (0.001) as in these areas, MSWD will be close to null and will introduce a lot of noise when correlating it with SMB or SAT.': Shouldn't you remove areas where SMB interannual variability and MSWD interannual variability are small too? I would suspect that all the high (negative) correlation for MSWD-SAT and MSWD-SMB found in the EAIS plateau are because of very small interannual variability in wind and SMB(?).*
Answer: We argue that areas with a small SMB and MSWD interannual variability are also interesting to look at. We only remove areas that have a negligible slope because correlating such a small number with SMB or SAT could introduce a lot of noise. The results are not radically different with and without the threshold applied on the slope (see Fig. 3). It reduces the average continent-wide correlation strength and increases the number of grid cells with p > p_{FDR}, but not significantly. We therefore choose to keep the threshold.

P8L223 *'Agosta et al. (2019) also show a strong link between modelled surface topography (surface curvature in their case) with SMB over the continent when wind speeds exceed 5 m s-1.': but in Agosta et al. 2019, it is a spatial link of time-averaged values, not a temporal link.*
Answer: We agree that Agosta et al (2019) clearly look at the spatial link of time-averaged values while we look at the temporal link. We have removed this citation P8 but still cite it later, in our discussion of MSWD and SMB page 11: "Other studies have shown the strong interactions between surface surface topography and winds. For instance, Agosta et al. (2019) examine the spatial link of time-averaged values of surface curvature and surface winds and they observe that above a certain threshold, winds will affect SMB locally in pattern that matches that of drifting snow fluxes as modeled by RACMO2.3.". We now also cite the work of Dattler et al. (2019) in our introduction (page 3) who show that, in their study area, the variability in accumulation is correlated with MSWD variability also. And have added a sentence to that effect page 12 L353-355: "Dattler et al. (2019) also show that, at length scales < 25 km, regions of the West Antarctic Ice Sheet show high spatial variability in accumulation simultaneously to high variability in wind speed and direction."

P8L264 *'We therefore expect that the areas regularly under the influence of strong katabatic winds will show a weaker MSWD-SMB correlation due to the episodic but persistent reduction in their SMB through wind scouring'. Here is one out of many examples where you can use RACMO outputs to verify your hypothesis, since you have access to all surface mass balance fluxes, including drifting snow fluxes, in this model.*
Answer: See response to a previous comment. However, a little further up page 12 (in the revised version), when we discuss the Amery Embayment and Adélie Land specifically, we refer to the added supplementary Fig. S11 which shows the average sublimation and snowdrift ablation fields for the ice sheet over 1979–2016 AD.

P10L288 *'Perhaps here snowfall input from further north is so high that it dominates the SMB and SAT records.' The same: you can use RACMO outputs to clarify what's happening.*

Answer: Same comment as a little further up.

Suspicion of wrong SMB interannual variability in ice cores
Sections 3.2 and 3.3 study the SMB-SAT link in ice core data, and aims at understanding why it is much weaker in ice cores than in models.
10L307 *'We observe a weak-to-null annual correlation between SAT and SMB in the ice cores (Fig.7) with an average value of 0.09±0.18 over all the ice cores, versus a continent-wide average value of 0.57±0.10 for the iGCMs and 0.54±0.22 for RACMO27.' I am wondering whether the low correlation between ice cores SMB and NB14 SAT is because of a too low or incorrect interannual variability of SMB in ice cores. I think this analysis is very interesting, but I cannot evaluate it further if I am not sure that the difference between ice cores and models is not because of wrong SMB interannual variability in ice cores. Can you show annual time series of ice core SMB vs. RACMO SMB? The results will have a major impact for reviewing the rest of the study.*
Answer: We agree with the reviewer that it is difficult to quantify whether the low correlation between ice cores SMB-SAT is because of a too low or incorrect SMB interannual variability of SMB in the ice cores. Ice core SMB errors are difficult to constrain (measurement errors, representativity errors due to processes such as a wind ablation that removes a part of the deposited annual snowfall). In addition, missing one year in the dating of the ice cores, for example, can shift the time series, and then the correlation between ice core-derived SMB and the independent SAT time series would be lost. However, we show (Figs. 7 and 8 of the manuscript) that the correlation between SMB and δ^{18}O, both ice core-derived records, is also low. However, in that case, SMB and δ^{18}O are both measured on the same core. It suggests that the low correlation is perhaps unrelated to a bad synchronization of the SMB and SAT variables. RCMs also include errors that are difficult to trace (difficulty of representing blowing snow or diamond dust). RACMO2.3 for example includes blowing snow processes but Agosta et al. (2019) have shown that its spatial variability is under-represented and that it is underestimated by a factor of 3. When comparing RCM and ice core results, it is thus not simple to assess the origin of the differences in interannual variations. The advantage of RCMs is that they are self-consistent: the SMB and SAT values simulated are linked by the physics of the model. Ice cores on the other hand can have different biases dependent on different variables (ablation, diffusion, measurement errors, location, etc). However, RCMs can only go back as far as we have direct satellite measurements to constrain the reanalyses that drive them at their boundaries (i.e. 1979 as previous to that, measurement biases increase, e.g. Bromwich et al., 2007). We need the ice core observations to go back further in time. To state more clearly why we compare model correlations to the ice core correlations, we have added the following sentence to this effect in the introduction: "Despite these processes that render our interpretation of ice core records difficult, we need the ice core observations to go back in time to validate model reconstructions before the period when we have direct measurements.". We have also added the following in section 3.3: "When comparing model (in particular RCM) and ice core results, it is thus not simple to assess the origin of the differences in interannual variations. The advantage of RCMs is that they are self-consistent: the SMB and SAT values simulated are linked by the physics of the model. However, RCMs also include errors that are difficult to trace (difficulty of representing blowing snow or diamond dust). RACMO2.3 for example includes blowing snow processes but Agosta et al. (2019) have shown that its spatial variability is under-represented and that it is underestimated by a factor of 3. Furthermore, RCMs can only go back in time as far as we have reliable reanalyses to drive them at their boundaries (often stopping around 1979 as previous to that, measurement biases increase, Bromwich et al., 2007)). Ice cores on the other hand can have different biases dependent on different variables (ablation, diffusion, measurement errors, location, etc). However, they allow us to go back further in time than direct observations.".

Minor comments
P2L35 *'temperature' : heat*
Answer: Replaced.

P2L35 *remove 'usually'*
Answer: Removed.

P2L35-36 *'that collect heat and moisture from further north, including the Southern Ocean, which they can release onto the AIS'. It's the same idea and mechanism than described in the previous sentence: 'Large-scale atmospheric circulation strongly controls SMB in Antarctica, bringing air masses with a high moisture and temperature content'. Merge the sentences.*
Answer: The two sentences have been merged as: "Large-scale atmospheric circulation (100s of km) strongly controls SMB in Antarctica. This large-scale atmospheric circulation embeds synoptic-scale cyclones that collect heat and moisture from further north, including the Southern Ocean, which they can release onto the AIS (Gorodetskaya et al., 2014; Sodemann and Stohl, 2009; Wang et al., 2019)."

P2L43-44 *'In addition, based on the Clausius-Clapeyron relationship, the increasing surface air temperature (SAT) due to climate change should induce a greater moisture holding capacity of the air': It's the increasing of air temperature (in the mid and upper troposphere) that induces an increase in moisture holding capacity and more precipitation, not the increase in *surface* air temperature. The confusion here comes from the fact that increase in SAT and in tropospheric air temperature are strongly correlated.*
Answer: We agree and the sentence has been appropriately reworded: "In addition, based on the Clausius-Clapeyron relationship, the increasing mid and upper troposphere temperature due the warmer climate implies that the vapor pressure of the air is higher, and therefore snowfall is increased (Frieler et al., 2015; Fudge et al., 2016). If this predicted increase in SMB is linked to increasing temperatures in the 21st century, it will be interesting to see if SMB and SAT are linked in the past centuries too, since an increase in SAT and tropospheric air temperature are strongly correlated. In which case, SMB records over time will be a helpful tool to constrain past climates (Dalaiden et al., 2020)."

P2L49 *'is often used as a proxy for SAT': Is it used as a proxy of SAT or a proxy of snowfall-weighted SAT?*
Answer: We have changed this to "is often used as a proxy of snowfall-weighted SAT (and by extension of SAT, Stenni et al., (2000) [...]".

P3L84 *AP is not introduced before*
Answer: We noticed that the first instance that "Antarctic Peninsula appears is P2L42, and have therefore defined the acronym there: "Antarctic Peninsula (AP,...)"

P3L86 *'over historical timescales': give the time period and the resolution.*
Answer: We have modified the sentence as follows: "Our work follows from that of Dalaiden et al. (2020), in which they show that SMB and SAT are strongly correlated interannually at the continental scale over millennial (1000–2005 AD) and historical (1850–2005 AD) timescales"

P4L91 *'1. Which processes link SAT and SMB at regional scales and how do they scale down from conclusions at the continental scale': You don't answer to this question.*
Answer: We have reformulated the question to: "Do the processes that link SAT and SMB at the continental scale also play a dominant role at the regional scale?". The title of section 3.1 has also been

changed accordingly.

P4L98-99 *'We hypothesize physical mechanisms that could explain the discrete areas of the AIS where the SMB-SAT relationship is weak.' Here you suppose this relationship is always strong. But in this article, you don't analyse why the SMB-SAT relationship is generally strong.*

Answer: This was indeed omitted because P3L86, we briefly summarized Dalaiden et al. (2020)'s conclusions on the SMB-SAT relationship at the continental scale, but we agree that it was too succinct. We propose to not change this paragraph much, but just modified the sentence to: "We hypothesize physical mechanisms that could explain the discrete areas of the AIS where the SMB-SAT relationship is weak, compared to the continent-wide positive SMB-SAT relationship.". However, we provide more discussion in section 3.1.1 where the strength of the SMB-SAT relationship is described and discussed.

P4L98-99 is now: We start with a brief description of the data sets and models used in this study. Then we compare the positive SMB-SAT relationship, as well the SMB-δ^{18}O relationship, obtained in the models at regional scale to the continental-scale results of Dalaiden et al. (2020).

Furthermore, we have re-organized section 3.1.1 a little and discuss our results in light of those of Dalaiden et al (2020) at the end as follow: " Dalaiden et al (2020) have shown that the relationship between SMB and SAT is positive on the continental scale for each of their seven Antarctic regions, whether they used the GCMs or RACMO2.3 simulations. The simple concept that Antarctic precipitation originates mainly from lower latitudes, coming from relatively warm and wet air masses, explains the co-variance of SMB and SAT at the continental scale as shown by Dalaiden et al (2020). This simple concept therefore also applies at the regional scale for interannual variations here. Indeed, for the temporal and spatial scales investigated, the annual correlation between SMB and SAT is positive for a large majority of the model grid points, despite a few regional differences due to the models' differing spatial resolutions."

P5L122 *'all four iGCMs show similar spatial variations of the correlation between SMB-SAT and δ^{18}O-SMB on the continent scale' : You didn't give on which time scale you correlate the time series. You should emphasis the time step (annual, from the text after) in the method, by always associating "correlation" with "annual".*

Answer: We agree and have added "annual" before correlation in this paragraph, and all the relevant places in the manuscript where we are talking specifically about the annual correlation of two variables, and not correlation values in general. And we have added "5-yearly" everywhere we are looking at 5-year averages of the variables correlated.

P6L172 *'Furthermore, the spatial distribution of the ice cores over the AIS is not homogeneous, with the majority of the ice cores located in the coastal areas, and very few in the interior (see supplementary Fig.S5). This certainly introduces a spatial bias in our ice core-based correlation towards coastal signals and processes.'*

The lower the accumulation, the lower the ice core resolution. So it is expected that annually resolved ice cores will be at the ice sheet margins. In addition, you should not write "coastal", as most of the ice cores are not at the coast but inland. You can maybe divide Antarctica in "low elevation" (<2200 m) and "high elevation" (>2200 m).

Answer: We agree with both comments, and have reformulated the paragraph as: "Furthermore, the spatial distribution of the ice cores over the AIS is not homogeneous. If we divide Antarctica into low elevation areas (i.e. <2200 m) and high elevation areas (i.e. >2200 m), the majority of the ice cores are located in the low elevation areas, and very few in high elevation areas (except for the large number of ice cores all located in DML, see supplementary Fig. S4). This certainly introduces a spatial bias in our

ice core-based annual correlation towards coastal signals and processes."
We have added the contour line = 2200 m of altitude on Fig. S4.

P7L185 *'We repeat the annual correlation of SAT and SMB using the RACMO27 simulations over 1979–2016 AD (see Fig.2).': Merge Fig. 2 to Fig. 1 so that we can compare patterns between iGCMs and RACMO2.*

Answer: These have been merged (now Fig. 1). Following earlier comments, Fig. 1 now shows the annual SMB-SAT correlation for each of the 4 iGCMs (previously supplementary Fig. S3), the iGCM average (previously Fig. 1, panel c) and the RACMO27 SMB-SAT correlation (previously Fig. 2). And Fig. 2 now shows the 5-yearly SMB-δ^{18}O correlation for each of the 4 iGCMs (previously Fig. S1) and the iGCM average (previously Fig. 1, panel a).

P7L200 *'Winds are known to affect SMB and SAT locally, through wind-based redistribution of SMB, turbulent warming from katabatics and Foehn warming effects on leeward slopes.': you should specify that the loss of correlation because of wind-based redistribution of SMB can be modelled by RACMO only, because it is the only model in this study that includes drifting snow modelling.*

Answer: We agree and have modified the text adapting your input as follows: "[...] turbulent warming from katabatics and foehn warming effects on leeward slopes. Additionally, the impact of wind on SMB and SAT due to wind-based redistribution can modify the link between the two variables but this can only be resolved by the RACMO2.3 simulations, because it is the only model in this study that includes drifting snow (although according to Agosta et al. (2019), drifting snow is strongly underestimated). To evaluate whether the lack of correlation between SAT and SMB is due to any of these wind effects, we correlate [...]"

P7L200 *'turbulent warming from katabatics and Foehn warming effects on leeward slopes': katabatics and surface winds in general (e.g. pressure gradient winds superimposed with katabatics) are also directly concerned by adiabatic warming, the same process involved in the foehn warming.*

Answer: We agree that in both cases, there is a warming effect, so we have modified this line as follows: "turbulent and adiabatic warming from katabatic winds and foehn effects on leeward slopes"

P11L347 *' Turner et al. (2019) show that more than 70% of the annual accumulation consists of extreme events that have a very short duration (one or more consecutive days).': warning. Turner et al. (2019) show that more than 70%* ***of the variance*** *of the annual precipitation is explained by extreme precipitation events, meaning the interannual variability, not the mean value.*

Answer: We have modified the text accordingly: "Turner et al. (2019) show that more than 70% of the variance of the annual precipitation is explained by extreme events that have a very short duration (one or more consecutive days)."

P14L427 *'to improve our confidence in using SMB as a direct proxy for SAT over the entire AIS.' You never mentioned this objective before. Can you develop it in the introduction?*

Answer: This was mentioned briefly in the introduction already P2L46 "If this predicted increase in SMB is linked to increasing SAT in the 21st century, it will be interesting to see if SMB and SAT are linked in the past too, in which case SMB records over time will be a helpful tool to constrain past climates." but perhaps the goal "to improve our confidence in using SMB as a direct proxy for SAT over the entire AIS." should be stated more explicitly. We have added this more explicitly at the end of our introduction section, P4L97: "Answering these questions will help constrain our confidence in using SMB as a direct proxy for SAT over the entire AIS. With relatively few in-situ observations, additional SAT proxies would be extremely beneficial for Antarctic climate reconstructions.”

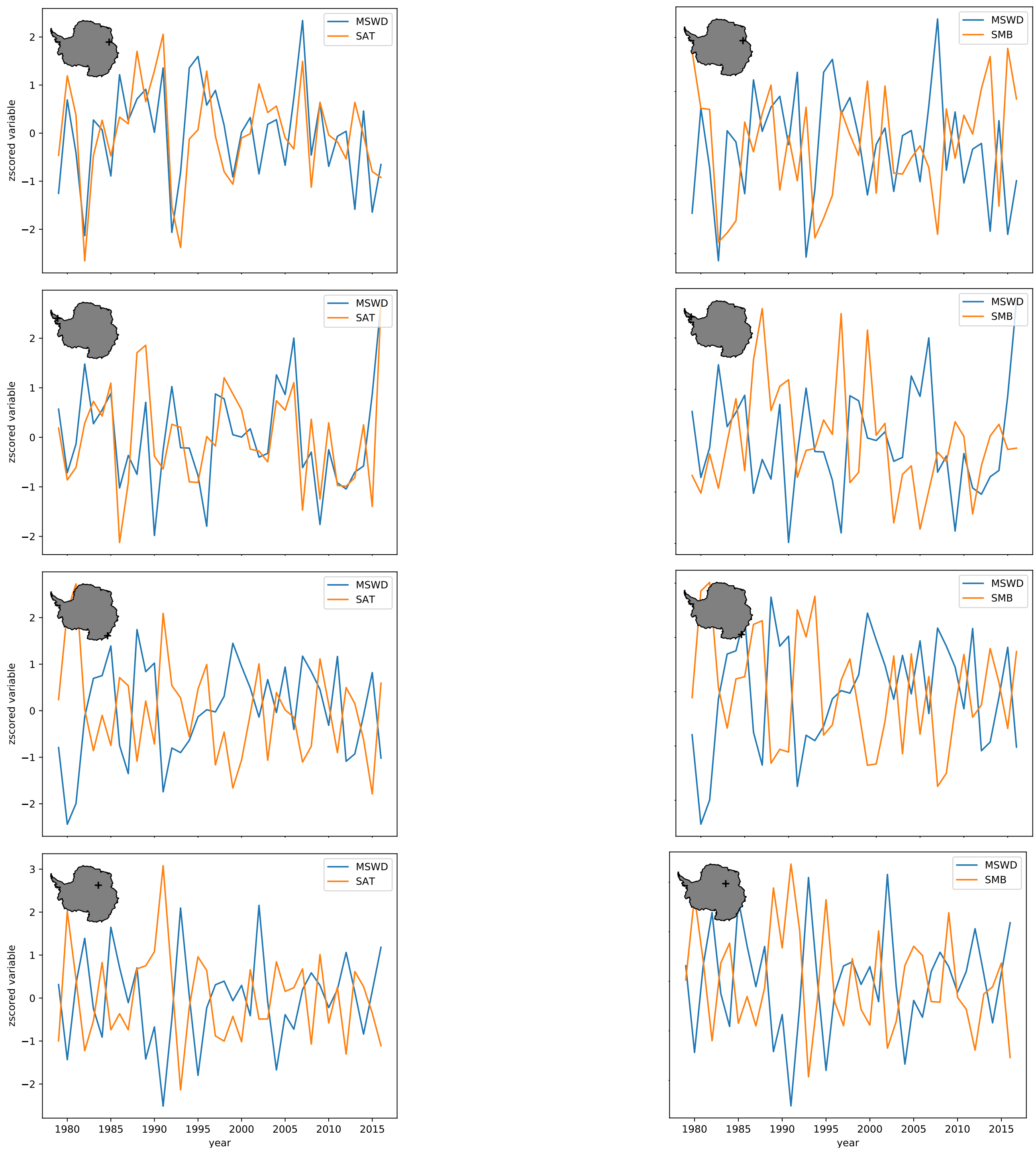

Figure 1: Timeseries of MSWD and SAT for the left panels, timeseries of MSWD and SMB for the right panels. These are provided for two locations that have weak-to-positive MSWD-SAT and MSWD-SMB correlations (top four panels) and two locations that have strongly negative MSWD-SAT and MSWD-SMB correlations (bottom four panels). Locations are indicated on the insets of each panel.

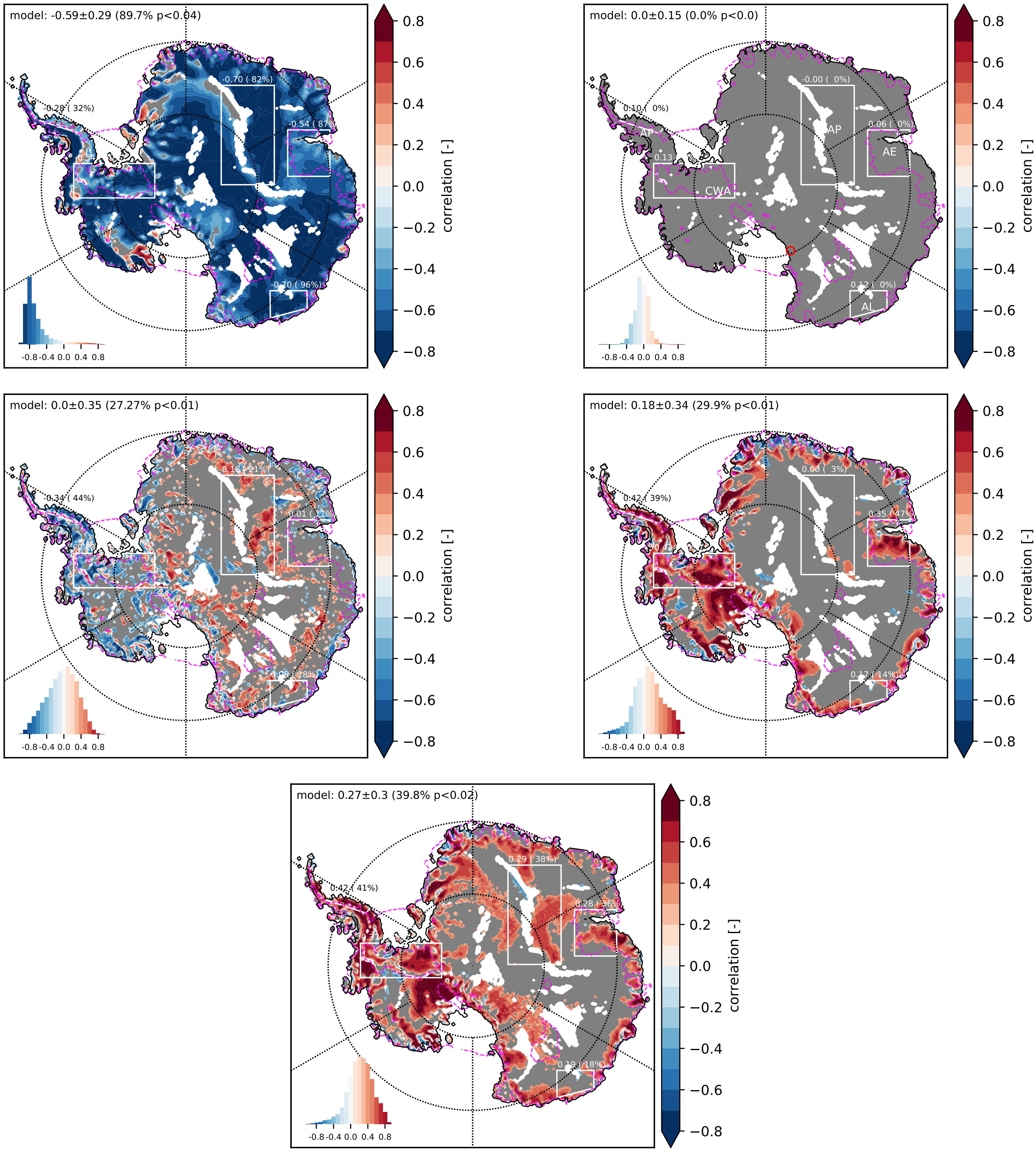

Figure 2: Annual correlation between MSWD and the components of SMB: (top left) MSWD-snowfall, (top right) MSWD-snowmelt, (middle left) MSWD-snowdrift, (middle right) MSWD-sublimation from snowdrift, (bottom) MSWD-sublimation, over the 1979–2016 AD time interval. Statistically insignificant areas (p ¿ p_{FDR}, the threshold p-value calculated) for each resolution are hashed in grey. The histogram displays the distribution of correlation values for each panel. Region-wide annual correlation mean, standard deviation and percentage of model area with p ¡ p_{FDR} are provided on each panel.

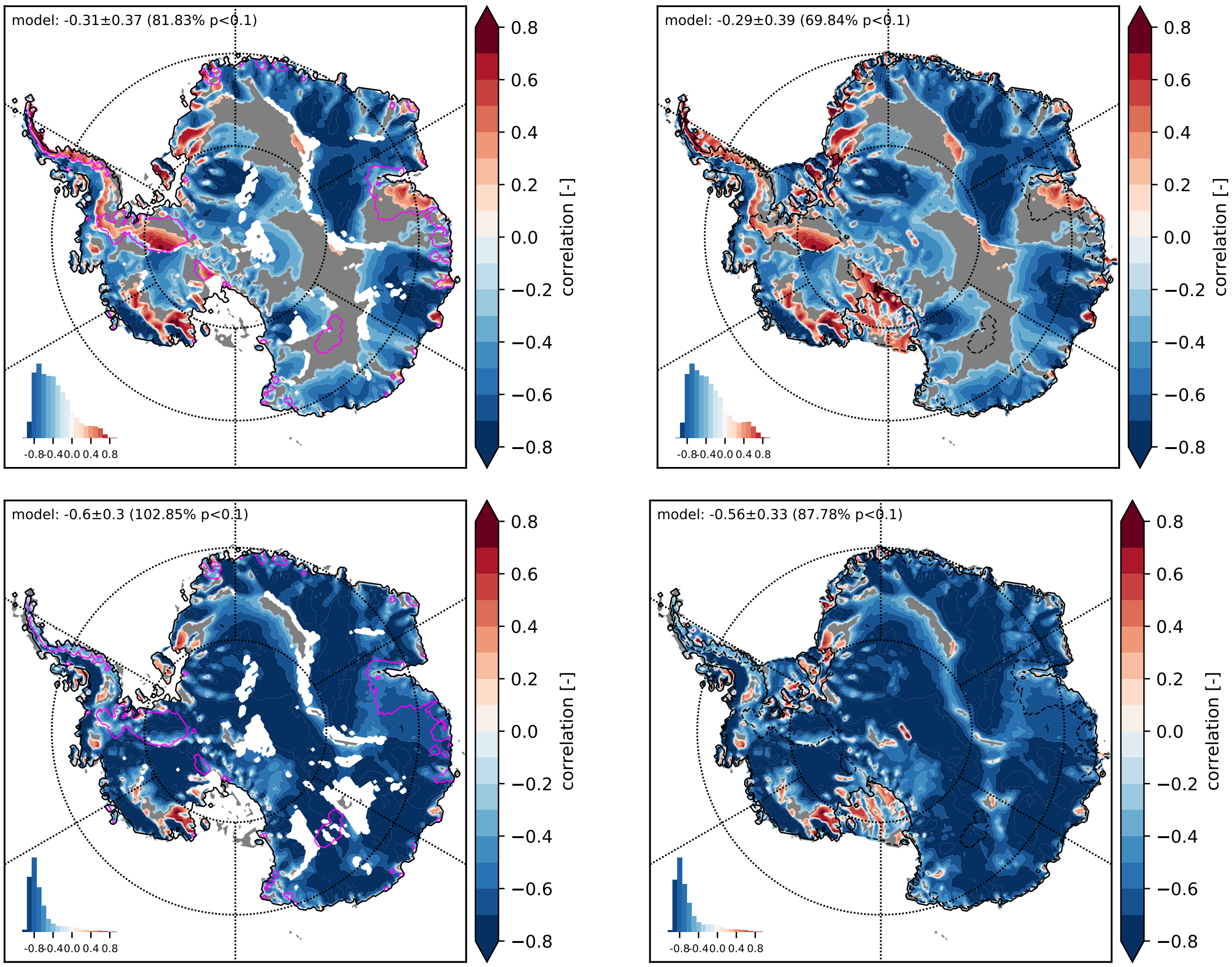

Figure 3: Annual correlation between (top) MSWD and SAT, (bottom) MSWD and SMB using RACMO27 simulations over 1979–2016 AD. Left panels show the results with the >0.1% slope threshold, right panels show the results without the slope threshold. Statistically insignificant areas (p ¿ p_{FDR}, the threshold p-value calculated) for each resolution are hashed in grey. The histogram displays the distribution of correlation values for each panel. Region-wide annual correlation mean, standard deviation and percentage of model area with p ¡ p_{FDR} are provided on each panel.

Response to RC2 comments on the submitted paper *Reconciling the surface temperature–surface mass balance relationship in models and ice cores in Antarctica over the last two centuries*

We thank the reviewer for their constructive comments. We have responded to all of them and have modified the paper accordingly. Our point-by-point answers follow.

Please note that review comments are in grey italics while our answers are not. Changes/additions to the original manuscript are indicated in blue.

Answers to RC2

In this article the authors investigate the relationship between the surface mass balance (SMB), surface air temperature (SAT) and d18O in models and ice cores. They analyze output of four GCM models and one regional climate model of which the GCMs are aware of isotopes. The dataset of ice cores consists of about 50 ice cores. They report a strong positive correlation between modelled SMB and SAT as well as d18O and SMB, which is in agreement with previous studies. However, there are regions where the relationships break for which the authors investigate reasons. Mainly they find a dependence on the prevailing winds that can strongly affect the relationship by e.g. leeside warming due to Föhn winds or adiabatic warming of the falling katabatic winds along the coast. Additionally, they report that the correlations found in ice cores are much lower than in the model and discuss reasons for this discrepancy. Overall, this is a very interesting study, which I recommend for publication in The Cryosphere. Before publishing, some major and a number of minor points should be clarified/improved as listed below.

Major

(1) Correlation testing *The authors present a number of correlation maps. When conducting a high number of significance tests on a gridded map, this increases the number of false rejection of the null hypothesis, (e.g. Wilks 2016). There are correction methods for this issue (e.g. Benjamin and Hochberg, 1995), which the authors should apply in their study.*
Benjamini, Y. and Hochberg, Y.: Controlling The False Discovery Rate – A Practical And Powerful Approach To Multiple Testing, J. Roy. Stat. Soc. Ser. B, 57, 289–300, 1995.
Wilks, D. S.: "The Stippling Shows Statistically Significant Grid Points": How Research Results are Routinely Overstated and Overinterpreted, and What to Do about It, B. Am. Meteorol. Soc., 97, 2263–2273, https://doi.org/10.1175/bams-d-15-00267.1, 2016.
Answer: Thank you for bringing these papers to our attention. We have now applied the FDR correction to the correlations calculated for our gridded and modified the text and figures as necessary. We describe the FDR correction in the methods' section pages 4-5, citing these two papers as references. Even choosing a control α_{FDR} value of 0.05 (stricter than our previous p-value of 0.1), we show that our results are robust and our conclusions are not changed significantly.

(2) Gridding of ice core data *The authors describe their method to analyze the ice core data on a grid. They mention that it is important to have enough ice cores per grid cell, however, the information about how many ice core measurements used per gridded value is missing (a figure or table in the supplementary material could do the job). First, they present gridded ice core results at 108 km x 108 km and 216 km x 216 km. Finally, they analyze results where they analyze results for different resolution between 108 km x 108 km and 684 km x 648 km (Fig. 9) where they only take into account grid cells with five or more ice cores. Based on figure 9, this criteria is not fulfilled for 108 km x 108 km. Thus, I wonder how many ice cores are available in the 108 km x 108 km and 216 km x 216 km grid cells. Does the analysis presented for 108 km x 108 km and 216 km x 216 km actually remove the general noise? For how many locations do these grid cells take into account more than one or two ice cores? This needs to be clearly stated as it will have a strong impact on the analysis.*
Answer: Fig. 8 presents the gridded ice core results at the 216 km x 216 km resolution only (for both the SMB-SAT correlation and the SMB-δ^{18}O correlation). We only describe the results obtained for the gridding at the 108x108 km resolution in the text, stating that "both the SMB-SAT and the SMB-δ^{18}O correlations remain at 0.09 and 0.13 respectively". Aggregation at this resolution does not improve our results, as too few series are averaged, which is why we do not show it. We have added "(not shown)" to that effect to be as clear as possible. And we specify now that Fig. 9 in the manuscript (now Fig. 10)

shows a scaling of 8 grid points (216 x 216 km grid).
When setting a minimum threshold of one ice core per box, it implies that we can retain cases that only use one ice core record, which implies no averaging has been effectively applied. The resulting correlation values are much more noisy (see the very large range of correlation values indicated by the grey bars on Fig. 1, top panel, at the end of this document). The threshold of 5 ice cores is one that allows us to retain several grid points for the scaling based on the RACMO27 grid. A table has been added, as suggested, in the supplement (Table S1) which provides the number of ice cores used per scaling of the RACMO27 grid. Each scaling of the RACMO27 grid retains at least two grid points that match the > 5 ice cores threshold. We tested a higher threshold than 5 ice cores, but there are too few ice core records, the results are not meaningful. Fig. 9 (now Fig. 10) of the main manuscript has been simplified as shown in Fig. 7 at the end of this document.
(Answering also to a later comment: "Did you consider calculating the correlation of the model only for grid cells for which ice core data exists? How does the comparison compare in this case? Could this result be used to underline the disagreement?") Fig. 10 shows the comparison, for a specific scaling of the RACMO27 grid cells, between the average of the ice core correlations in that grid box including n by n model grid cells, versus the average of the RACMO27 correlations over the same grid boxes. Until now, the up-scaling of the model correlations was done using model values over the whole n by n grid cells (Fig. 6, panel a). We now calculate, for the model results, correlations averages in the n by n model grid cells using only the RACMO27 grid points where ice cores exist (Fig. 6, panel b). The conclusions are unchanged (a much higher correlation for RACMO27 versus the ice cores in both cases). However, we modify Fig. 10 in the manuscript to reflect this change, as well as its legend. And we have modified the text accordingly p15 L471-475: "For comparison, we calculate the individual mean and the aggregate value of the SMB-SAT annual correlation for the RACMO27-simulated SMB and SAT fields, only retaining the RACMO27 grid points where ice cores exist (also shown on Fig. 10 in green). This to compare the model-derived and ice core-derived annual correlations locally. As for the ice cores, the aggregate value is always higher than the individual mean for the RACMO27-derived SMB-SAT annual correlation, but the difference is small (up to a 0.1 correlation increase)."

(3) Figure 9 *Figure 9 needs strong improvement. In the caption it is stated that the size of the colored dots is a function of the number of ice cores aggregated. There is need for a legend giving information about the actual number of ice cores for the different dot sizes. The dots for the model in the legend are far too small (black and gray dots). The dots in the legend could all have the same size.*
Answer: We agree that this figure is too dense and needs to be simplified (now Fig. 10 in the manuscript). The dots are now all the same size, and the information about how many ice cores are used for each dot is now given in Table S1 of the supplementary material. We have decided, for clarity, to remove the individual grid points that were shown in light colors, and show their max and min correlation values as a range on the plot (shown by the grey bars). Only the averages are shown by the colored dots (which used to be the dark dots). The same simplification has been applied to model results.

Minor
General:
Avoid "see Figure...", "shown on Fig..." just reference the figures. For the figures add a space after Fig., i.e. Fig.1 → Fig. 1
Answer: We have applied your suggestions.

Avoid spoken language, i.e. try to reduce the number of non-informative sentences, e.g. "Let us first focus on the link between wind redistribution and SAT." (P.8, L228) or "To explain this, we have to first

describe average conditions." (P.8, L247) or "Now that we have a better understanding from the models let us look at..." (P.10, L.398). These are some examples but there are more in the text.
Answer: We have reworded some of these: P8L228 has become "We will first examine[...]"; P8L247 has become "During average weather conditions in coastal areas,[...]; P10L398 has become "We will next examine in-situ measurements of SMB, SAT and δ^{18}O.". We have not found any other obvious examples of this.

P.2, L24: *sea-level rise → SLR*
Answer: We have opted to explicitly write "sea level rise" every time as it it is the only place in the manuscript that we mention sea level rise.

P.2, L35: *temperature → heat*
Answer: Replaced.

P.2, L34-36: *The first sentence leaves the reader wondering where the air comes from. Consider reformulation of the two sentences.*
Answer: The first two sentences have been reworded as follows: "Large-scale atmospheric circulation (100s of km) strongly controls SMB in Antarctica. This large-scale atmospheric circulation embeds synoptic-scale cyclones that collect heat and moisture from further north, including the Southern Ocean, which they can release onto the AIS [...]"

P.2, L45: *twice mentioned the increased SAT. Is it a positive feedback, i.e. increasing SAT → increased snowfall → increase in SAT? If yes, consider reformulation, if no remove one of the increased SAT.*
Answer: We thank the reviewer for noticing this confusing formulation. Also taking the other reviewer's comment into consideration, this paragraph has been changed as follows: "In addition, based on the Clausius-Clapeyron relationship, the increasing mid and upper troposphere temperature due to climate change implies that the vapor pressure of the air is higher, and therefore snowfall is increased (Frieler et al., 2015). If this predicted increase in SMB is linked to increasing temperatures in the 21st century, it will be interesting to see if SMB and SAT are linked in the past too, since an increase in SAT and tropospheric air temperature are strongly correlated. In this case, SMB records over time will be a helpful tool to constrain past climates."

P.3, L80: *at → as*
Answer: Changed.

P.3, L85: *(Dalaiden et al., 2019) → Dalaiden et al. (2019)*
Answer: Changed. Also, note that the Dalaiden et al. (2019) The Cryosphere Discussions paper has now been published in The Cryosphere and all references have been changed to Dalaiden et al. (2020), here and in the manuscript.

P.3, L87: *Here, for the second time you define the local scale. Redefine one*
Answer: We have chosen to remove the definition of local scale earlier (*'We will refer to this wind-based redistribution as the "local scale"'*) and keep it defined here P3L87 as that is spatial scale that we use in the whole manuscript.

P.4, L91-95: *Add "?" to the questions*
Answer: Added.

P.4, L107: *"(with the additional fourth made available recently, . . .)" Mention which model is new.*
Answer: This is now mentioned explicitly: "with the additional fourth made available recently, iCESM1, "

P.4, L108: *Add the reference of Brady et al., 2019 as not all the models are described in Dalaiden et al., 2020.*
Answer: Added, as well as Stevenson et al. (2019).

P4. L114: *"by a sea surface temperatures..." → "by sea surface temperatures"*
Answer: Modified.

P.5, L120-121: *The authors use a different number of ensemble members for the different iGCMS. By averaging over several ensemble members variability is lost. It would be interesting to know how this affects the results, please discuss.*
Answer: We are sorry that the wording of this sentence was confusing. What we did was: (1) we calculated the correlation of the two variables (SMB-SAT or SMB-δ^{18}O) for every grid point for each model member (3 members for iCESM1 and 7 members for iHadCM3). (2) We calculated the mean of the correlation values obtained per grid point over all the model members that belong to iCESM1 or iHadCM3 to get the mean SMB-SAT and SMB-δ^{18}O correlation for each model. (3) We interpolated then all four iGCM correlation results (ensemble means for iCESM1 and iHadCM3, ECHAM5-MPI/OM and ECHAM5-wiso correlation results) onto the RACMO27 grid, for both the SMB-SAT annual correlations and the SMB-δ^{18}O 5-yearly correlations. (4) We then calculated the mean over all four iGCMs to get the resulting iGCM plots shown in Fig.1. The sentence has now been changed to: "For the iCESM1 and iHadCM3 GCMs ensembles that include three and seven simulations, respectively (each has slightly different initial conditions), we first calculate the correlation of the two variables (SMB-SAT or SMB-δ^{18}O) for every grid point for each ensemble member (3 for iCESM1 and 7 for iHadCM3). Then we obtain the mean of the correlation values per grid point over each ensemble of simulations for both iCESM1 or iHadCM3. These ensemble means can then be compared to the correlations calculated for ECHAM5-MPI/OM and ECHAM5-wiso."

P.5, L121: *Consider reformulations "we average over their ensemble of simulations to obtain mean representation of SMB, SAT and $\delta^{18}O$ for each iGCM." → "we retrieve the ensemble mean of SMB, SAT and $\delta^{18}O$ for each iGCM."*
Answer: Same comment as above.

P.5, L123: *Mention the most important findings of the evaluation. What about the model that is not evaluated in Dalaiden et al., 2019?*
Answer: Based on the comments of both reviews, we have chosen to provide an evaluation for SMB for all four iGCMs, as well as of the SAT and sea-level pressure (SLP) fields. SMB and SAT are evaluated against RACMO27 and SLP is evaluated against ERA-Interim (to provide sufficient northerly coverage), over the 1979–2000 AD time interval (an interval common to all models). The evaluation is described at length in the supplement (S2). In addition to the evaluation in S2, we add the following short paragraph P5 after the description of the models: "Dalaiden et al. (2020) provide an evaluation of first three iGCMs used, and we provide an evaluation of the SMB, SAT and the atmospheric circulation (we use sea-level pressure) for all four iGCMs in Supplement S2. SMB and SAT are evaluated against RACMO27, while sea-level pressure is evaluated against ERA-Interim as the ERA-Interim grid extends further north. The

evaluation is done over the 1979–2000 AD time period, the longest period of overlap for all the models examined. We show that all four models produce realistic SMB, SAT and sea-level pressure outputs, with biases likely linked to differences in their physics as well as their spatial resolutions."

P.5, L126: *significative → significant*
Answer: Changed.

P.5, L129-130: *Explicitly give the number of years taken into account. Avoid "∼" as the time periods are clearly defined.*
Answer: These have been changed to 130 years and 40 years.

P.5, L130/P.5, L141: *Please clarify the choice of the time periods. You mention "...a shorter () timescale covering 1961-2000 AD for comparison to the RCM simulations and measured SAT." However, the RCM start in 1979. Why don't you take a time period that matches between the iGCMs and the RCM? I guess this would be 1979-2000?*
Answer: The reason for this is that we wanted to keep as many years as possible for correlating the climate variables (SMB, SAT and δ^{18}O). RACMO covers 1979-2016 = 38 years. Truncating the iGCM data to start in 1979, would have meant we only had 22 years of data, which is very short to have meaningful correlation results. We thus prefer to have a similar length for all models. This is now specified at the end of this paragraph as: "We choose to use the 1961–2000 AD time interval instead of starting in 1979 AD as for the RCM simulation, so that all model simulations have a similar length (40 years and 38 years for the iGCMs and the RCM, respectively) and their correlation results are meaningful." In addition, we have compared the SMB-SAT correlations over the 1961–2000 AD and the 1979–2000 AD time intervals and the correlation strengths are unchanged, although the correlations over the shorter 1979–2000 AD time interval lose in significance (more areas with p $> p_{FDR}$, e.g. see iCESM1 in Fig. 2 at the end of this document). For the SMB-δ^{18}O correlations, the 1979–2000 AD interval is too short to calculate a 5-yearly correlation.

P.5, L132: *Here and in the Figures 1, and S1-S4 you first mention δ^{18}O-SMB followed by SMB-SAT. However, in the analysis you first analyze SMB-SAT. Flip the order in both the text (here) and the figures.*
Answer: We agree, and have flipped the order in the text here and this has been taken into account in modifying Figs. 1 and 2 of the manuscript as described later in this review.

P.5, L143: *to studying → to study*
Answer: Changed.

P.5, L147: *remove "," before etc.*
Answer: Removed.

P.6, L158: *Reformulate: "Ice cores record variations with depth of ice's δ^{18}O."*
Answer: Reworded as: "Ice cores record variations of the δ^{18}O of the ice with depth".

P.6, L164-168: *How well does this temperature reconstruction method work? Why do you need to rely on this? Could you use SAT from reanalysis instead? Are there weather stations in the close proximity of the ice core locations? For locations where weather stations are available, how well does the SAT reconstruction method agree with the measurements? Could you present correlations of ice cores to station measurements for some locations?*

Answer: We use this SAT reconstruction as it is based on the only direct observations of temperatures from weather stations over the last 50 years. Prior to 1979, reanalysis data have well known biases (e.g. Bromwich et al., 2007). This SAT reconstruction uses 15 weather stations (many along the coast), based on which they produce estimates of monthly gridded mean temperature anomalies for the whole continent over the 1958–2012 AD time period. They use a kriging technique, originally developed for the reconstruction of Antarctic snowfall (Monaghan et al. 2006), to then interpolate the data between the stations. We now provide a map of the station locations used in the reconstruction in the supplementary material (Fig. S4, panel c). And we have added a more detailed description of this SAT dataset in section 2.3: "Because ice cores do not provide a direct measurement of SAT, we rely on the Nicolas and Bromwich (2014) SAT reconstruction. Nicolas and Bromwich (2014) use SAT records from 15 weather stations around the AIS (mostly coastal, Fig. S4c) to produce estimates of monthly gridded mean temperature anomalies for the whole continent over 1958–2012 AD. The reconstruction is based on a kriging technique, originally developed for the reconstruction of Antarctic snowfall (Monaghan et al., 2006), to interpolate the data between the stations. The interpolated SAT field allows us to correlate SAT and SMB directly at the ice core locations so as to compare to the RACMO2.3 results."
At the end of this document, we show the correlation of three ice core δ^{18}O records with the weather station SAT records used in the Nicolas and Bromwich (2014) reconstruction. We choose these three sites for their proximity to a weather station (Fig. 3 at the end of this document), over the 1960–2010 AD time interval. We can see that for the three locations randomly selected, the δ^{18}O-SAT correlation is positive, as expected, since δ^{18}O is a proxy for snowfall-weighted SAT. However, although positive, the SAT-δ^{18}O correlation is not necessarily as robust everywhere on the continent. This agrees with e.g. Klein et al. (2019) who show that the 5-yearly SAT-δ^{18}O correlation can already be quite varied over the much longer 0–2000 AD time interval. Reference: Klein, F., Abram, N. J., Curran, M. A. J., Goosse, H., Goursaud, S., Masson-Delmotte, V., Moy, A., Neukom, R., Orsi, A., Sjolte, J., Steiger, N., Stenni, B., and Werner, M.: Assessing the robustness of Antarctic temperature reconstructions over the past 2 millennia using pseudoproxy and data assimilation experiments, Clim. Past, 15, 661–684, https://doi.org/10.5194/cp-15-661-2019, 2019.

***P.6, L177:** Consider starting the results and discussion section with your results and discuss the comparison to other studies later.*

Answer: We have moved this sentence that compares our results to those of Dalaiden et al (2020) towards the end of this section 3.1.1, reworded as: "Dalaiden et al (2020) have shown that the relationship between SMB and SAT is positive on the continental scale for each of their seven Antarctic regions, whether they used the GCMs or RACMO2.3 simulations. The simple concept that Antarctic precipitation originates mainly from lower latitudes, coming from relatively warm and wet air masses, explains the co-variance of SMB and SAT at the continental scale as shown by Dalaiden et al (2020). This simple concept therefore also applies at the regional scale for interannual variations here. Indeed, for the temporal and spatial scales investigated, the annual correlation between SMB and SAT is positive for a large majority of the model grid points, despite a few regional differences due to the models' differing spatial resolutions."

***P.6, L184:** Figures S1 and S2 are about $\delta^{18}O$. Don't mention them here. I think only Fig. S3 is relevant to this section. Reorder the figures in the supplementary material and only mention the related ones.*

Answer: We have now moved part of the supplementary figures to the main manuscript. Fig. 1 now shows the annual SMB-SAT correlation for each of the 4 iGCMs (previously supplementary Fig. S3), the iGCM average (previously Fig. 1, panel c) and the RACMO27 SMB-SAT correlation (previously Fig. 2). And Fig. 2 now shows the 5-yearly SMB-δ^{18}O correlation for each of the 4 iGCMs (previously Fig.

S1) and the iGCM average (previously Fig. 1, panel a). The other correlations (different time resolutions and time intervals) are kept in the supplement as appropriate.

P.7, L191: Avoid generalizing, as you only have two different resolutions and two different time periods (which are partially overlapping).
Answer: We have modified *"Whatever the temporal and spatial scale,* to: "For the temporal and spatial scales investigated," and moved it further down in the paragraph to link to the Dalaiden et al. (2020) study.

P.8, L223-224: *How do the findings by Agosta et al. (2019) relate to your findings? Indicate the link more clearly.*
Answer: We now discuss Agosta et al. (2019) results further down in this section (p12 L352-354): : "For instance, Agosta et al. (2019) examine the spatial link of time-averaged values of surface curvature and surface winds and they observe that above a certain threshold, winds will affect SMB locally in pattern that matches that of drifting snow fluxes as modeled by RACMO2.3." We also reference the Dattler et al. (2019) paper which discusses similar findings: "Dattler et al (2019) also show that, at length scales < 25 km, regions of the West Antarctic Ice Sheet show high spatial variability in accumulation simultaneously to high variability in wind speed and direction."

P.8, L225: *"very positive", reformulate to "strongly positive" or "positive".*
Answer: Changed.

P.8, L225: *"weaker-to-positive" this needs to be reformulated. What you refer to is a weaker-negative-to-positive correlation. This needs to be specified.*
Answer: For clarity, we have changed the sentence to: "However, a number of areas show a strongly positive MSWD-SAT annual correlation, simultaneously with a weaker (less negative) or positive MSWD-SMB annual correlation."

P.8, L226: *"(outlined here with a magenta line)": Why using a magenta line (Figs. 4 and 5) and not the black dashed lines as in Fig. 2? Magenta lines are harder to see. Remove "here", i.e. "(outlined with a magenta line)".*
Answer: We chose to plot the lines in magenta because they were difficult to see in black due to the blue–white-red color scheme of the maps (while Fig. 2 was only in red tones). "Here" is now removed.

P.8, L231: *"very positive" $\rightarrow$ "strongly positive"*
Answer: Changed.

P.8, L232: *To me it looks like the effect is not present over the whole range of the Trans-Antarctic Mountains, i.e. I can't see the effect for the eastern part of the mountain range. Please, clarify.*
Answer: We believe this might be because the Antarctic Peninsula is very thin and the eastern side if more difficult to see at this scale, especially since we do not show the ice shelf values. We have added a zoomed-in view of the correlations (both MSWD-SAT and MSWD-SMB) for the AP in supplementary Fig. S9.

P.8, L236: *"this leeward side" $\rightarrow$ "the leeward side"*
Answer: Changed.

P.8, L.239: "here" → "in this area"
Answer: Changed.

P.8, L.241: Be specific about the difference between the low level westward winds and upper level winds bringing the warm air masses from the north.
Answer: We now explicitly specify the following page 10: "Berkner Island (BI on Fig. 1, panel f) shows a very distinctive negative MSWD-SAT annual correlation on its eastern side and positive on its western side, which matches the dominant westward wind direction in this area in the lower level of the atmosphere"

P.8, L.244: Did you test whether the correlation is significantly less negative? Otherwise, avoid using significantly.
Answer: We have removed "significantly", since we meant it more here as "visibly".

P.9, L.255: "...become weaker or increase". This is not clear, please clarify. Do you mean "become weaker or positive"?
Answer: Yes, we meant "become weaker or positive", we have now changed it in the text.

P.9, L.256: "bottom panel" → use a), b),... for all the figure panels.
Answer: This has been changed everywhere in the manuscript and supplement.

P.9, L.268: Instead of "marked on Fig. 2" use either "AE on Fig. 2" (or "marked as AE on Fig. 2"). Same for BG (P.9, L274) and AL (P.9, L.277).
Answer: They have all been changed to e.g.: 'AE' on Fig. 2.

P.9, L.271: "i.e." instead of "so"
Answer: Changed.

P.9, L.272: Change "very positive" to "strongly positive"
Answer: Changed.

P.9, L.277: Does the model confirm especially high precipitation in the Adélie Land?
Answer: Adélie Land is in a coastal regime and therefore show a high snowfall rate, above 500 mm w.e. yr^{-1} and up to 2000 mm w.e. yr^{-1}. See Fig 5, top right panel. We have modified this paragraph as follows: "For example, Adélie Land ('AL' on Fig. 2) displays high snowfall rates (above 500 mm w.e. yr−1 based on RACMO2.3 results), but is also known for its record-high katabatics (van den Broeke et al., 2002). This region does not display particularly weak MSWD-SMB or MSWD-SAT annual correlations in RACMO2.3 results."

P.9, L.282: The lines on Fig. 2 are not magenta but black dashed.
Answer: Thank you for spotting this, it has been changed.

P.10, L.288: "Perhaps here snowfall input from further north is so high that it dominates the SMB and SAT records." Do the model results confirm this? The models might have the different components of the SMB to check this.
Answer: This was a hypothesis but it is difficult to verify it in this case as we would need daily data to look into the local variability. So we prefer to simply remove this sentence and keep the description

factual.

P.10, L.290: RACMO05? (= RACMO5?)
Answer: Yes, it was a typo and has been corrected everywhere it appeared in the manuscript.

P.10, L.295: Try to avoid generalization. Consider changing "all scales" to "all investigated scales".
Answer: We agree and have added "investigated" in that sentence.

P.10, L.310: Reference figures for iGCMs and RACMO.
Answer: The figures are now referenced accordingly, taking into account the changes in Figs. 1 and 2 (see previous comments).

P.11, L.318: "...an important process, process that..." → "...an important process, i.e. a process that..." or "...an important process, that..."
Answer: We have opted for "...an important process, i.e. a process that...", thank you.

P.11, L.339: instead of "as discussed below" reference Section.
Answer: It is in the same section, so perhaps this phrasing is unnecessary. We have removed it.

P.11, L.342: You mention that the correlations of the cores with an inhomogeneous distribution over the continent are probably not representing the continental or even regional correlation. Then, you mention that the model shows mainly positive correlations where the ice cores are located. Did you consider calculating the correlation of the model only for grid cells for which ice core data exists? How does the comparison compare in this case? Could this result be used to underline the disagreement?
Answer: We have responded to this question in the 2nd comment of this review and therefore refer the reviewer to the earlier response.

P.11, L.344: remove "outlined"
Answer: Removed.

P.12, L.356: reference the 108x108 km results as "not shown"
Answer: We have added "not shown" after "[...] remain at 0.09 and 0.13 respectively".

P.12, L.366: "Results are shown in Fig. 9." No need for a whole sentence, just give reference as (Fig. 9).
Answer: This has been changed to "(only three grid points contain at least five ice cores at the 648 x 648 km grid resolution, Fig. 9)".

P.12, L.368: "all spatial scales": Avoid generalization, i.e. "all investigated spatial scales"
Answer: Modified.

P.12, L.375-376: Please clarify this sentence.
Answer: We have reworded it to: "Examining the ice core-based results, we note that increasing the number of ice core records that are initially averaged results in a visible increase of the SMB-SAT annual correlation, but the trend is weak."

P.21, Fig.7: significantive → significant
Answer: Changed.

P.21, Fig.7: *Maybe change "Large dots indicate..." to "Large gray encircled dots indicate..."*
Answer: This has been changed as suggested to "Large gray encircled dots indicate [...]".

P.22, Fig.8: *Why don't you show the standard deviation and percentage of p<0.1 on these graphs? What does the size of the dots display? Provide information in the caption and a legend for sizes.*
Answer: The standard deviation and percentage of p< p_{FDR} have been added (see Fig. 8 of the manuscript). The size of the dots displays the number of records averaged over, and we now provide size information in the caption and legend as suggested.

Suppl., P.8, Fig S9: *specify on which level wind speed and direction is shown.*
Answer: We have changed the caption to "Mean 10 m wind speed[...]".

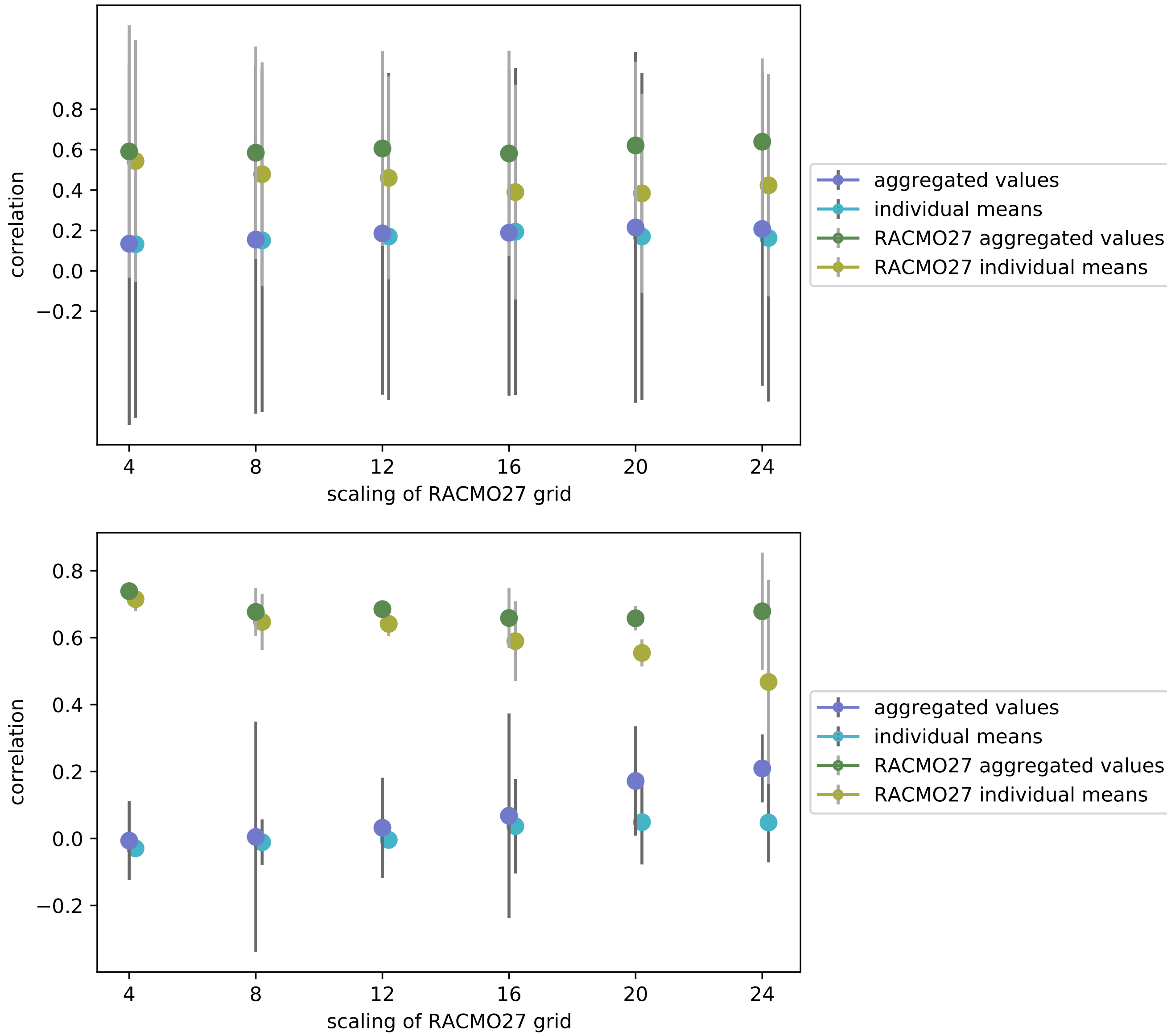

Figure 1: SMB-SAT annual correlation as a function of grid spacing for the aggregated records versus mean of the individual annual correlations for the ice cores (dark and light blues, respectively) and RACMO27 simulations (in dark and light green, respectively). Only grid points with at least (top) one and (bottom) five ice cores are kept. Annual correlations are over the 1958–2010 AD time interval.

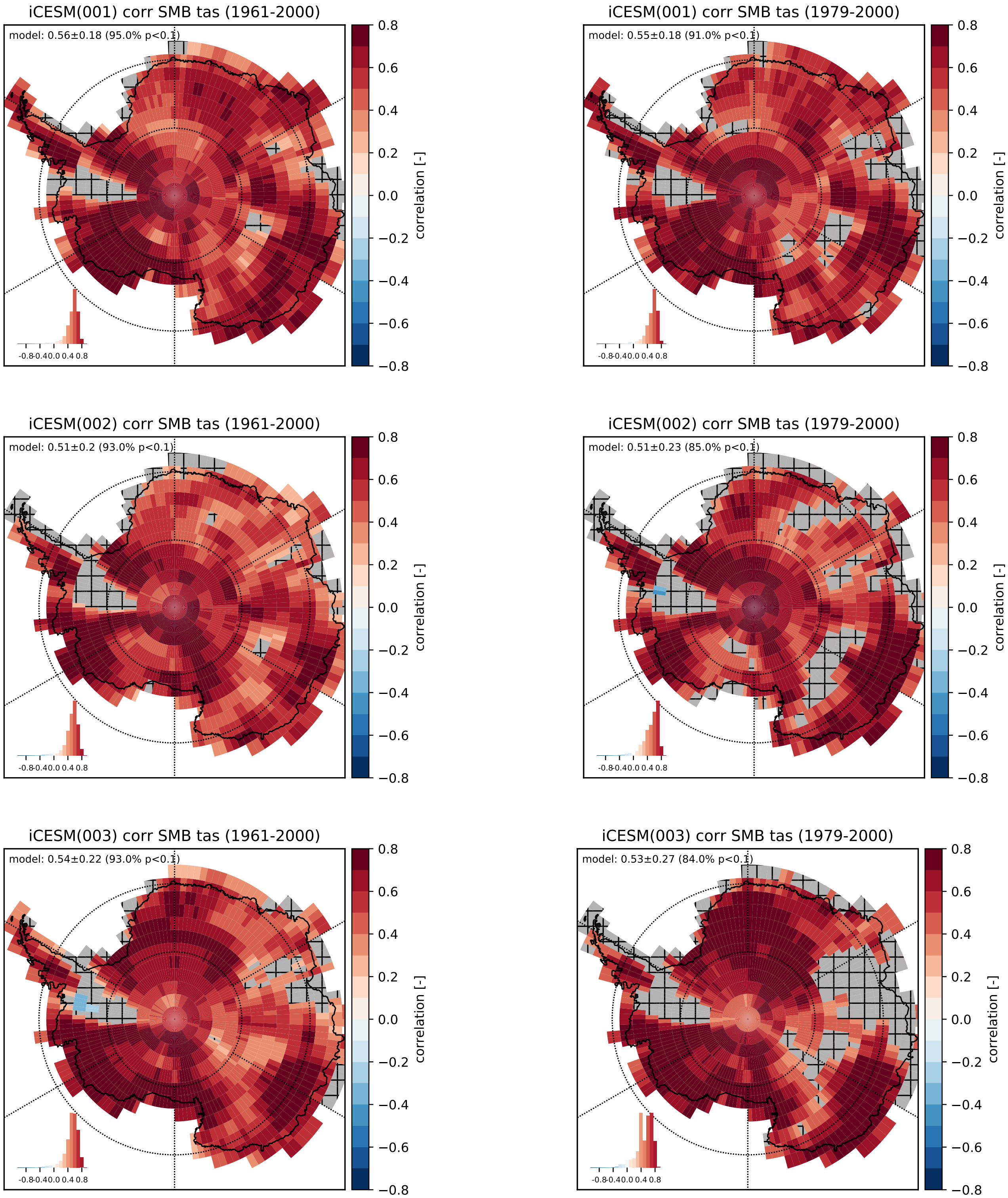

Figure 2: Annual correlation between SMB and SAT over (left) the 1961–2000 and (right) the 1979–2000 AD time intervals for each of the 3 iCESM1 simulations.

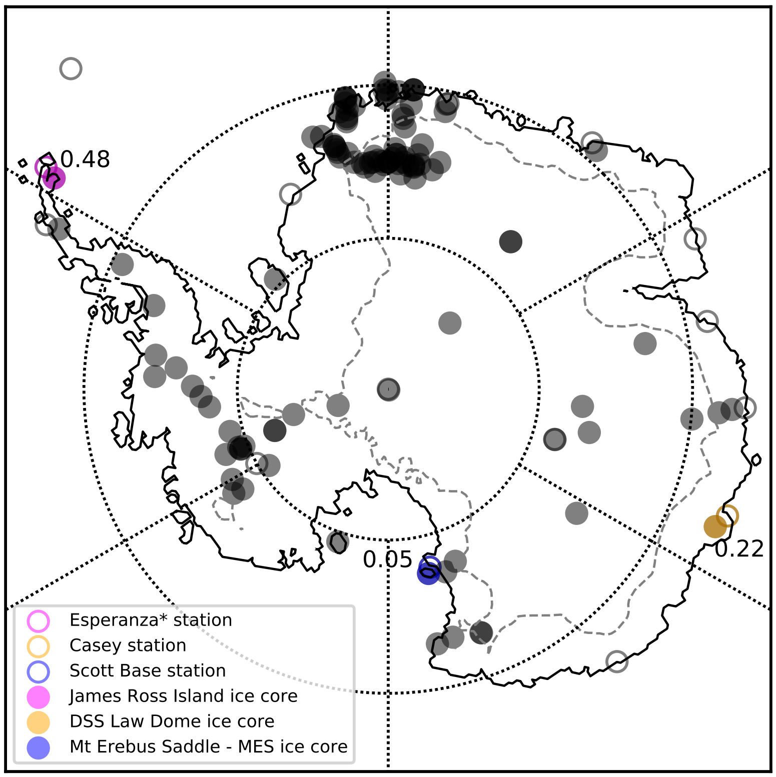

Figure 3: Annual correlation between ice core δ^{18}O records and the weather station SAT records used in the Nicolas and Bromwich (2014) SAT reconstruction for 3 select locations where the weather stations and the ice cores are in close proximity, over the 1960–2010 AD time interval. Correlation values are given on the figure itself. The filled black dots are the locations of the rest of the δ^{18}O ice core records and the empty black dots are the locations of the rest of the weather stations in the Nicolas and Bromwich (2014) SAT reconstruction.

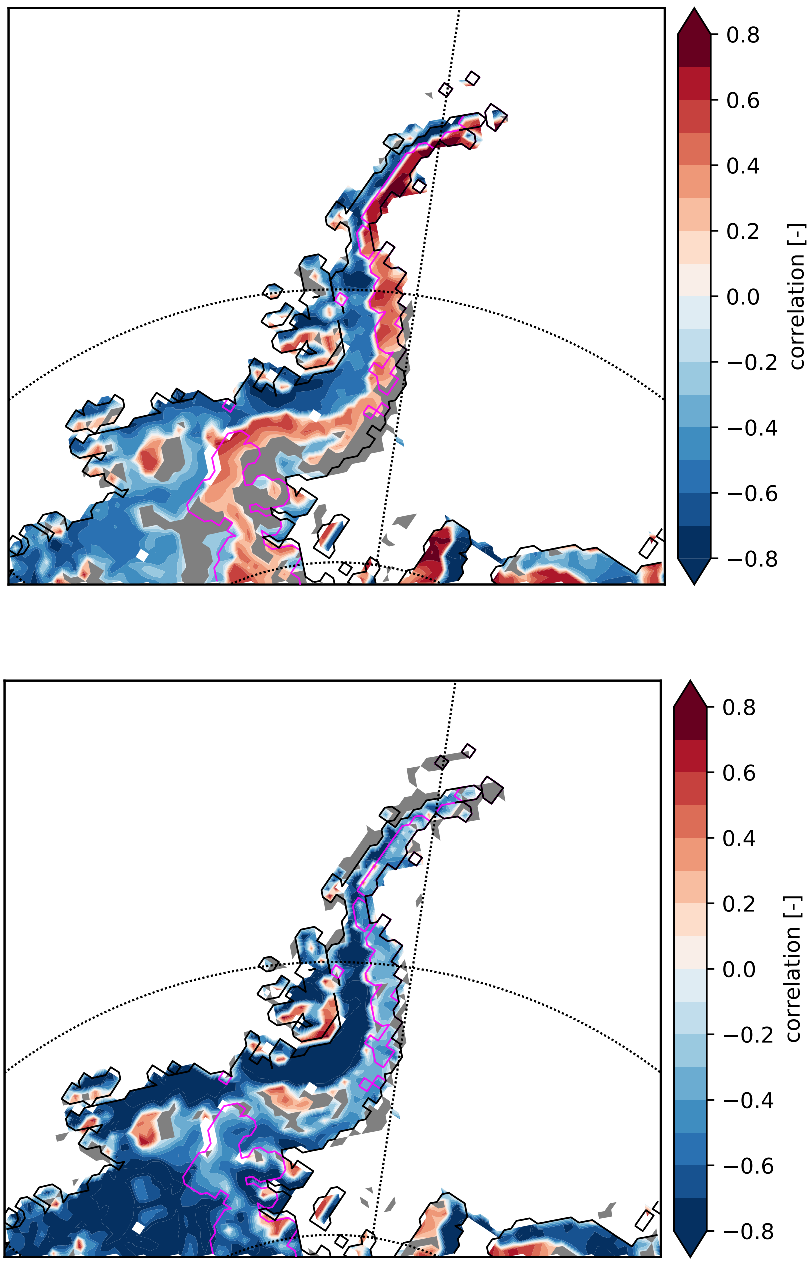

Figure 4: Zoomed view of the AP region: correlation between MSWD and (top) SAT and (bottom) SMB for the AIS calculated from RACMO27 simulations over the 1979–2016 AD time interval. Magenta lines outline the areas with a weak SMB-SAT correlation from Fig. 2 in the main manuscript.

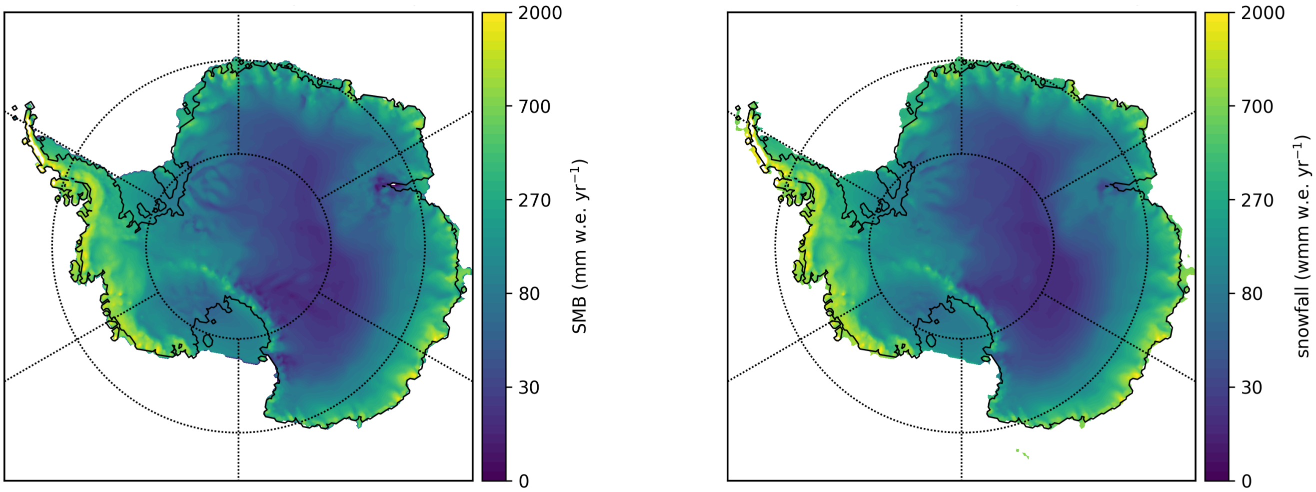

Figure 5: (left) mean SMB in mm w.e. yr^{-1} vs (right) mean snowfall in mm w.e. yr^{-1} in the RACMO27 simulations over the 1979–2016 AD time interval.

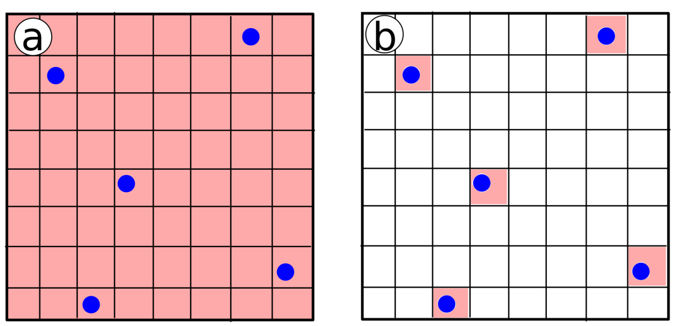

Figure 6: Sketch of the averaging of the model and ice core data for Fig. 10 of the manuscript. Example for averaging over 8 x 8 grid cells : the small cells represent the original RACMO27 grid cells, the blue dots the ice core locations, and the red coloring the RACMO27 grid cells used in the average. Sketch (a) is how we calculated the averages shown in Fig. 7 (top panel) of this document: we compare the ice core average correlations (both average correlation and correlation of the averages) to the average RACMO27 correlation over the whole larger (red) grid cell (both average correlation and correlation of the averages as well). Sketch (b) is what we show in Fig. 7 (bottom panel) of this document for comparison: we compare the ice core average correlations to the average RACMO27 correlations using only the original RACMO27 grid cells that contain an ice core instead of the whole larger grid cell. Sketch b is what we use in Fig. 10 of the manuscript to compare ice core and model values locally.

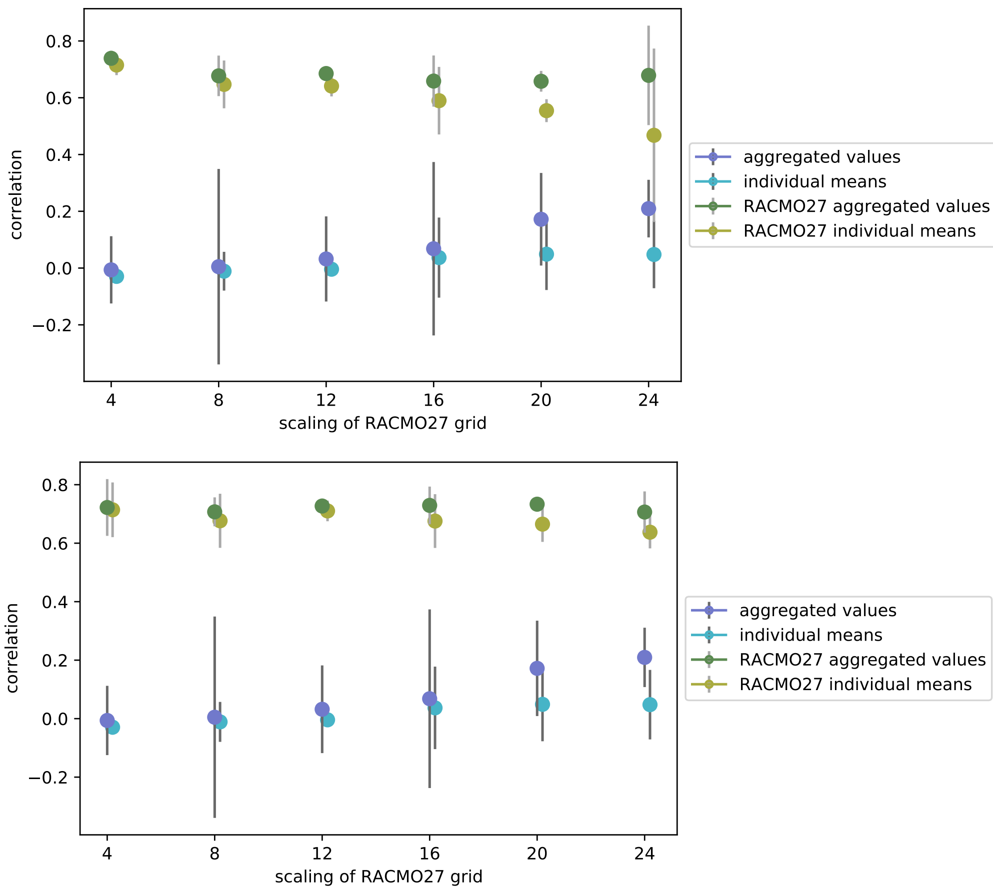

Figure 7: SMB-SAT annual correlation as a function of grid spacing for the aggregated records versus mean of the individual annual correlations for the ice cores (dark and light blues, respectively) and RACMO27 simulations (in dark and light green, respectively). For n the scaling value, RACMO27 correlations use (top panel) the whole n by n grid points, (bottom) only the RACMO27 grid points where ice cores exist. Only grid points with at least five ice cores are kept. Annual correlations are over the 1958–2010 AD time interval for the ice core data, and over 1979–2016 AD for the RACMO27 data.

Reconciling the surface temperature–surface mass balance relationship in models and ice cores in Antarctica over the last two centuries

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Abstract. Ice cores are an important record of the past surface mass balance (SMB) of ice sheets, with SMB mitigating the ice sheets' sea level impact over the recent decades. For the Antarctic Ice Sheet (AIS), SMB is dominated by large-scale atmospheric circulation, which collects warm moist air from further north and releases it in the form of snow as widespread accumulation or focused atmospheric rivers on the continent. This ~~implies~~ suggests that the snow deposited at the surface of the AIS should record strongly coupled SMB and surface air temperature (SAT) variations. Ice cores use δ^{18}O as a proxy for SAT as they do not record SAT directly. Here, using isotope-enabled global climate models and the RACMO2.3 regional climate model, we calculate positive SMB-SAT and SMB-δ^{18}~~O-SMB-~~O annual correlations over ~90% of the AIS. The high spatial resolution of the RACMO2.3 model allows us to highlight a number of areas where SMB and SAT are not correlated, and show that wind-driven processes acting locally, such as ~~Foehn~~ foehn and katabatic effects, can overwhelm the large-scale atmospheric ~~input~~ contribution in SMB and SAT responsible for the positive SMB-SAT annual correlations. We focus in particular on Dronning Maud Land, East Antarctica, where the ice promontories clearly show these wind-induced effects. However, using the PAGES2k ice core compilations of SMB and δ^{18}O of Thomas et al. (2017) and Stenni et al. (2017), we obtain a weak annual correlation, on the order of 0.1, between SMB and δ^{18}O over the past ~150 years. We obtain an equivalently weak annual correlation between ice core SMB and the SAT reconstruction of Nicolas and Bromwich (2014) over the past ~50 years, although the ice core sites are not spatially co-located with the areas displaying a low SMB-SAT annual correlation in the models. To resolve the discrepancy between the measured and modeled signals, we show that averaging the ice core records in close spatial proximity increases their SMB-SAT annual correlation. This increase shows that the weak measured ~~correlation likely~~ annual correlation partly results from random noise present in the ice core records, but the change is not large enough to match the annual correlation calculated in the models. Our results indicate thus a positive correlation between SAT and SMB in models and ice core reconstructions but with a weaker value in observations that may be due to missing processes in models or some systematic biases in ice core data that are not removed by a simple average.

Copyright statement.

1 Introduction

In the context of current climate change and sea level rise ~~(SLR)~~ in the last century, it is important to better constrain the future contributions from the Antarctic Ice Sheet (AIS) to ~~SLR,~~ sea level rise. The AIS is projected to be the largest source of ~~sea-level~~ sea level rise over centennial to millenial timescales, with a potential contribution of 58.3 m ~~of potential SLR~~ if the entire ice sheet were to melt (Stocker et al., 2013; Pörtner et al., in press). To better predict the timing and rate of the AIS contributions to ~~SLR~~sea level rise, we need to better constrain its mass balance. The grounded AIS mass balance is the difference between surface mass balance (SMB), i.e. the addition of mass at the surface of the ice sheet, and ice discharge through basal hydrology and calving (Lenaerts et al., 2019). The AIS mass balance is currently negative due to increased ice discharge at the grounding lines (Shepherd et al., 2018), particularly enhanced in the Amundsen Sea Embayment (Mouginot et al., 2014; Rignot et al., 2019), ~~outpacing SMB~~ outpassing a positive trend in SMB (Medley and Thomas, 2019). SMB could play a bigger role in mitigating future ~~SLR~~sea level rise, but it is still not well understood. For the AIS, the SMB signal is generally dominated by snow accumulation (Agosta et al., 2019; Van Wessem et al., 2018). The main SMB sinks for the AIS are sublimation and wind ablation and melt water runoff, although the latter is negligible for the AIS due to the very low surface temperatures.

Large-scale atmospheric circulation (100s of km) strongly controls SMB in Antarctica~~, bringing air masses with a high moisture and temperature content (Lenaerts et al., 2019)~~. This large-scale ~~(100s of km) atmospheric circulation usually~~ atmospheric circulation embeds synoptic-scale cyclones that collect heat and moisture from further north, including the Southern Ocean, which they can release onto the AIS ~~(Gorodetskaya et al., 2014; Sodemann and Stohl, 2009; Wang et al., 2019)~~(Gorodetskaya et al., 2014; . SMB shows a large coast-to-interior gradient with very low SMB values in the continental interior (Scarchilli et al., 2011; Fujita et al., 2011; Favier et al., 2013; Frezzotti et al., 2007), although atmospheric rivers can bring mid-latitude moisture very deep into the interior (Gorodetskaya et al., 2014). Large-scale atmospheric modes ~~of variability~~ dominate snow accumulation variability in Antarctica (Lenaerts et al., 2019). Notably, the Southern Annular Mode has been shown to have a dominant role in driving snow accumulation variability, particularly in the Antarctic Peninsula ~~(Thomas et al., 2008, 2015, 2017)~~ (AP, Thomas et al., 2008, 2015, 2017) and to largely explain the observed SMB trend patterns across the entire AIS during the 20th century (Medley and Thomas, 2019). In addition, based on the Clausius-Clapeyron relationship, the increasing ~~surface air temperature (SAT) due to climate change should induce a greater moisture holding capacity~~ mid and upper troposphere temperature due the warmer climate implies that the vapor pressure of the air is higher, and therefore ~~increased snowfall (Frieler et al., 2015) with increased SAT~~snowfall is increased (Frieler et al., 2015; **?**). If this predicted increase in SMB is linked to increasing ~~SAT~~ temperatures in the 21st century, it will be interesting to see if SMB and SAT are linked in the past ~~too~~centuries too, since an increase in SAT and tropospheric air temperature are strongly correlated (Kirtman et al., 2013). In this case, ~~in which case~~SMB records over time will be a helpful tool to constrain past ~~climates~~temperature reconstructions (Dalaiden et al., 2020).

Ice cores provide an important local and regional record of snow accumulation (Thomas et al., 2017), while the δ^{18}O measured in the ice cores is often used as a proxy ~~for SAT (Stenni et al., 2000; Frieler et al., 2015)~~of snowfall-weighted SAT (and by extension of SAT, Stenni et al., 2000). The SMB and SAT records should be correlated, regardless of whether SMB is controlled by the Clausius-Clapeyron law or by synoptic-scale atmospheric circulation. Several studies have already shown SMB and δ^{18}O to co-vary in ice cores and SMB and SAT to co-vary in models in specific AIS regions. Medley et al. (2018) calculate a sensitivity between SMB and SAT around 19 mm w.e. °C^{-1} over Queen Maud Land using global atmospheric models, Frezzotti et al. (2004) measure a linear snow accumulation increase of ~15 mm w.e. per °C increase in firn temperature in ice cores over Adélie Land and Frieler et al. (2015) observe and model a linear increase ranging from ~4.5 to 7% K^{-1} over the AIS. However, Medley and Thomas (2019) have recently shown that, despite a continent-wide temperature warming, SMB trends vary strongly spatially at the continent scale. Both the ice core records and the models used in the study point to a complex SMB-SAT relationship. ~~?~~ Dalaiden et al. (2020) have described the co-variance of SMB-SAT on millennial and centennial timescales for seven distinct Antarctic regions. However, ~~the same authors~~ they already display a large discrepancy in the strength of the co-variance at this continental scale between the ice core records and the model predictions.

Added complexity in snow accumulation records originates from smaller-scale (several kilometers or less) wind-based redistribution of snow that is superimposed on ~~large-scale atmospheric circulation accumulation sources. We will refer to this wind-based redistribution as the "local-scale"~~the patterns originating from the spatial variability in precipitation. Wind speeds that reach a threshold speed (~5 m s^{-1}) can pluck snow from the surface and redeposit it up to several kilometers away where winds decelerate or remove it through blowing snow sublimation (Frezzotti et al., 2004; King et al., 2004; Lenaerts et al., 2019; Agosta et al., 2019). Due to the temperature inversion that commonly occurs near the surface of the ice sheet, the surface air is negatively buoyant and flows down-slope through the influence of gravity (van den Broeke et al., 2002). Whillans (1975) shows a strong relationship between slope, wind strength and mass drift transport. With increased distance and steepness of slope, these dry cold air masses originating from the interior accelerate significantly as they flow down towards the coast, the so-called katabatic winds (Bromwich, 1989; Bromwich and Liu, 1996), reaching speeds of ~~19.4~~ 20 m s^{-1} in Adélie Land (van den Broeke et al., 2002), and up to 90 m s^{-1} measured at Cape Denison (Ball, 1957). Katabatics can cause widespread snow redistribution over kilometers and thus affect the local SMB.

Winds can also impact surface accumulation over even shorter spatial scales (10s of meters to kilometers)~~when they flow over surface topography~~. As surface winds flow over surface topography, they typically erode the windward side and deposit on the leeward side, thus reworking the SMB record spatially (Black and Budd, 1964; Budd, 1971; Dattler et al., 2019). If winds are very persistent in direction and speed, wind redistribution of the snow pack can create fields of dunes ~~(Frezzotti et al., 2002b; Arcone et al., 2012a; Das et al., 2013)~~ (Frezzotti et al., 2002b; Arcone et al., 2012a; Das et al., 2013) or blue ice areas (Spaulding et al., 2012). Winds also have a strong effect on SAT at the ~~local-scale~~ local scale and therefore affect the co-variance of SMB-SAT. For instance, Lenaerts et al. (2017) show that persistent katabatic winds on the Dronning Maud Land (DML) coast can strongly warm the air temperature through enhanced air column mixing at the grounding line.

An additional influence on SAT at the ~~local-scale~~local scale, but also at ~~large-scale~~larger spatial scales, is when large-scale (synoptic) winds interact with surface topography that acts as an obstacle to air flow. A thermodynamic effect will occur, known at the ~~Foehn~~ foehn effect. This ~~Foehn~~ foehn effect can occur across mountain ranges (e.g. the ~~Trans-Antarctic Mountains~~AP mountain chain) or isolated bumps (e.g. ice promontories or ice rises). Cooling and condensation during uplift of the air mass will remove moisture which implies latent heating of the air and results in warmer air descending on the lee side of the surface topography (Elvidge et al., 2015; Elvidge and Renfrew, 2016). This has been well documented for the AP (Datta et al., 2018, 2019).

Despite these processes that render our interpretation of ice core records difficult, we need the ice core observations to go back in time to validate model reconstructions before the period when we have direct measurements.

Our work follows from that of ~~(?)~~Dalaiden et al. (2020), in which they show that SMB and SAT are strongly interannually correlated at the continental scale over ~~historical~~ millennial (1000–2005 AD) and historical (1850–2005 AD) timescales. Here, we examine whether the relationship remains strong at the model grid point scale (which we refer to as the regional scale) and the ice core scale (referred to hereafter as the local scale). For this, we use a suite of Global Climate Models (GCM), a Regional Climate Model (RCM) and published ice core compilations available for the AIS. Combining both in-situ measurements and model simulations allows us to characterise the SMB-SAT relationship over these different spatial scales. In summary, we want to understand the following aspects of the link between SAT and SMB:

1. ~~Which processes~~ Do the processes that link SAT and SMB at ~~regional scales and how do they scale down from conclusions at the continental scale~~the continental scale also play a dominant role at the regional scale?

2. How does the SMB-SAT link in models at the regional scale compare to that in ice cores at the local scale?

3. Can our improved understanding of processes at the regional scales explain why the SMB-SAT link measured in ice cores is different to the link as measured in models?

In addition to an improvement of our understanding of the dynamics of the system and the processes controlling SMB, answering these questions will help constrain our confidence in using SMB as a direct proxy for SAT over the entire AIS. With relatively few in-situ observations, additional SAT proxies would be extremely beneficial for Antarctic climate reconstructions.

Because of the resolution of the ice cores, the focus of our analysis will be interannual variations, both for models and observations. We start with a brief description of the data sets and models used in this study. Then we compare the positive SMB-SAT relationship, as well the SMB-δ^{18}O relationship, obtained in the models at regional scale to ~~compare to~~ the continental-scale results of ~~?~~Dalaiden et al. (2020). We hypothesize physical mechanisms that could explain the discrete areas of the AIS where the SMB-SAT relationship is weak, compared to the continent-wide positive SMB-SAT relationship. We then examine the SMB-SAT relationship in the ice core data, and attempt to reconcile the differences between the results at this local scale and those from the models at the regional scale.

2 Methods and Data

2.1 Isotopic global climate models

To study longer-term regional climate variability, we use modeled SMB and SAT from four isotope-enabled GCMs (iGCMs hereafter) taken from the Coupled Model Intercomparison Project Phase 5 (CMIP5). These were chosen specifically because (1) they have historical simulations for the required variables (SAT, and precipitation and sublimation/evaporation for SMB), (2) they simulate water isotope variations (δ^{18}O) explicitly, which can be compared directly to water isotopes from the ice cores and (3) for consistency with those used in the ~~?~~ Dalaiden et al. (2020) study (with the additional fourth made available recently, ~~Brady et al. (2019)~~iCESM1, Brady et al. (2019); Stevenson et al. (2019)). The iGCM characteristics are detailed in ~~? but we~~ Dalaiden et al. (2020) and Brady et al. (2019) but we briefly describe their relevant characteristics to this study~~briefly~~:

- ECHAM5-MPI/OM is a fully coupled GCM that includes atmospheric and oceanic components, and covers the period 800–2000 AD. It is forced by natural and anthropogenic forcing (Sjolte et al., 2018) and has a spatial resolution of 3.75° × 3.75° (for the atmospheric component).

- ECHAM5-wiso is a GCM that only includes an atmospheric component and covers the period 1871–2011 AD driven by ~~a~~ sea surface temperatures and sea ice (Rayner et al., 2003) at a spatial resolution of ~1° (Steiger et al., 2017).

- iHadCM3 is the isotope-enabled version of the fully coupled version of GCM HadCM3 ~~(Turner et al., 2016; Holloway et al., 2016)~~ (Turner et al., 2016; Holloway et al., 2016) and covers the period 1851–2003 AD at a spatial resolution of 3.75° × 2.5° (for the atmospheric component).

- iCESM1 is an isotope-enabled version of CESM1 (Brady et al., 2019). It has active atmosphere, land, ocean, river transport and sea ice model components, with a spatial resolution of ~2° for the atmospheric model. The simulations cover 850–2005 AD. iCESM1 is an addition to the iGCM model list of the ~~?~~ Dalaiden et al. (2020) study.

~~Because~~ Dalaiden et al. (2020) provide an evaluation of first three iGCMs used, and we provide an evaluation of the SMB, SAT and the atmospheric circulation (we use sea-level pressure) for all four iGCMs in Supplement S2. SMB and SAT are evaluated against RACMO27, while sea-level pressure is evaluated against ERA-Interim as the ERA-Interim grid extends further north. The evaluation is done over the 1979–2000 AD time period, the longest period of overlap for all the models examined. We show that all four models produce realistic SMB, SAT and sea-level pressure outputs, with biases likely linked to differences in their physics as well as their spatial resolutions (see supplement S2).

For the iCESM1 and iHadCM3 ~~have~~ GCMs ensembles that include three and seven simulations, respectively (each has slightly different initial conditions), we ~~average over their~~ first calculate the correlation of the two variables (SMB-SAT or SMB-δ^{18}O) for every grid point for each ensemble member (3 for iCESM1 and 7 for iHadCM3). Then we obtain the mean of the correlation values per grid point over each ensemble of simulations ~~to obtain a mean representation of SMB, SAT and δ^{18}O for each iGCM. Although there are slight spatial differences, all four iGCMs show similar spatial variations of the correlation between SMB-SAT and δ^{18}O-SMB on the continent scale (see Fig.S1-S4, ? provide an evaluation of the iGCMs used here).~~ for both iCESM1 or iHadCM3. These ensemble means are then compared to the correlations calculated for ECHAM5-MPI/OM and ECHAM5-wiso, as well as with observations.

As we conduct a high number of significance tests on gridded maps, we increase the number of false rejections of the null hypothesis (Wilks, 2016). We apply the correction method to gridded maps, as described by Benjamini and Hochberg (1995) , which controls the "False Discovery Rate" (FDR), i.e the fraction of erroneously rejected null hypotheses. For N local hypothesis tests (i.e. number of model grid points), we obtain N p-values (p_i) for i = 1 to N. Local null hypotheses are rejected if their p-values are no larger than a threshold level (p_{FDR}) calculated from the distribution of the sorted p-values p_i, as described by Wilks (2016):

$$p_{(FDR)} = max_{i=1,...N}[p_{(i)} : p(i) <= (i/N)\alpha_{FDR}] \qquad (1)$$

In our case, we choose control an α_{FDR} value of 0.05, which allows us to calculate a p_{FDR} value for each correlation map. The threshold p-value p_{FDR} determines if a correlation is significant or not. In the case of the iHadCM3 and iCESM1 models, we do not average the p-values obtained from the different members as for the correlation values, but rather apply a threshold of at least 50% of p-values < p_{FDR} to define whether a grid point correlation value is significant (which we then simply label as “significant” on the figures).

To compare the iGCM continent-wide correlations to the RCM-derived correlations, we interpolate the iGCM correlation results onto the RCM grid and average over all four iGCMs (Fig. 4 and 2, panels e). P-values are not interpolated but rather a threshold of at least 50% of p-values < ~~0.1~~ p_{FDR} is used to define whether a grid point correlation value is ~~significative. Note that we choose a threshold p-value of 0.1 due to the short length of some data sets. The individual iGCM correlation results can be found in supplementary Fig.S1-S4~~significant, the same way it was done for iHadCM3 and iCESM1 ensemble members.

In this study, we focus on two time intervals for the iGCMs: a longer (~~~150 year~~130 years) timescale covering 1871–2000 AD to compare to the measured ice core SMB and δ^{18}O data, and a shorter (~~~40~~ 40 years) timescale covering 1961–2000 AD for comparison to the RCM simulations and measured SAT. Since the ice core δ^{18}O data in the regional compilation of Stenni et al. (2017) are 5-yearly in resolution, and we wish to build upon the findings of the Dalaiden et al (2020) study which uses 5-yearly data, we also look at 5-yearly correlations between SMB and δ^{18}O for the iGCMs. To ensure that ~~a shorter time interval~~ the time period selected does not impact the correlations, we calculate the ~~δ^{18}O-SMB and~~ SMB-SAT ~~correlations~~ and SMB-δ^{18}O correlation over the 1871–2000 AD (annually for SMB-SAT and 5-yearly for SMB-δ^{18}O) and the 1961–2000 AD intervals (annually) for the iGCMs (Fig. S1 and S2). We show that ~~both correlations are very~~ correlation strengths are similar over the two time intervals, both in spatial distribution and in continent-wide average (see ~~Fig.??). The main difference is that~~Section 3). As expected, with a shorter time interval, p-values tend to increase (e.g. compare Fig. 4 over 1871–2000 AD and Fig. S1 over the 1961–2000 AD interval). Using 5-year averages (Fig. 2) instead of yearly values of SMB and δ^{18}O (Fig. S3) does not impact the correlation strength significantly (iGCM average 0.47±0.13 vs 0.45±0.12), but it increases the p-values (80% vs 95% significant grid cells), due to the ~~shorter time interval , the surface area with a correlation p-value > 0.1 increases~~time series’ effective shortening. We choose to use the 1961–2000 AD time interval instead of starting in 1979 AD as for the RCM simulation, so that all model simulations have a similar length (40 years and 38 years for the iGCMs and the RCM, respectively) to ensure that the correlation results are as meaningful as possible.

2.2 RACMO2.3p2 regional climate model

For regional climate variability at a higher spatial resolution, we use the RCM Regional Atmospheric Climate MOdel version 2.3p2 (RACMO2.3 hereafter) which provides SMB, SAT and other relevant atmospheric variables for the entire AIS. RACMO2.3 combines the atmospheric dynamics of the High Resolution Limited Area Model (HIRLAM5, Unden et al., 2002) and the physics package of the European Centre for Medium-range Weather Forecasts (ECMWF, 2009). It is forced at its boundaries by the ERA-Interim reanalysis from ECMWF over 1979–2016 AD. This version of RACMO is coupled to a multi-layer snow model which includes a snow albedo and a drifting snow scheme (Lenaerts et al., 2010), thus making it particularly well suited to ~~studying~~ study polar regions. RACMO2.3 has been demonstrated to have the best fit to recent AIS SMB observations compared to other atmospheric and reanalysis models (Wang et al., 2016). A ~~more~~ detailed description of RACMO2.3 can be found in Van Wessem et al. (2018). In this study, we use the 27 km horizontal gridding simulations over the entire AIS (Van Wessem et al., 2018), as well as the 5.5 km horizontal gridding simulations focused on the DML region (~25°W–45°E, Lenaerts et al., 2017). The latter configuration at higher resolution allows studying in more details a region with complex surface topography and SMB records ~~(Lenaerts et al., 2017, 2014, ,etc.)~~(Lenaerts et al., 2017, 2014). Both RACMO2.3 simulations cover 1979–2016 AD. We will refer to these as RACMO27 and RACMO5 hereafter.

2.3 In-situ measurements

The annual correlations obtained from the model simulations are compared to in-situ measurements of SMB, SAT and δ^{18}O from ice cores and weather stations.

Ice cores provide a measurement of SMB based on the measured distance between distinct seasonal depth markers within the ice core on historical timescales. The annual layer thickness is corrected for densification, compaction and ice flow to produce a water equivalent snow accumulation. We use the Thomas et al. (2017) compilation, the most comprehensive SMB compilation to date for the AIS. Thomas et al. (2017) use 79 ice cores over the AIS to obtain a SMB record with an annual resolution that covers the last millenium up to 2010 AD.

Ice cores record variations ~~with depth of the ice's~~ of the δ^{18}O of the ice with depth. Here we use the Stenni et al. (2017) compilation (a total of 112 ice cores) over the AIS to obtain a δ^{18}O record that covers the past millennium up to 2014 AD with ~~a 5-year~~ yearly resolution for 0–2014 AD and 5-yearly resolution for the regional averages. The ice core δ^{18}O record can ~~also~~ be used as a proxy for ~~SAT. However, studies have shown that δ^{18}O is not a perfect proxy for SAT (?Klein et al., 2019; ?; Goursaud et al., 2019 . ?~~ snowfall-weighted SAT, but the link between the two variables can be complex and sometimes is quite weak (Dalaiden et al., 2020; Klein . Dalaiden et al. (2020) have shown that the ~~correlation between~~ annual correlation between SMB and δ^{18}O ~~and SMB was weaker than the correlation of SAT with SMB~~ was weaker (but still significant) than the annual correlation of SMB with SAT for seven distinct regions at the continental scale.

Because ice cores do not provide a direct measurement of SAT, we rely on the Nicolas and Bromwich (2014) SAT reconstruction~~which uses~~. Nicolas and Bromwich (2014) use SAT records from 15 weather stations around the AIS (mostly coastal~~) to calculate an interpolated AIS-wide SAT field. This~~, Fig. S4c) to produce estimates of monthly gridded mean temperature anomalies for the whole continent over 1958–2012 AD. The reconstruction is based on a kriging technique, originally developed for the reconstruction of Antarctic snowfall (Monaghan et al., 2006), to interpolate the data between the stations. The interpolated SAT field allows us to correlate SAT and SMB directly at the ice core locations so as to compare to the RACMO2.3 results. ~~The Nicolas and Bromwich (2014) reconstruction is limited to the 1958–2012 AD time interval.~~ To calculate the significance of our correlations, we choose a p-value of 0.05.

In the Thomas et al. (2017) and Stenni et al. (2017) ice core data compilations, most of the ice core records start ~~~~~after 1800 AD, ~~which is why~~ and we choose to correlate the SMB and temperature signals ~~over the same timescales as the models,~~ starting in 1871 AD in order to compare to the models. Furthermore, the spatial distribution of the ice cores over the AIS is not homogeneous~~, with~~. If we divide Antarctica into low elevation areas (i.e. $<$2200 m) and high elevation areas (i.e. $>$2200 m), the majority of the ice cores are located in the ~~coastal~~ low elevation areas, and very few in ~~the interior (~~high elevation areas (except for the large number of ice cores all located in DML, see supplementary Fig. ~~S5~~S4). This certainly introduces a spatial bias in our ice core-based annual correlation towards coastal signals and processes.

3 Results and Discussion

3.1 ~~How do~~ Do the processes that link ~~SAT and~~ SMB and SAT at the continental scale ~~vary~~ also play a dominant role at the regional scale?

3.1.1 Strength of the link between SMB and SAT at the regional scale

~~? have shown that the relationship between SMB and SAT is positive on the continental scale for each of their seven Antarctic regions, whether they used the GCMs or RACMO2.3 simulations. Here, we~~ We calculate the annual correlation between SMB and SAT at the regional scale over 1871–2000 AD, the time interval shared by all iGCMs. We obtain a positive annual relationship between SMB and SAT at the regional scale with a continent-wide average value of 0.57 and a spatial standard deviation of ±0.10 (hereafter referred to as ±0.10) over the four iGCMs (the individual iGCMs continent averages range from ~~0.52-0.59~~0.54-0.60) with a p-value ~~< 0.1~~ $\leq p_{FDR}$ for more than ~~95~~96% of each ~~GCM~~iGCM's surface area (Fig. ~~??, panel c). Moreover, the maximum and minimum correlations obtained are consistent between iGCMs, in magnitude and spatial distribution (see supplementary Fig. S1-S4)~~4), and $>$ 99% on average. We note some spatial differences between models, in particular we focus on five distinct regions of the ice sheet: (1) the AP (also "AP" on Fig. 4) shows weak correlations for iCESM1 and ECHAM5-wiso (0.22-0.24, 57-76% significant grid cells) and positive correlations for ECHAM/MPI-OM and iHadCM3 (0.51-0.60, 100% significant), (2) central West Antarctica ("CWA") which shows the same contrast between iCESM1 and ECHAM5-wiso versus ECHAM/MPI-OM and iHadCM3 (0.31-0.48, 78-91% significant versus 0.63 and 100% significant), (3) the East Antarctic Plateau ("EAP") which shows positive and 100% significant correlations (0.58-0.70);

the Amery Embayment ("AE") and Adelie Land ("AL") which show positive correlations (0.49-0.57 and 0.49-0.69, 100% significant). Areas of weaker SMB-SAT correlations are only observed in iCESM1 and ECHAM5-wiso, which could arise from the models' finer spatial resolution compared to iHadCM3 and ECHAM5-MPI/OM. The SMB-SAT correlation remains positive overall for all models. We obtain the same result if we take non-overlapping 5-year averages of the SMB and SAT variables to calculate their 5-yearly correlation (~~see~~ supplementary Fig. ~~S6).~~ S5).

We repeat the annual correlation of SAT and SMB using the RACMO27 simulations over 1979–2016 AD (~~see Fig. ??~~Fig. 4, panel f). At this spatial scale, the annual correlation is also positive in the large majority of ~~regions~~ the ice sheet with a similar range of correlation values and a continent-wide average value of 0.54±0.22~~.~~, which is within the range of the iGCM average (0.57±0.10). For the same five distinct regions, we can see that the EAP and AL are also positive and 100% significant. For AP and CWA that had a lower correlation for iCESM1 and ECHAM5-wiso, we see a stronger weakening down to 0.27 with a lower percentage of significant grid cells (48%). The AE area is most distinct with a correlation average of 0.22 and ~30% significant grid cells. The much higher spatial resolution of RACMO27 with respect to the iGCMs is likely behind these differences and the higher percentage of areas with a weaker correlation value, if we compare to what we observed for the iGCMs.

Moving down to RACMO5 simulations, the highest spatial model resolution available to us, we show that the annual correlation in the DML region is also positive, with a regional average value of 0.48±0.18 (comparable to an average value of 0.52±0.21 for RACMO27 for the same region, ~~see~~ Fig. 3). ~~This implies that the~~ The annual correlation of SMB and SAT is therefore similar over the 1871–2000 AD and the 1979–2016 AD time intervals, and from a spatial resolution of > 1° down to 5.5 km. ~~Whatever~~ We observe a positive correlation for the continent as a whole, strongly positive values for the EAIS plateau and WAIS (with always the presence an area of non significant correlation in central West Antarctica), but weaker values with proximity to the coast, along the eastern side of the AP and in the Amery Embayment.

Dalaiden et al. (2020) have shown that the relationship between SMB and SAT is positive on the continental scale for each of their seven Antarctic regions, whether they used the GCMs or RACMO2.3 simulations. The simple concept that Antarctic precipitation originates mainly from lower latitudes, coming from relatively warm and wet air masses, explains the co-variance of SMB and SAT at the continental scale as shown by Dalaiden et al. (2020). This simple concept therefore also applies at the regional scale for interannual variations here. Indeed, for the temporal and spatial ~~scale, the~~ scales investigated, the annual correlation between SMB and SAT is positive for a large majority of the model grid points~~. It is also~~ , despite a few regional differences due to the models' differing spatial resolutions.

The correlation between SMB and SAT remains true for summer- or winter-only months (average SMB-SAT correlation of 0.43±0.21 or 0.56±0.21, respectively using RACMO27, ~~see~~ supplementary Fig. ~~S7~~S6) or on monthly timescales after removing the seasonal cycle (0.54±0.17 on average, ~~see~~ supplementary Fig. ~~S8~~S7).

3.1.2 Wind effects on SMB and SAT signals

There are a few areas, spatially consistent between the RACMO27, RACMO5 simulations and the iGCMs, where the SMB-SAT annual correlation is not as strong. In those areas, shaded in grey on Fig. ~~??~~ 4, panel f, for RACMO27, and outlined on subsequent figures, the annual correlation is either insignificant (p-value > 0.1p_{FDR}) or negative. A weak SMB-SAT annual correlation suggests that physical processes must affect SMB, SAT or both enough locally that they break the relationship between SMB and SAT seen at large scale in other regions. Winds are known to affect SMB and SAT locally, through wind-based redistribution of SMB, turbulent warming from katabatics and Foehn warming and adiabatic warming from katabatic winds and foehn effects on leeward slopes. The impact of wind on SMB and SAT due to this redistribution can modify the link between the two variables but this can only be resolved by the RACMO2.3 simulations, because it is the only model in this study that includes drifting snow (although according to Agosta et al. (2019), drifting snow is strongly underestimated). To evaluate whether the lack of correlation between SAT and SMB is due to such any of these wind effects, we correlate modelled surface winds to our two variables of interest.

If we define positive wind direction to be pointing down-slope, we expect wind to be negatively correlated to both SAT and SMB on average. Large-scale air masses, originating over the Southern Ocean and further north, bring warm moist air towards the interior as they flow up-slope, thus inducing a strong and negative correlation. Any area of the AIS that does not show this negative correlation between wind and SAT or SMB implies that the large-scale atmospheric air circulation does not dominate, and evidenced in a weak link between SMB and SAT.

Because wind direction with respect to surface slope and wind strength influence SMB and SAT locally (Frezzotti et al., 2004; King et al., 2004; Black and Budd, 1964; Grima et al., 2014), we take both into account in the Mean (surface) Slope in the (mean) Wind Direction (MSWD). MSWD is defined as the dot product between the mean surface slope and the mean wind direction (Scambos et al., 2012; Das et al., 2013; Dattler et al., 2019):

$$\overrightarrow{MSWD}MSWD = \overrightarrow{ws}_{10m} \cdot \overrightarrow{slope} \qquad (2)$$

with $\overrightarrow{ws}_{10m}$ the wind speed 10 m above the surface, and define $\overrightarrow{slope}$ as pointing down-slope. Winds flowing Since we define a positive MSWD as a wind pointing down-slopewill therefore , we expect winds coming from the coast up into the interior to have a negative MSWD, and winds flowing from the interior to the coast to have a positive MSWD (Fig. 4, and supplementary Fig. S8).

Surface The surface slope is calculated using the surface topography used in the RACMO2.3 simulations. As the ratio of vertical distance over horizontal distance, it slope has units of $m \cdot m^{-1}$, i.e. unitless. We then remove areas of the AIS with a negligible slope (<0.001) as in these areas, MSWD will be close to null and will introduce a lot of noise when correlating it with SMB or SAT. We then correlate SAT and SMB to this MSWD.

Large-scale air masses, originating over the Southern Ocean and further north, bring warm moist air towards the interior as they flow up-slope. At the annual time scale, these up-slope winds (negative MSWD) will therefore bring a higher temperature and SMB (positive anomaly), and thus induce a strong and negative annual MSWD-SAT and MSWD-SMB correlation (Fig. 4, scenario 1a). Similarly, winds flowing down-slope (positive MSWD) will bring drier and colder air (negative anomaly) from the interior to the coast, and will also induce a strong and negative annual correlation of MSWD with SAT and SMB (Fig. 4, scenario 2a). Any area of the AIS that does not show this negative annual correlation between wind and SAT or SMB implies that the changes cannot be interpreted simply in terms of large-scale circulation at the annual scale or descending cold air from the interior (so in that case, scenarios 1b and 2b). We are aware that cyclonic activity is punctual in time. However, by correlating MSWD to SMB and SAT over 1979–2016 AD, we make the hypothesis that we capture the first order variations of cyclonic activity at interannual timescales, and therefore the variability in the sources of heat and moisture for the continent.

We calculate the annual correlation of MSWD with both SAT and SMB at the 27 km and 5.5 km scales, using the RACMO27 and RACMO5 simulations ~~, shown on~~ (Figs. 5 and 6). Examining the results, MSWD is negatively correlated to SAT over most of the continent, with a continent-wide average of -0.31±0.37 at the 27 km scale, and a DML average of -0.4±0.35 at the 5.5 km scale (Fig. 5). MSWD is also mostly negatively correlated to SMB with a continent-wide average of ~~-0.6~~ -0.60±0.30 at the 27 km scale, and a DML average of -0.52±0.30 at the 5.5 km scale (Fig. 6). ~~Agosta et al. (2019) also show a strong link between modelled surface topography (surface curvature in their case) with SMB over the continent when wind speeds exceed 5 m s^{-1}.~~

However, a number of areas show a ~~very~~ strongly positive MSWD-SAT ~~correlation~~ annual correlation, simultaneously with a ~~weaker-to-positive~~ weaker (less negative) or positive MSWD-SMB ~~correlation, that~~ annual correlation. In addition, these areas are co-located with the areas where the SMB-SAT annual correlation is weak (outlined ~~here~~ with a magenta line). Those areas are at roughly the same locations in the 5.5 km and 27 km simulations for the DML area.

~~Let us first focus on the link between wind redistribution and SAT~~We will first examine the wind-SAT interactions. The areas where the SMB-SAT annual correlation is weak have a strong and positive MSWD-SAT annual correlation. We note that these areas tend to be on the leeward side of surface topography. The clearest example of this is found along the AP (~~see~~ Fig. 5~~). Here, Westerlies are the dominant year-around air mass trajectory (Marshall et al., 2006) and the whole eastern~~, and supplementary Fig. S9 for a zoomed-in view): the eastern (leeward) side of the AP shows ~~a very~~ positive MSWD-SAT ~~signature aligned along the Trans-Antarctic Mountains. The Trans-Antarctic Mountains create~~ correlation values around 0.4, with a low SMB-SAT annual correlation of 0.38 on average for the iGCMs and 0.15 for RACMO27. Here, Westerlies are the dominant year-round air mass trajectory (Marshall et al., 2006). The mountain chain along the AP creates a long barrier perpendicular to the air masses' dominant trajectory. The warmer air masses coming from the ocean are forced up the windward side (MSWD < 0, bringing warmer SAT from the ocean), which leads to a negative ~~correlation as snowfall (and thus SMB) is enhanced on this~~ annual MSWD-SAT correlation as this warm air is pushed-up on the windward side. ~~As the moisture-depleted~~ During this process, the air is depleted of moisture and as the now-drier air masses flow back down on the leeward side, the temperature increases (MSWD > 0 and SAT increase further) due to the ~~Foehn~~ foehn effect, thus leading to a positive annual MSWD-SAT correlation on this leeward side ~~.~~

~~The Trans-Antarctic Mountains~~ (Fig. 4, scenario 1b), as observed on Fig. 5. The AP mountains represent very steep topography but this MSWD-SAT positive/negative polarity is also observed in regions with less dramatic topography. Berkner Island (~~BI~~ "BI" on Fig. ~~??~~4, panel f) shows a very distinctive negative MSWD-SAT annual correlation on its eastern side and positive on its western side, which matches the dominant westward wind direction ~~here~~in this area in the lower level of the atmosphere. Zooming in on the DML coast (Fig. 5, panel b), each ice promontory and ice rise shows a distinctive east-west MSWD-SAT annual correlation, with the positive annual correlation found on the west sides, matching the dominant year-round westward wind direction in the area (~~see~~ supplementary Fig. ~~S9~~S10).

After examining the link with SAT, we will now focus on the link with between MSWD and SMB. We see that the areas with a low SMB-SAT annual correlation tend to have a significantly less negative/weak MSWD-SMB annual correlation. These areas correspond to (1)areas that are scenario 1b (Fig. 4), i.e. leeward of surface topography as dicussed above or (2) areas where katabatic winds are especially strong. For case (or scenario 2b (Fig. 4) when katabatic winds modify the local SMB. For scenario 1), we observe that the MSWD-SMB correlation weakens or becomes positive annual correlation weakens on the leeward side of surface topography, such the coastal ice promontories (Fig. 6). To explain this, we have to first describe average conditions. In Indeed, during average weather conditions in coastal areas, synoptic air masses carry moist air across the surface topography, releasing a significant fraction of their moisture as snow on the windward side, creating a dry accumulation shadow on the leeward side. This has been observed by Lenaerts et al. (2014) and Kausch et al. (2020) for the ice rises of the DML coast. Small-scale accumulation asymmetries across ice rises have also been observed in other regions (King et al., 2004; Morse et al., 1998) (King et al., 2004; Morse et al., 1998) and can occur on larger scales, such as across ice divides (Urbini et al., 2008) or the Trans-Antarctic Mountains (Datta et al., 2018). Stronger winds will AP mountain chain (Datta et al., 2018). However, stronger winds can affect this accumulation asymmetry by bringing more moisture and therefore more snow on the windward side, while the leeward side will either remain dry, or begin accumulating more snow if wind speeds allow for redistribution (Frezzotti et al., 2004). In the presence of strong winds, the MSWD-SMB correlation will therefore be strongly negative on the windward sides of ice topography and become weaker or increase on the leeward sidesbecome weaker on leedward slopes. This is particularly visible over across the ice promontories and ice rises on Fig. 6(bottom panel), panel b, where the western sides of these ice promontories and ice rises correspond to the leeward sides based on the dominant year-round winds for the area (see Fig. S9supplementary Fig. S10).

Now considering case (scenario 2), winds blowing from the continent interior towards the coast are of moderate strength and tend to flow at some angle to the steepest slope when they initiate near the center of the ice sheet, carrying cold dry air from the interior (Parish and Bromwich, 1987). However, when slopes become sufficiently steep, these winds can pick up a lot of speed and blow almost directly down-slope, forming a katabatic wind regime (Parish and Bromwich, 1987). Katabatic winds transport cold dense air down-slope which can cause widespread erosion of the snow-pack through surface friction locally (MSWD-SMB correlation < 0) and re-deposition of this snow further down-slope (MSWD-SMB correlation > 0). They can also cause a warming of the SAT locally at the grounding lines through increased turbulence where the surface slope breaks from steep ice to flat shelf ice (Lenaerts et al., 2017). We therefore expect that the areas regularly under the influence of strong katabatic winds will show a weaker , or cooling through ablation/sublimation. The Byrd Glacier outlet into the Ross Ice Shelf (red circle on Figs. 5 and 6, panel a) is an example of an area where katabatics are strong year-round and affect SMB significantly (Ligtenberg et al., 2014; Bromwich, 1989; Parish and Bromwich, 1987). Due to the channeling of the wind down-slope (MSWD > 0) and high sublimation/erosion of the surface (supplementary Fig. S11), most of Byrd Glacier is completely covered with blue ice (SMB = 0 or negative), which agrees with our observed negative MSWD-SMB correlation due to the episodic but persistent reduction in their SMB through wind scouring (Agosta et al., 2019). In those areas, katabatic winds reduce SMB sufficiently to overwhelm the original synoptic SMB signal (Scambos et al., 2012; Das et al., 2013). The

~~turbulence-induced warming effect of these katabatic winds is also observed in the~~ annual correlation. It also shows a negative MSWD-SAT ~~correlation.~~ annual correlation, which matches with the lowered SAT due to the strong ablation/sublimation.

The Amery Embayment (~~marked~~ "AE" on Fig. ~~??) is a good example of a region where katabatic winds are highly present. As a result, the~~ 4, panel f) is an example where the impact of the strong katabatic winds is mitigated. The Amery Embayment is associated with ~~very~~ strong sublimation rates (surface and blowing snow sublimation, supplementary Fig. S11), lowering the local SMB and creating areas of exposed blue ice (Markov et al., 2019)~~with a reduced albedo in summer (so high SATs)~~, but part of this snow gets redeposited down-slope. The Amery Embayment shows ~~therefore~~ a weaker MSWD-SMB annual correlation and a ~~very~~ strongly positive MSWD-SAT ~~correlation, both spatially more extensive~~ annual correlation on the eastern side of the Amery Embayment where katabatics ~~reach~~ start further inland and flow directly down-slope ~~(Parish and Bromwich, 1987). The Byrd Glacier outlet into the Ross Ice Shelf (marked on Fig.??) is also an area where katabatics are strong enough to affect SMB significantly (Ligtenberg et al., 2014; Bromwich, 1989; Parish and Bromwich, 1987). Due to channeling of the wind and high sublimation/erosion of the surface, most of Byrd Glacier is completely covered with blue ice (SMB = 0 or negative), which agrees with our observed weak MSWD-SMB correlation.~~ (Parish and Bromwich, 1987, and supplementary Fig. S10).

In other cases, large-scale air mass input could be sufficiently high that katabatic winds do not affect the deposited surface snow enough to break the large-scale link between SMB and SAT. For example, Adélie Land (~~marked~~ "AL" on Fig. ~~??),~~ 4, panel f) displays high snowfall rates (above 500 mm .w.e yr−1 based on RACMO2.3 results), but is also known for its record-high katabatics (van den Broeke et al., 2002)~~, .~~. This region does not display particularly weak MSWD-SMB or MSWD-SAT ~~correlations in~~ annual correlations in the RACMO2.3 results.

We therefore expect that the areas regularly under the influence of strong katabatic winds will show a weaker MSWD-SMB annual correlation due to the episodic decrease and increase of their SMB through wind scouring and redeposition, respectively, (Agosta et al., 2019). In those areas, katabatic winds can affect the SMB sufficiently to overwhelm the original synoptic SMB signal (Scambos et al., 2012; Das et al., 2013), but not systematically. At the annual timescale, which is our timescale of interest to compare to the ice core data, the net effect of katabatic winds on SMB is uncertain. Other studies have shown the strong interactions between surface surface topography and winds. For instance, Agosta et al. (2019) examine the spatial link of time-averaged values of surface curvature and surface winds and they observe that above a certain threshold, winds will affect SMB locally in pattern that matches that of drifting snow fluxes as modeled by RACMO2.3. Dattler et al. (2019) also show that, at length scales $<$ 25 km, regions of the West Antarctic Ice Sheet show high spatial variability in accumulation simultaneously to high variability in wind speed and direction.

If we now combine the effects of the wind on SAT and SMB, we see that the areas that have a low SMB-SAT annual correlation (outlined by ~~magenta~~ dashed black lines on Fig. ~~??~~4, panel f for RACMO27) correspond to a generally positive MSWD-SAT ~~correlation (~~annual correlation (average of 0.03 versus -0.31 for the whole ice sheet, Fig. 5) and ~~weak~~ weaker MSWD-SMB ~~correlation (Fig~~annual correlation (average of -0.42 versus -0.6 for the whole ice sheet, Fig. 6). The winds, ~~Foehn~~ foehn or katabatics, affect local SAT and SMB in those areas but not to the same extent. The synoptic signal consisting of warm and moist air input, or descending cold dry air input, is therefore overwhelmed by wind-induced local SAT or SMB changes, resulting in a weak SMB-SAT annual correlation. Interestingly, we note that the ice rises present on the ice shelves themselves along the DML coast on Fig. 3 do not show a weak SMB-SAT annual correlation. However, they show both positive MSWD-SMB and MSWD-SAT annual correlations on their leeward sides, both negative MSWD-SMB and MSWD-SAT annual correlations on their windward sides. ~~Perhaps here snowfall input from further north is so high that it dominates the SMB and SAT records.~~

3.1.3 Spatial-scale dependence of the modelled SAT-SMB annual correlation

To further analyse the spatial scale dependence of the SAT-SMB annual correlation, we smooth the ~~RACMO05~~ RACMO5 SMB and SAT fields over a step-wise increasing grid spacing, going up to 27.5 km. We calculate the annual correlation between SMB and SAT for each spatial ~~resolutions~~ resolution (Fig. 7). We see that spatial ~~scaling~~ smoothing has little effect on the SMB-SAT annual correlation in the model, whose average value remains between 0.48-0.49. Similarly, the areas where the SMB-SAT annual correlation was already weak do not change spatially, and remain co-located with the areas that have a weak SMB-SAT annual correlation at the 27 km scale (shown as dashed black lines). In conclusion, based on the models, the link between SAT and SMB is positive, and valid at all investigated spatial scales, with the exception of areas where wind-induced processes sabotage the link locally.

3.2 Strength of the SMB-SAT link in the ice core data

~~Now that we have a better understanding from the models, let us look at the~~ We next examine in-situ measurements of SMB, SAT and δ^{18}O.

Because ice cores provide δ^{18}O and not SAT directly, we first examine the correlation between SMB and δ^{18}O ~~and SMB~~ in the models to compare to the ice core records.

The iGCM simulations give a SMB-δ^{18}~~O-SMB~~ O continent-wide average ~~correlation of 0.45~~5-yearly correlation of 0.47$\pm$~~0.12~~ 0.13 over 1871–2000 AD (~~see Fig. ??, panel a~~Fig. 2), compared to the average SMB-SAT annual correlation of 0.57$\pm$0.10 for the same time interval (Fig. ~~??, panel c). We thus~~ 4). The strength of the correlation is weaker for SMB-δ^{18}O than for SMB-SAT for each iGCM, and the percentage of significant grid cells is greatly reduced (although part that reduction is due to the use of 5-yearly averages, instead of annual, supplementary Fig. S3). If we examine the same five regions as described previously for Fig. 4, we see that the 4 iGCM results are consistent, albeit with differences in percentage of significant grid cells. We draw the same conclusions at the regional scale as ~~?~~ Dalaiden et al. (2020) at the continental scale: the SMB-SAT annual correlation is stronger than the SMB-δ^{18}~~O-SMB~~ O annual correlation at the regional scale, with a difference on the order of ~0.1.

We then calculate the ~~correlation between δ^{18}O-SMB and~~ annual correlation between SMB-SAT and the 5-yearly correlation between SMB-δ^{18}O for the ice cores, using the Nicolas and Bromwich (2014) ~~compilation for SAT measurements~~SAT reconstruction over 1958–2010 AD. We showed earlier that the timescale used does not affect our conclusions in terms of ~~correlation (see Fig. ??). Therefore we can~~ annual correlation. We can therefore compare SMB-SAT annual correlations over different time intervals between the models and the observations. We observe a weak-to-null annual correlation between SAT and SMB over 1958–2010 AD in the ice cores (Fig. 8) with an average value of 0.09$\pm$0.18 over all the ice cores, versus a continent-wide average value of 0.57±0.10 for the iGCMs (Fig. 4, panel e) and 0.54±0.22 for RACMO27 (Fig. 4, panel f). The same is true for the correlation between 5-yearly correlation between SMB and δ^{18}O and SMB over 1871–2010 AD with a continent-wide average value of 0.13±0.25 (5-yearly and over 1871–2010 ADFig. 8), versus a continent-wise average value of 0.47±0.13 for the iGCMs (Fig. 2). We note no observable difference in the correlation annual correlation strength between SAT-SMB and SMB-δ^{18}O-SMB O in the ice core records, as opposed to in the models.

3.3 Can our improved understanding of processes at regional scales help to explain why the SMB-SAT link measured in ice cores is different to the link as estimated in models?

We list six potential reasons why ice cores might show a weaker relationship between SMB and SAT or between SMB and δ^{18}O or SMB and SAT O than the models. (1) First, we argue that the difference in annual correlation between the models and the observations could arise in because of the representation of large scale processes in the models. In other words, the models (iGCMs and RCMs alike) may not represent the reality well enough because they are missing an important dynamic process, i.e. a process that acts to weaken the annual correlation between SMB and SAT. However, we argue that this is unlikely since the iGCM and RACMO2.3 simulations agree despite their different fundamental representations of the physics at work and different resolutions. (2) A second hypothesis is that the models do not represent processes well enough at the scale of a few 10s of kilometers. 5.5 km, the RACMO2.3 spatial scale, is a spatial resolution that is still too coarse to resolve small-scale SAT or SMB-modifying processes. In particular, wind redistribution has been shown to be under-estimated in the polar-focussed polar-focused RCMs (Agosta et al., 2019). Turton et al. (2017) have shown that a spatial resolution of 1.5 km is required to simulate Foehn foehn flow accurately over the AP. In addition, we also know from observations that a lot of local-scale local scale snow redistribution effects occur to form sastrugi, dunes, etc, which are not resolved in simulations at the 5.5 km scale (Ligtenberg et al., 2014).

(3) On the data side, we know that the Nicolas and Bromwich (2014) SAT data set is not representative of the entire AIS. With only 15 data points for the entire AIS, mostly located around the coast (supplementary Fig. S4c), this data set has a strong coastal-signal bias(see Nicolas and Bromwich (2014) supplementary material for the weather station distribution)coastal signal bias. We have shown in Fig. ?? 4, panel f, that the coastal regions correspond to weaker SMB-SAT annual correlations. However, it does not explain why the SMB-δ^{18}O-SMB O annual correlation is also weak. (4) Also on the data side, the ice cores might contain a noisy record of SMB and δ^{18}O, therefore reducing the measured correlation between the two. We have to keep in mind that ice cores are point measurements on the ice sheet, with a surface area of ~31 cm^2. The ice cores are affected both by (a) measurement errors due to depth, density and age uncertainties (Parrenin et al., 2012)and (b) , and surface wind processes which act to redistribute the snow at the surface and therefore reduce or increase SMB very locally (e.g. ice crests, sastrugi, ice crusts, etc) or on large areas (e.g. dune fields, Das et al., 2013), thus inducing a representativity error. This local noise, sampled in the ice core records, might get averaged out at the 5.5 km scale in models. A large number of ice cores might help reduce the noise contained in individual records, if this noise is random. However, estimating this may be hampered by the relatively low number of historical ice core records (53 ice cores were used here to calculate the SMB-SAT and SMB-δ^{18}O annual correlations using the Stenni et al. (2017) and Thomas et al. (2017) compilations), as discussed below.

(5) In addition, many of the ice cores retrieved so far from the AIS, and used in the Stenni et al. (2017) and Thomas et al. (2017) compilations, are clustered in the coastal areas, with a higher sampling in West Antarctica than in East Antarctica. This implies that the SMB-SAT annual correlation calculated based on these ice core compilations is likely not representative of the continent-wide, or even regional, SMB-SAT annual correlation. However, it cannot explain the discrepancy with the model-derived annual correlations as most of the ice cores used are located where the models locally predict a positive SMB-SAT ~~correlation (outlined~~ annual correlation (i.e. outside of the grey shading on Fig. 8). (6) Finally, we examine the correlation between SMB and SAT on annual timescales, but we know that SMB (snowfall in this case) is brought to the AIS in very episodic ways (atmospheric rivers, etc, Gorodetskaya et al., 2014). Using annual values might not be representative of the conditions during accumulation. Turner et al. (2019) show that more than 70% of the ~~annual accumulation consists of~~ variance of the annual precipitation is explained by extreme events that have a very short duration (one or more consecutive days).

When comparing model (in particular RCM) and ice core results, it is thus not simple to assess the origin of the differences in interannual variations. The advantage of RCMs is that they are self-consistent: the SMB and SAT values simulated are linked by the physics of the model. However, RCMs also include errors that are difficult to trace (difficulty of representing blowing snow or diamond dust). RACMO2.3 for example includes blowing snow processes but Agosta et al. (2019) have shown that its spatial variability is under-represented and that it is underestimated by a factor of 3. Furthermore, RCMs can only go back in time as far as we have reliable reanalyses to drive them at their boundaries (often stopping around 1979 as previous to that, measurement biases increas Ice cores on the other hand can have different biases dependent on different variables (ablation, diffusion, measurement errors, location, etc). However, they allow us to go back further in time than direct observations.

To see whether the lack of correlation between SMB and SAT in ice cores versus models is due to the presence of local random noise in the ice core records, we aggregate ice cores onto a regularly spaced grid, similarly to how we smoothed the RACMO2.3 data previously (~~see~~ Fig. 7). Since there are few ice cores (53), we use the RACMO27 model grid and average the ice core records every four grid points, i.e. we aggregate ice cores on a 108 x 108 km regular grid. So that high accumulation sites do not dominate the averages calculated, we first normalize the ice core records (SMB and SAT) by subtracting the mean value over 1960–1990 AD (a period common to all ice cores) and dividing by the standard deviation over that same period (i.e. we use their z-score value). If the lack of correlation between SMB and SAT is due to random noise that operates below the RACMO5 spatial scale, we should see an increase in the SMB-SAT annual correlation using the aggregated climate records. ~~Of course, we will only see an increase in the SMB-SAT with ice core aggregation if we have enough ice cores.~~ We observe that both the SMB-SAT and the SMB-δ^{18}~~O-SMB~~ O annual correlations remain at 0.09 and 0.13 respectively (not shown). If we average records every eight grid points (216 x 216 km grid), the SMB-SAT annual correlation increases up to 0.12 from 0.09 previously, while the SMB-δ^{18}~~O-SMB~~ O annual correlation increases to 0.16 from 0.13 previously (~~see~~ Fig. 9). This ~~is more consistent with what we concluded from the models, and suggests that~~ suggests that a small part of the discrepancy between ice cores and models ~~is in fact~~ could be due to noise at the ice core level. The ~~correlation remains~~ annual correlation remains very low compared to the models, however.

We repeat the scaling experiment but increase further the distance over which we aggregate the ice core records, from every four RACMO27 grid points step-wise up to every 24 RACMO27 grid points (i.e. 648 x 648 km grid). We only retain grid points that aggregate five or more ice cores to have sufficient averaging of the ice core records (Fig. 10). For each retained grid point, we calculate (1) the mean of the SMB-SAT annual correlation of each individual ice core aggregated (= “individual ~~mean”~~means”, in light blue on Fig. 10) and (2) the annual correlation of the averaged SMB and SAT records from the aggregated ice cores (= “aggregate ~~value”~~values”, in dark blue on Fig. 10). Due to the scarcity of ice core measurements, few grid points satisfy our condition of five or more ice cores (e.g. only three grid points contain at least five ice cores at the 648 x 648 km grid resolution~~). Results are shown in~~ , corresponding to the spacing of 24 grid points on Fig. 10). Two conclusions emerge from this scaling experiment: (1) ~~the aggregate correlation is generally~~ on average, the aggregate annual correlation is higher than the individual mean ~~correlation (and always higher if we use at least ten ice cores)~~annual correlation, (2) this is true at all investigated spatial scales. ~~Per grid point, averaging~~ Averaging the climate signals in the ice core records before calculating the annual correlations (i.e. the aggregate value) increases the ice core SMB-SAT annual correlations by ~0.1-0.2, reaching a correlation up to ~~0.2-0.3 if at least 10 ice cores are aggregated~~0.3.

For comparison, we calculate the individual mean and the aggregate value of the SMB-SAT annual correlation for the RACMO27-simulated SMB and SAT fields, ~~for the same grid points as for the ice cores~~ only retaining the RACMO27 grid points where ice cores exist (also shown on Fig. 10 in ~~grey~~green). This allows us to compare the model-derived and ice core-derived annual correlations locally. ~~Similarly to~~ As for the ice cores, the aggregate value is always higher than the individual mean for the RACMO27-derived SMB-SAT ~~correlation.~~ annual correlation, but the difference is small (up to a 0.1 correlation increase).

~~We note there is a weak but positive trend in~~ Examining the ice core-based results, ~~where~~ we note that increasing the number of ~~records averaged over increases~~ ice core records that are initially averaged results in a visible increase of the SMB-SAT ~~correlation~~annual correlation, but the trend is weak. The SMB-SAT annual correlation is consistently lower for the ice cores than for the models, aggregate and individual mean values alike. The gap between the models and the ice cores reduces with spatial scaling but remains large (~0.4-0.5 for the same individual mean or aggregate mean). We conclude that there is some random local noise in the ice core records that can be removed by simple averaging over multiple cores. Aggregating the ice core records increases the signal-to-noise ratio of their climate records. However, the increase in correlation is low. Models may overestimate the annual correlation at scale of tens of kms but it is also likely that we are not able to increase the signal-to-noise ratio sufficiently in the records and reach the obtained model ~~correlation.~~ annual correlation.

Another explanation is that we are not able to quantify some systematic processes and effects that occur between the model scale and the ice core scale that must be taken into account. In that case, retrieving multiple cores in different regions is maybe not the most appropriate option (if only for practical reasons). We need to better understand the spatial representativity of the ice core records. The sparse distribution of the ice core measurements impacts their representativity for the whole ice sheet. Frezzotti et al. (2004) had calculated at the time that the total number of accumulation data point measurements (including stakes and non-ice core measurements) reached 1,860 for the entire AIS, representing one data point every 6,500 km^2.

We know that the surface of the ice sheet is incredibly rough at the scale of an ice core which will greatly influence the climate records retrieved through wind-topography dynamic feedbacks (Frezzotti et al., 2002a). Furthermore, the location of an ice core is often chosen based on surface topography and surface features: smooth surface, absence of dunes or surface erosion, top of a dome or of an ice rise, etc. However, dynamic processes, although not acting today, might have been active in the past, as evidenced from ice-penetrating radar data (e.g. Arcone et al., 2012b; Cavitte et al., 2016; Frezzotti et al., 2002a), and therefore can have affected the ice core records examined.

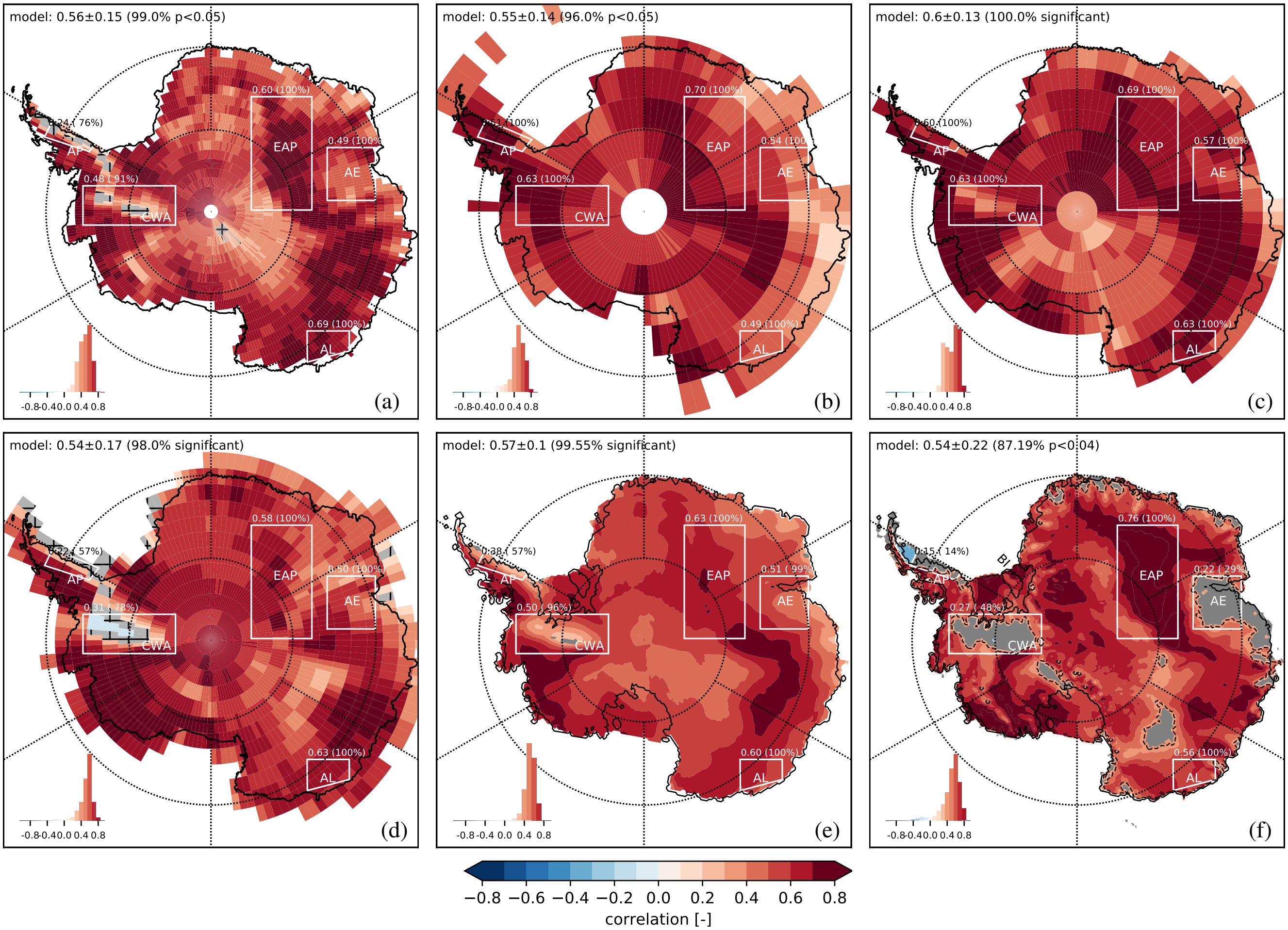
Both the snow accumulation and the isotopic signal recorded in ice cores contain a signature of the post-depositional processes occurring at the surface and the intermittency of precipitation (Casado et al., 2019). Extreme precipitation events can explain 70% of the variance of annual precipitation (Turner et al., 2019), for which the greatest contribution occurs in coastal areas. This would suggest that the ice core climatic signal contains only a snapshot of conditions, rather than a continuous record. This is especially important in the stable water isotope records, which are already precipitation biased (only recording temperature during periods of snowfall) and further complicated by isotopic diffusion. Based solely on physical processes, the local noise in some regions overwhelms the climatic signal at timescales of less than 1000 years (Casado et al., 2019). Using only high accumulation sites (> 0.5 m yr^{-1} at least once over the 1958–2010 AD interval), the resulting SMB-SAT ice core annual correlation average over the continent increases from 0.09 ± 0.18 initially for all cores to 0.28 ± 0.25. Keeping only high accumulation sites seems thus to reduce the impact of post-depositional effects. We are however left with a 13-ice core compilation, with a strong spatial bias towards West Antarctica and the AP.

4 Conclusions

We have shown that there is a positive annual correlation between SMB and SAT over the AIS, particularly in the interior of the ice sheet~~, and~~. We have also shown that the annual correlation between SMB and δ^{18}O is also positive although it is weaker than for SMB and SAT. This confirms what has already been shown at the continental scale ~~(?)~~(Dalaiden et al., 2020). The main source of accumulation over the AIS comes from further north through large-scale atmospheric circulation that carries warm moist air to the continent (Gorodetskaya et al., 2014; Wang et al., 2019), therefore resulting in the overall positive SMB-SAT annual correlation observed. There are a few areas of the AIS where the SMB-SAT annual correlation does not hold strong, generally found in the coastal areas. These are areas where wind-driven processes act on the SMB or SAT locally, through ~~Foehn~~ foehn and katabatic warming and erosion. If the winds are sufficiently strong, they overwhelm the synoptic-scale inputs that induce the positive SMB-SAT and SMB-δ^{18}O annual correlations.

In models, the SMB-SAT annual correlation does not seem to be strongly scale-dependent~~, which we expect due to the lack of noise in models in general~~. However, the spatial resolution of the models does influence whether we can resolve small-scale topography where wind processes have a dominant influence (e.g. individual ice promontories) and therefore detect a local reduction in the SMB-SAT link. At the ice core scale, we have shown that the annual correlation between SMB and SAT is much weaker (even though the ice cores are located in regions with a high model SMB-SAT annual correlation), corroborating the observations made at the continental scale by ~~?~~Dalaiden et al. (2020). Averaging ice core records in close spatial proximity improves their SMB-SAT annual correlation, probably due to random noise averaging. Such an increase of the SMB-SAT annual correlation with averaging indicates that the processes detected in the models can also be detected in ice core data, even if the strength of the SMB-SAT link remains lower than in the models. However, in addition to this random noise, ice cores might be affected by a number of local processes that perturb the measured annual correlation between SMB and SAT systematically and cannot be removed through simple averaging. Choosing only high accumulation ice core sites ~~help~~ helps improve the measured annual correlation between SMB and SAT but reduces the number of ice cores left to a handful.

This implies that we must correct for the local processes present in each ice core record so that their spatial representativity is closer to that of the models, or models must increase their spatial resolution to better resolve wind effects, in order to improve our confidence in using SMB as a direct proxy for SAT over the entire AIS.



for panels a-e: (a) ECHAM5-wiso, (b) ECHAM-MPI/OM, (c) iHadCM3 (7 simulation average), (d) iCESM1 (3 simulation average), (e) averaged over all the isotopic GCMs. Annual correlation between SMB and SAT ~~for RACMO2.3~~ over 1979–2016 AD for RACMO2.3 at the 27 km spatial resolution for panel (f). Statistically insignificant areas (p > ~~0.1~~ p_{FDR}, the threshold p-value calculated) are in grey~~, outlined with a dashed black line~~. The histogram displays the distribution of correlation values. Continent-wide annual correlation mean, standard deviation and percentage of model area with p < ~~0.1~~ p_{FDR} are provided on ~~the figure~~each panel (for panel e, average over all 4 isotopic GCMs). ~~Specific locations~~ The five regions mentioned are annotated~~on the figure~~: '~~BI~~AE', ~~Berkner Island~~ Amery Embayment - '~~BG~~AL', ~~Byrd Glacier~~ Adélie Land - 'EAP', East Antarctic Plateau - 'AP', Antarctic Peninsula, 'CWA', central West Antarctica, as well as 'BI', Berkner Island.

for panels a-e: (a) ECHAM5-wiso, (b) ECHAM-MPI/OM, (c) iHadCM3 (7 simulation average), (d) iCESM1 (3 simulation average), (e) averaged over all the isotopic GCMs. Annual correlation between SMB and SAT ~~for RACMO2.3~~ over 1979–2016 AD for RACMO2.3 at the 27 km spatial resolution for panel (f). Statistically insignificant areas (p > ~~0.1~~ p_{FDR}, the threshold p-value calculated) are in grey~~, outlined with a dashed black line~~. The histogram displays the distribution of correlation values. Continent-wide annual correlation mean, standard deviation and percentage of model area with p < ~~0.1~~ p_{FDR} are provided on ~~the figure~~each panel (for panel e, average over all 4 isotopic GCMs). ~~Specific locations~~ The five regions mentioned are annotated~~on the figure~~: '~~BI~~AE', ~~Berkner Island~~ Amery Embayment - '~~BG~~AL', ~~Byrd Glacier~~ Adélie Land - 'EAP', East Antarctic Plateau - 'AP', Antarctic Peninsula, 'CWA', central West Antarctica, as well as 'BI', Berkner Island.

Figure 1. ~~d18O-SMB,~~Annual correlation between SMB and SAT over 1871–2000 AD ~~d18O-SMB,1961–2000 AD SMB-SAT,1871–2000~~

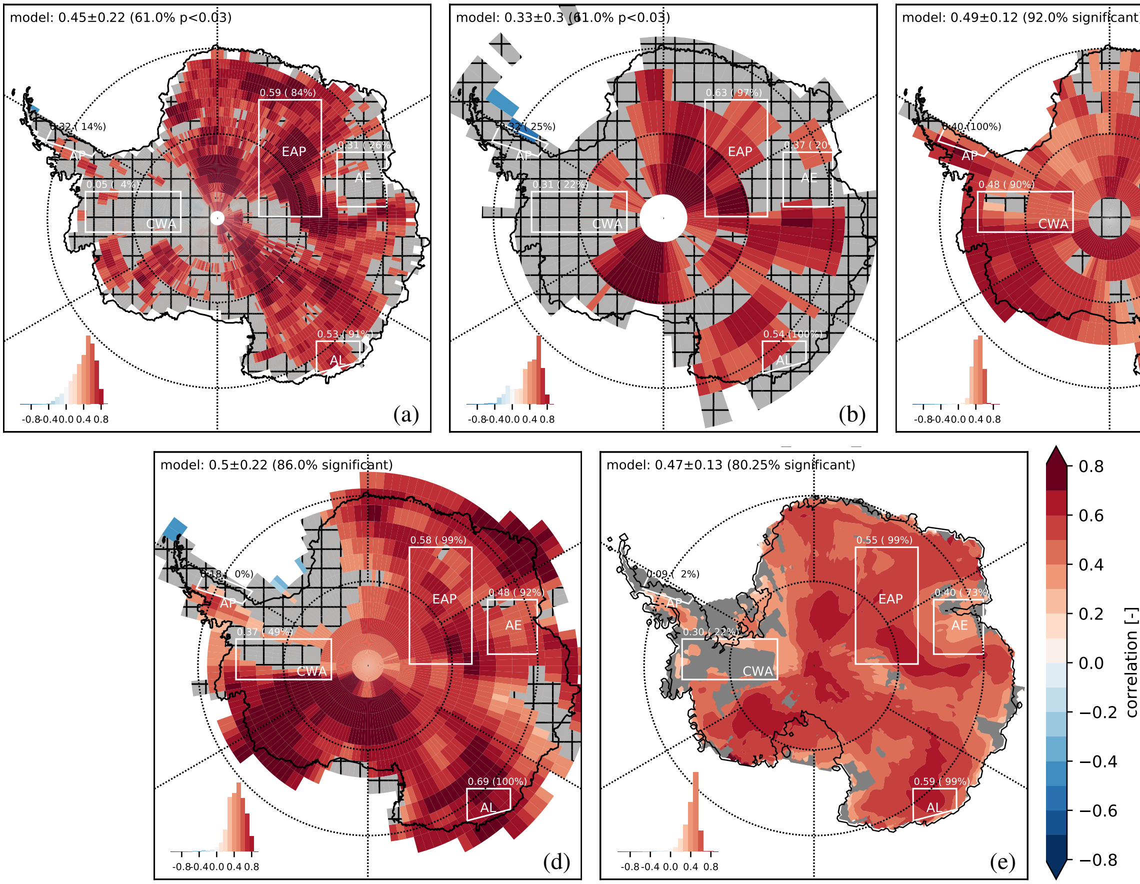


Figure 2. 5-yearly correlation between SMB and δ^{18}O over 1871–2000 AD for panels a-e: (a) ECHAM5-wiso, (b) ECHAM-MPI/OM, (c) iHadCM3 (7 simulation average), (d) iCESM1 (3 simulation average), (e) averaged over all the isotopic GCMs. Statistically insignificant areas ($p > p_{FDR}$, the threshold p-value calculated) are in grey. The histogram displays the distribution of correlation values. Continent-wide annual correlation mean, standard deviation and percentage of model area with $p < p_{FDR}$ are provided on each panel (for panel e, average over all 4 isotopic GCMs). The five regions mentioned are annotated: 'AE', Amery Embayment - 'AL', Adélie Land - 'EAP', East Antarctic Plateau - 'AP', Antarctic Peninsula, 'CWA', central West Antarctica.

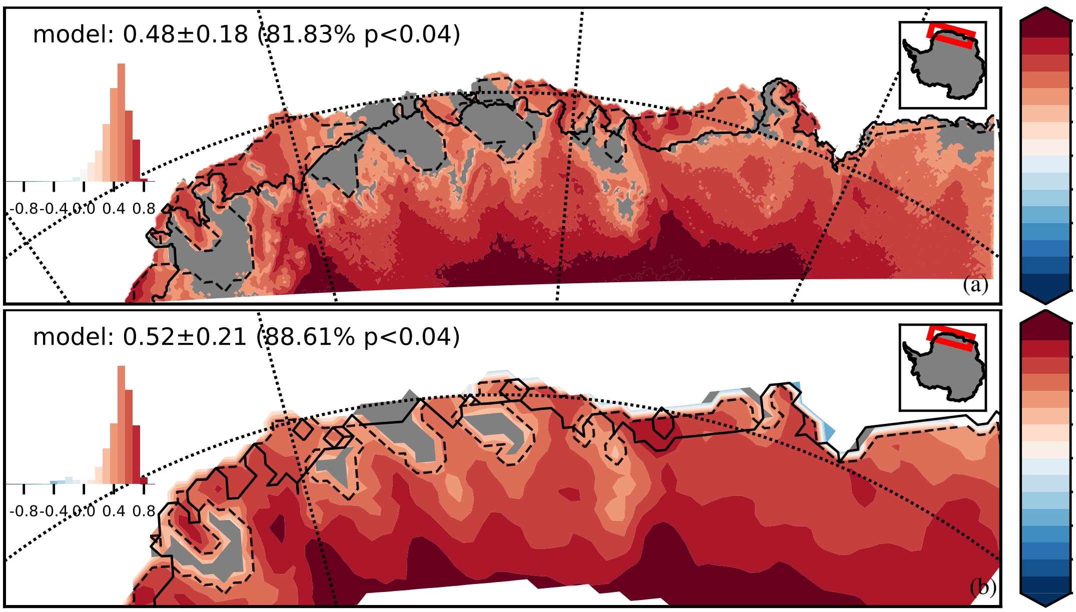


Figure 3. ~~RACMO5~~Annual correlation between SMB and SAT for RACMO2.3 over 1979–2016 AD at the (a) 5.5 km and (b) 27 km spatial resolution for Dronning Maud Land. Statistically insignificant areas (p > p_{FDR}, the threshold p-value calculated) are in grey. The dashed black lines on both panels correspond to the areas with p > p_{FDR} at the 27 km resolution. The histogram displays the distribution of correlation values. Region-wide annual correlation mean, standard deviation and percentage of model area with p < p_{FDR} are provided on each panel.

~~RACMO27 Annual correlation between SMB and SAT for RACMO2.3 over 1979–2016 AD at the (a) 5.5 km and (b) 27 km spatial resolution for Dronning Maud Land. Statistically insignificant areas (p > 0.1) are in grey. The dashed black lines on both panels correspond to the areas with p > 0.1 at the 27 km resolution. The histogram displays the distribution of correlation values. Region-wide correlation mean, standard deviation and percentage of model area with p < 0.1 are provided on each panel.~~

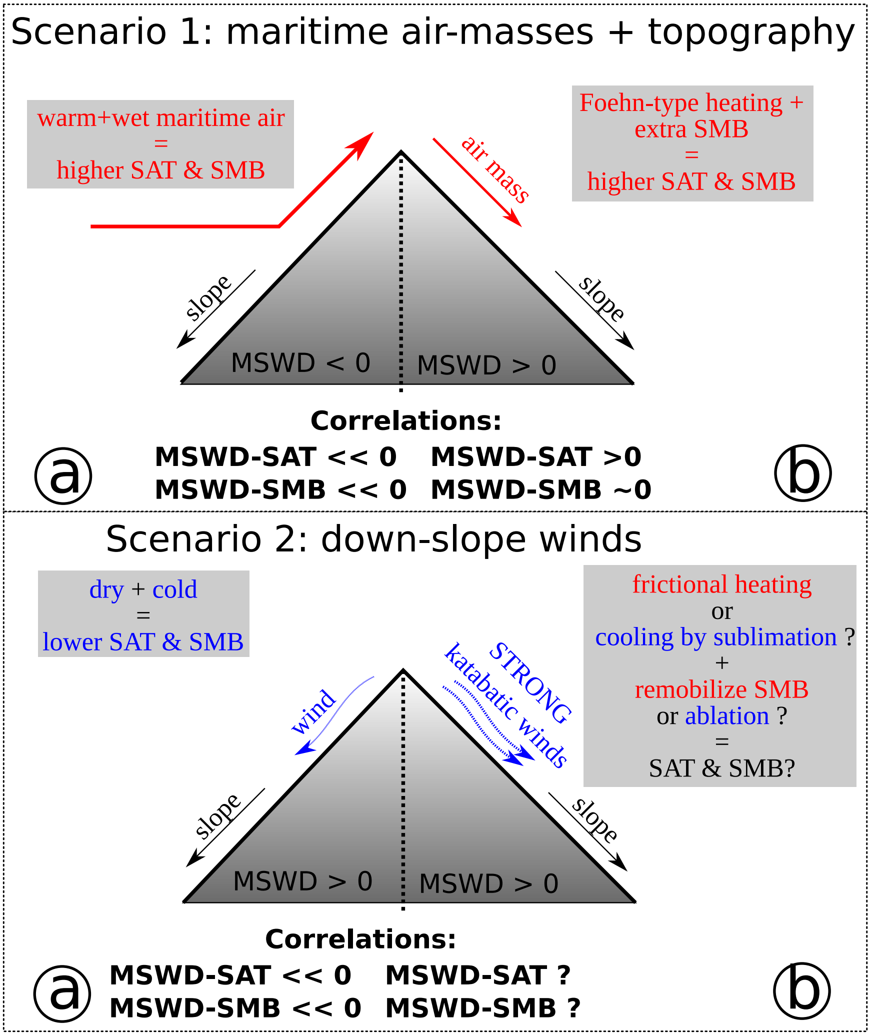


Figure 4. Sketch of slope, wind, MSWD and the resulting correlations expected for the two scenarios described: (1) ocean-sourced warm and moist air interacting with topography and (2) down-slope and strong katabatic winds interacting with the surface.

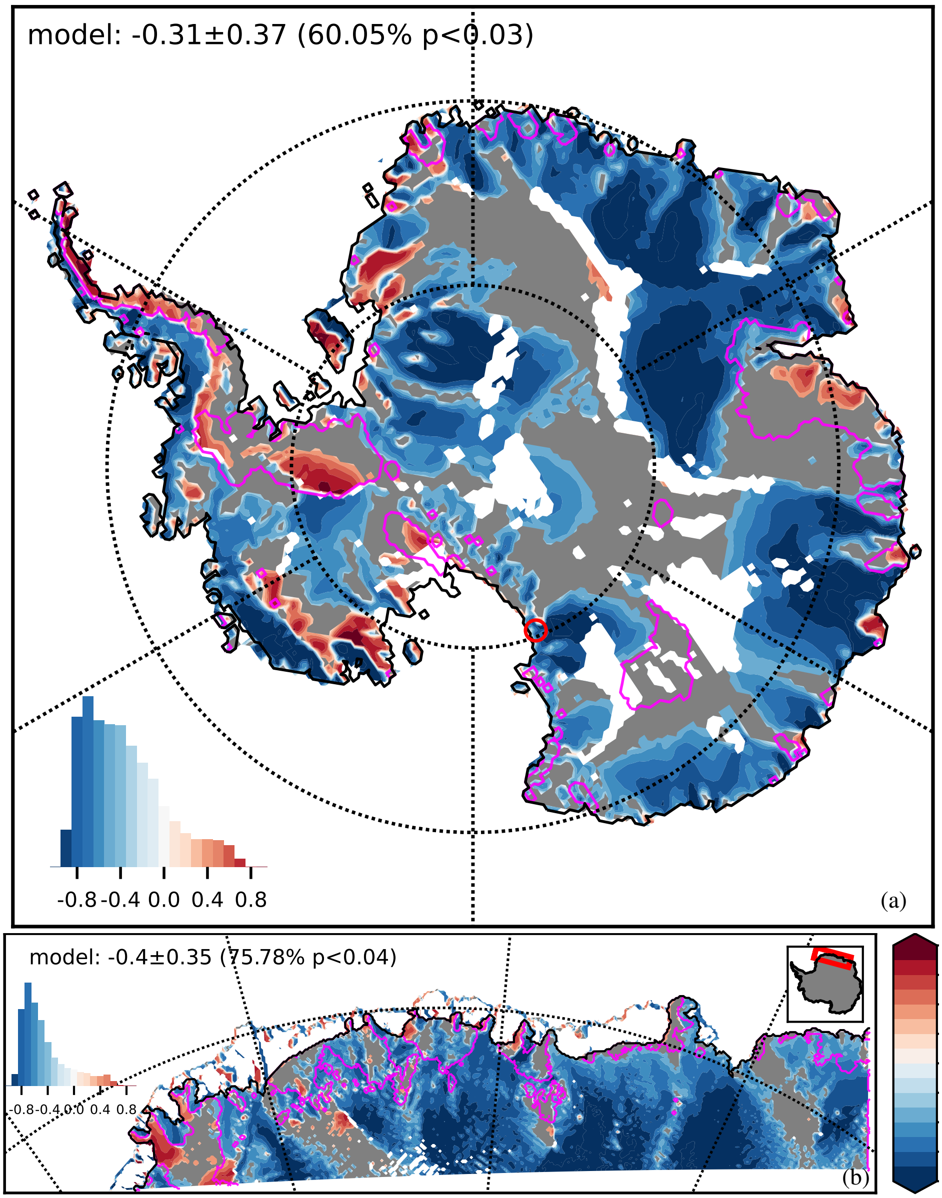


Figure 5. Annual correlation between MSWD and SAT using (~~top~~a) RACMO27 and (~~bottom~~b) RACMO5 simulations over 1979–2016 AD. Statistically insignificant areas (p > ~~0.1~~p_{FDR}, the threshold p-value calculated) are in grey. Areas with a slope smaller than 0.1% are removed and appear in white. Magenta lines outline the areas that have a weak SMB-SAT annual correlation in Fig. ~~??~~4, panel f. The histogram displays the distribution of correlation values. Continent- or region-wide annual correlation mean, standard deviation and percentage of model area with p < ~~0.1~~ p_{FDR} are provided on each panel. A red circle locates the Byrd Glacier outlet discussed in the manuscript.

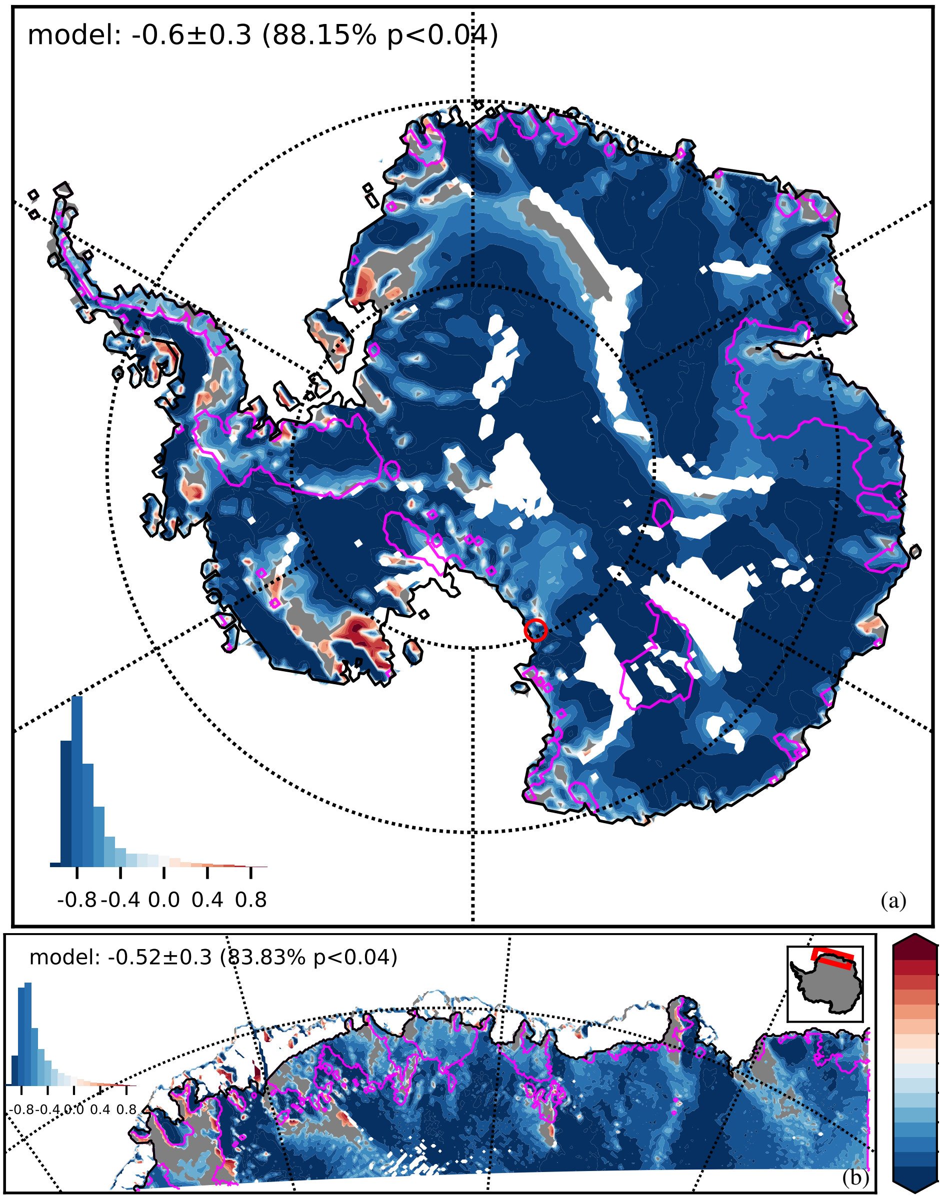


Figure 6. Annual correlation between MSWD and SMB using (~~top~~a) RACMO27 and (~~bottom~~b) RACMO5 simulations over 1979–2016 AD. Statistically insignificant areas (p > ~~0.1~~ p_{FDR}, the threshold p-value calculated) are in grey. Areas with a slope smaller than 0.1% are removed and appear in white. Magenta lines outline the areas that have a weak SMB-SAT annual correlation in Fig. ~~??~~4, panel f. The histogram displays the distribution of correlation values. Continent- or region-wide annual correlation mean, standard deviation and percentage of model area with p < ~~0.1~~ p_{FDR} are provided on each panel. A red circle locates the Byrd Glacier outlet discussed in the manuscript.

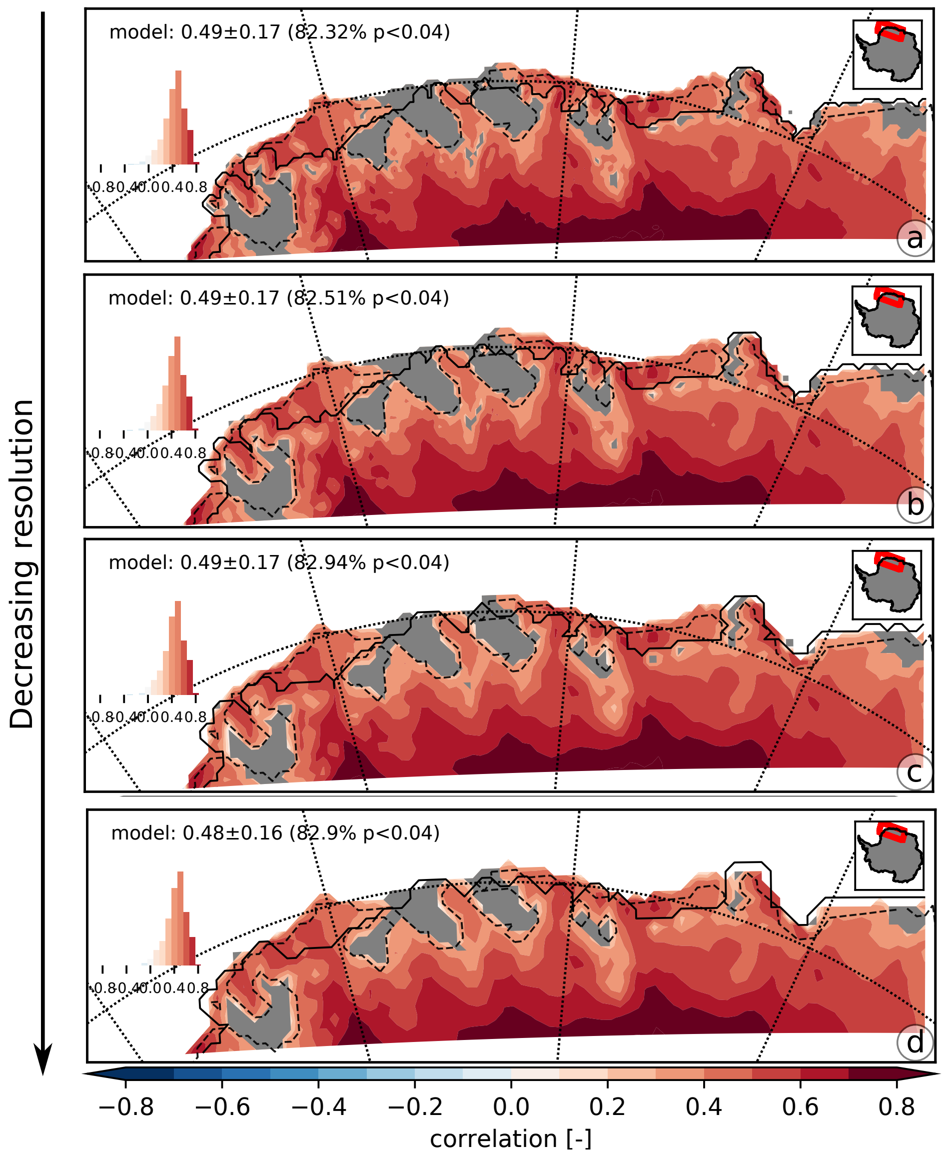


Figure 7. Annual correlation between SMB and SAT for RACMO05 RACMO5 simulations over increasing grid scalings from top to bottom: (a) 11 km, (b) 16.5 km, (c) 22 km and (d) 27.5 km over 1979–2016 AD. Statistically insignificant areas (p > 0.1p_{FDR}, the threshold p-value calculated) for each resolution are hashed in grey. A dashed black line outlines the areas with a low SAT-SMB annual correlation from Fig. ?? 4, panel f, for comparison. The histogram displays the distribution of correlation values for each panel. Region-wide annual correlation mean, standard deviation and percentage of model area with p < 0.1 p_{FDR} are provided on each panel.

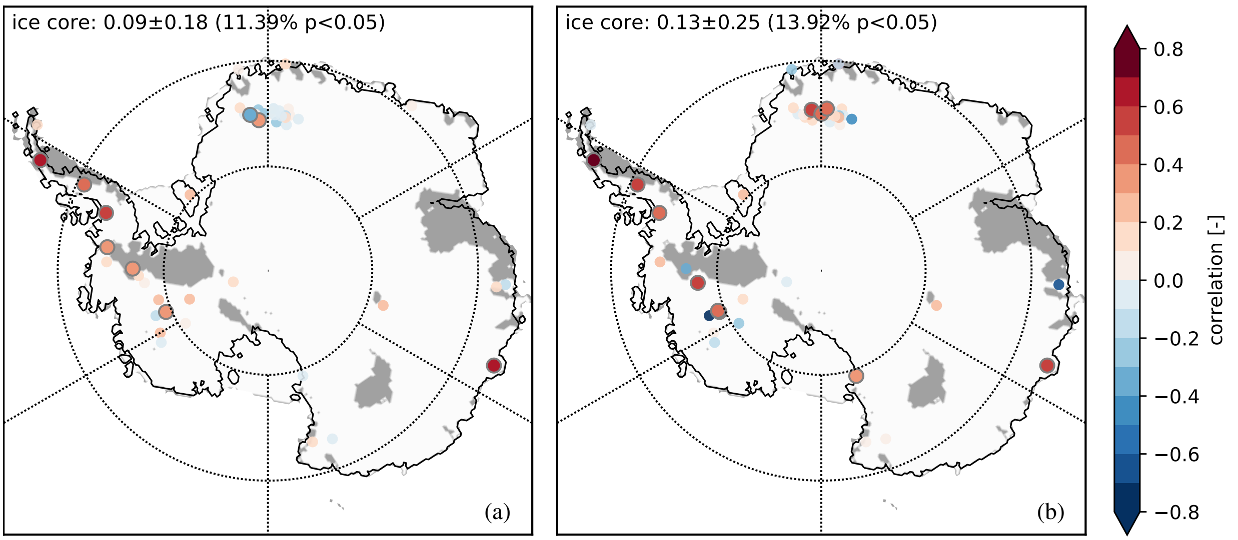


Figure 8. Ice core correlations (a) annually for SMB-SAT over 1958–2010 AD and (b) 5-yearly for SMB-δ^{18}O over 1871–2010 AD. Large grey encircled dots indicate that the correlation value is significant, smaller dots indicate a p-value > 0.05. Statistically insignificant areas (p > p_{FDR}) of the RACMO27 SMB-SAT annual correlation are hashed in grey for reference. The average annual correlation, standard deviation and percentage of ice cores with p < 0.05 is provided on each panel.

δ^{18}O-SMB Ice core correlations (a) annually for SMB–SAT over 1958–2010 AD and (b) 5-yearly for δ^{18}O-SMB over 1871–2010 AD. Large dots indicate that the correlation value is significantive, smaller dots indicate a p-value > 0.1. Statistically insignificant areas (p > 0.1) of the RACMO27 SMB-SAT correlation are hashed in grey for reference. The average correlation, standard deviation and percentage over all the ice cores is provided on each panel.

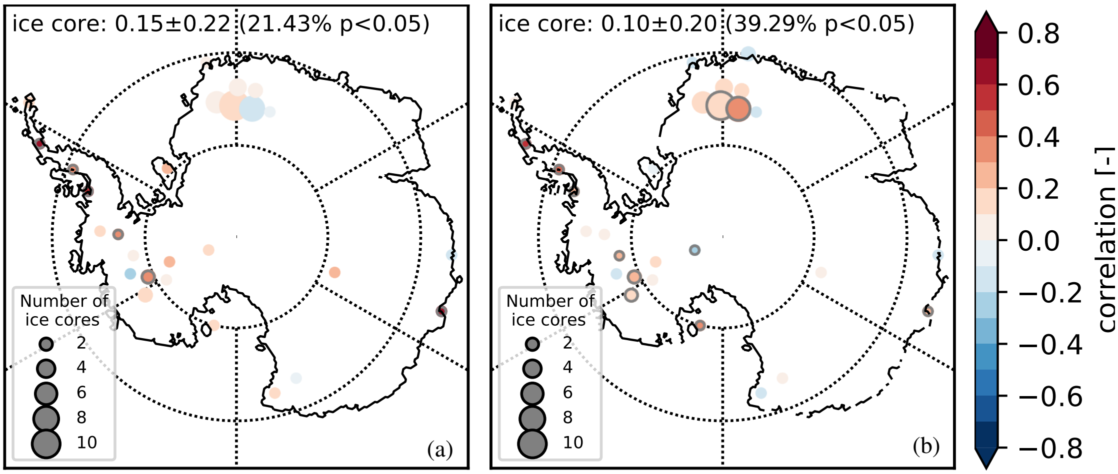


Figure 9. Aggregated ice core annual correlations on a 216 x 216 km grid for (a) SMB-SAT annually over 1958–2010 AD and (b) SMB-δ^{18}O 5-yearly over 1871–2010 AD. Grey encircled dots indicate that the correlation value is significant ($p < 0.05$). The size of the dot represents the number of ice cores aggregated, with the legend is given on each panel. The average annual correlation, standard deviation and percentage of ice cores with $p < 0.05$ is provided on each panel.

~~δ^{18}O-SMB Aggregated ice core correlations on a 216 x 216 km grid for (a) SMB-SAT annually over 1958–2010 AD and (b) δ^{18}O-SMB 5-yearly over 1871–2010 AD. The mean correlation over all the ice cores is provided on each panel.~~

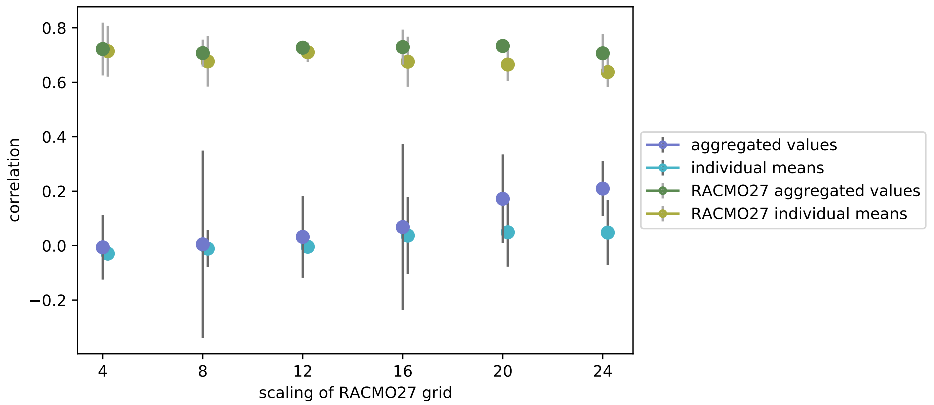


Figure 10. SMB-SAT annual correlation as a function of grid spacing for the aggregated records versus mean of the individual annual correlations for the ice cores (blues dark and yellowslight blues, respectively) and RACMO27 simulations (in dark and light greygreen, respectively). The size grey bars indicate the full range of correlation values with the mean indicated by the colored dots is a function of dot. For the number of RACMO27 simulation results, only RACMO27 grid cells where ice cores aggregated for that grid pointexist are used. Only For both ice cores and RACMO27, only grid points with at least (top) five and (bottom) ten ice cores are kept. Correlations Annual correlations are over the 1958–2010 AD time interval for the ice core data, and over 1979–2016 AD for the RACMO27 simulations.

Data availability. RACMO2.3 simulations are available by request to J.M. (Melchior) van Wessem (j.m.vanwessem@uu.nl); CMIP5 simulations are available at http://pcmdi9.llnl.gov; iHadCM3 simulations are available by request to Max Holloway (max.holloway@sams.ac.uk); ECHAM5-wiso simulations are available at https://doi.org/10.5281/zenodo.1249604; ECHAM5/MPI-OM simulations are available by request to Jesper Sjolte (jesper.sjolte@geol.lu.se). The δ^{18}O Stenni et al. (2017) compilation is available at https://www.ncdc.noaa.gov/paleo-search/study/22589, the SMB Thomas et al. (2017) compilation is available by a request to Elizabeth R. Thomas (lith@bas.ac.uk), the SAT Nicolas and Bromwich (2014) compilation is available at http://polarmet.osu.edu/datasets.

Author contributions. MGPC and HG designed the experiments and MGPC carried them out. QD provided analysis support, JTML provided RACMO support, ERT provided ice core support. MGPC prepared the manuscript with contributions from all co-authors.

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Supplement to: Reconciling the surface temperature–surface mass balance relationship in models and ice cores in Antarctica over the last two centuries

Marie G.P. Cavitte et al.

1 Supplementary Material **Summary**

– Figures S1, S2 ~~, S3 and ?? show the correlation between δ^{18}O and SMB~~ and S3 show the annual correlation between SMB and SAT, and SMB and ~~SAT~~ δ^{18}O for each iGCM model at its original spatial resolution, ~~over the 1871–2000 AD and~~ and the average over all four iGCMs interpolated onto the RACMO27 grid, over the 1961–2000 AD time intervals ~~. Fig.S4~~ (Fig. S1 and S2) and the 1871–2000 AD time interval (Fig. S3).

– Figure S4 (a,b) shows the spatial distribution of the ice cores used for the SMB-SAT and SMB-δ^{18}~~O-SMB correlations . Fig.~~O correlations and (c) shows the spatial distribution of the weather stations used in the Nicolas and Bromwich (2014) SAT reconstruction.

– Figure S5 shows the 5-yearly SMB-SAT correlation averaged over the four iGCMs. ~~Fig.S6 show~~

– Figure S6 shows the correlation of SMB and SAT at the seasonal timescale. ~~Fig.S7 show~~

– Figure S7 shows the correlation of SMB and SAT at the monthly timescale. ~~Fig.~~

– Figure S8 shows the RACMO2.3 (Van Wessem et al., 2018) MSWD calculated as described in the main manuscript, averaged over the entire period (1979–2016 AD).

– Figure S9 shows a zoomed-in view of the Antarctic Peninsula region of the MSWD-SAT and MWSD-SMB annual correlations.

– Figure S10 shows the RACMO2.3 (Van Wessem et al., 2018) 10-m wind strength and direction averaged over the entire period (1979–2016 AD).

– Figure S11 shows the RACMO2.3 (Van Wessem et al., 2018) sublimation and sublimation from snowdrift averaged over the entire period (1979–2016 AD).

– Section 2 provides an evaluation of the iGCMs, with the associated Figs. S12, S13 and S14.

~~ECHAM5-wiso ECHAM5-MPI-OM~~

2 Model evaluation

Overall, the mean SMB over the Antarctic Ice Sheet (AIS) simulated by the iGCMs is in good agreement with the mean SMB simulated by RACMO27 over the 1979–2000 AD time interval (R^2 = 0.49-0.65, maximum bias[1] of ∼37 mm w.e. yr^{-1}, Fig. S12). We choose to compare the iGCM simulations to RACMO2.3 since the latter includes physics specific to polar regions. As such, RACMO2.3 (and RACMO27 specifically in this case to have a continent-wide field of SMB) is highly appropriate for an Antarctic SMB evaluation. Both iGCMs and RACMO27 show a pattern of high SMB (> 500 mm w.e. yr^{-1}) along the coast and low SMB (< 30 mm w.e. yr^{-1}) in the interior. We note that ECHAM5-wiso and ECHAM5-MPI/OM show a mean SMB bias of ∼30-40 mm w.e. yr^{-1} above that of RACMO27 (R^2 = 0.63 and 0.49 respectively, while iCESM1 shows a bias of ∼ -11 mm w.e. yr^{-1} with respect to RACMO27 (R^2 = 0.65) and the iHadCM3 SMB mean value is very close to that of RACMO27 (bias of ∼-2, R^2 = 0.58). The biggest differences between the iGCMs and RACMO27 in general occur along the coasts, in particular the West Antarctic coast and the Antarctica Peninsula, reaching up to 500 mm w.e. yr^{-1}. In addition, ECHAM5-MPI/OM, which has the coarsest spatial resolution, also shows a positive bias in the interior of ∼200 mm w.e. yr^{-1}. This agrees with previous studies that have shown that the lower resolution of GCMs induces under-estimations of SMB in coastal areas and in general over-estimations of SMB in the interior (Palerme et al., 2017; Krinner et al., 2007; Agosta et al., 2015). As the iGCM with the lowest spatial resolution of this study, ECHAM5-MPI/OM shows the largest biases (coastal and in the interior). Despite these (known) biases, the simulated SMB by each of the four iGCMs shows minor differences locally with the RACMO27 SMB, expected due to the differing physics involved in each model and range of spatial resolutions.

To evaluate the simulated SAT by the iGCMs, we compare the SAT simulated by the iGCMs for the AIS to that simulated by RACMO27 as well (Fig. S13). The four iGCMs produce the same spatial pattern as RACMO27, that is higher SATs at the coast and the lowest SATs in the interior (R^2 = 0.91-0.97). The average SAT over the continent is within 1°C of the RACMO27 average, except for iCESM1 which shows a mean bias of ∼5°C. However, if we look at the difference between the iGCM SAT and the RACMO27 SAT (right column of Fig. S13), we see that the differences are spatially variable. iCESM1 underestimates SAT for most of the ice sheet surface while the opposite is true for ECHAM5-wiso. ECHAM5-MPI/OM and iHadCM3 show SAT overestimation around the coast and along the Trans-Antarctic Mountains and SAT underestimation over the west and east Antarctic interiors. Differences remain on the order of ±3°C, with only a few regions, in particular for iCEMS1 and ECHAM5-MPI/OM, where differences reach up to 12°C. Overall, despite the discrepancies, all four iGCMs produce a realistic simulated SAT with lower temperatures in the center of the ice sheet, warmer temperatures over the coastal regions, as expected, and a similar gradient between the interior and the coast for all models, which gives us confidence in using these four iGCMs in our study.

We then evaluate the sea-level pressure (SLP) simulated by the iGCMs by comparing them to the simulated SLP by ERA-Interim (Dee et al., 2011) which allows us to examine the SLP further north of the Antarctic continent compared to RACMO2.3 (Fig. S14). We calculate the average SLP over the ocean below -40°S of latitude. Over that area, the average

[1] We define bias as the spatial mean value of the iGCM variable over the period considered minus the spatial mean value of the reference model chosen, RACMO27 in this instance. The spatial mean value of each iGCM variable is calculated from the iGCM values after interpolation onto the reference model grid, RACMO27 in this case. This is true for the SAT and SLP evaluation as well, see below.

SLP values for the iGCMs are very close to that of ERA-Interim (R^2 = 0.89-0.99), with up to 2 hPa difference except for iHadCM3 which shows a mean SLP bias of ∼5.2 hPa lower than ERA-Interim. The same spatial pattern of SLP with the three climatological low-pressure systems over the Southern Ocean is found in all models. The absolute minimum is found in the Amundsen Sea Embayment for iCESM1 and iHadCM3 as in ERA-Interim. For ECHAM5-wiso and ECHAM5-MPI/OM, the absolute minimum is found offshore Princess Elisabeth Land and Enderby Land, respectively, although a weaker minimum is located in the Amundsen Sea Embayment. Looking at the difference between each iGCM simulation and that of ERA-Interim (right column, Fig. S14), we see that differences never exceed ∼7 hPa locally, except for iHadCM3 where differences reach up to ∼8 hPa. Despite each iGCM's different local bias, all four iGCMs reproduce the same average and spatial pattern of SLP over the ocean as ERA-Interim.

spacing	number of ice cores
4	6
4	5
8	5
8	10
8	7
12	18
12	7
16	5
16	11
16	17
20	5
20	26
24	8
24	21
24	9

Table S1. ~~iHadCM3~~Number of ice cores aggregated as a function of RACMO27 grid spacing for Fig. 10 of the main manuscript, with only grid points that aggregate five or more ice cores retained to have sufficient averaging of the records. E.g. at the grid spacing of 4, two grid points are retained. These are then both included in the gray range of correlation values shown in Fig. 10.

~~ECHAM5-wiso ECHAM5-MPI-OM iHadCM3~~
~~ECHAM5-wiso ECHAM5-MPI-OM iHadCM3~~
~~ECHAM5-wiso ECHAM5-MPI-OM iHadCM3~~

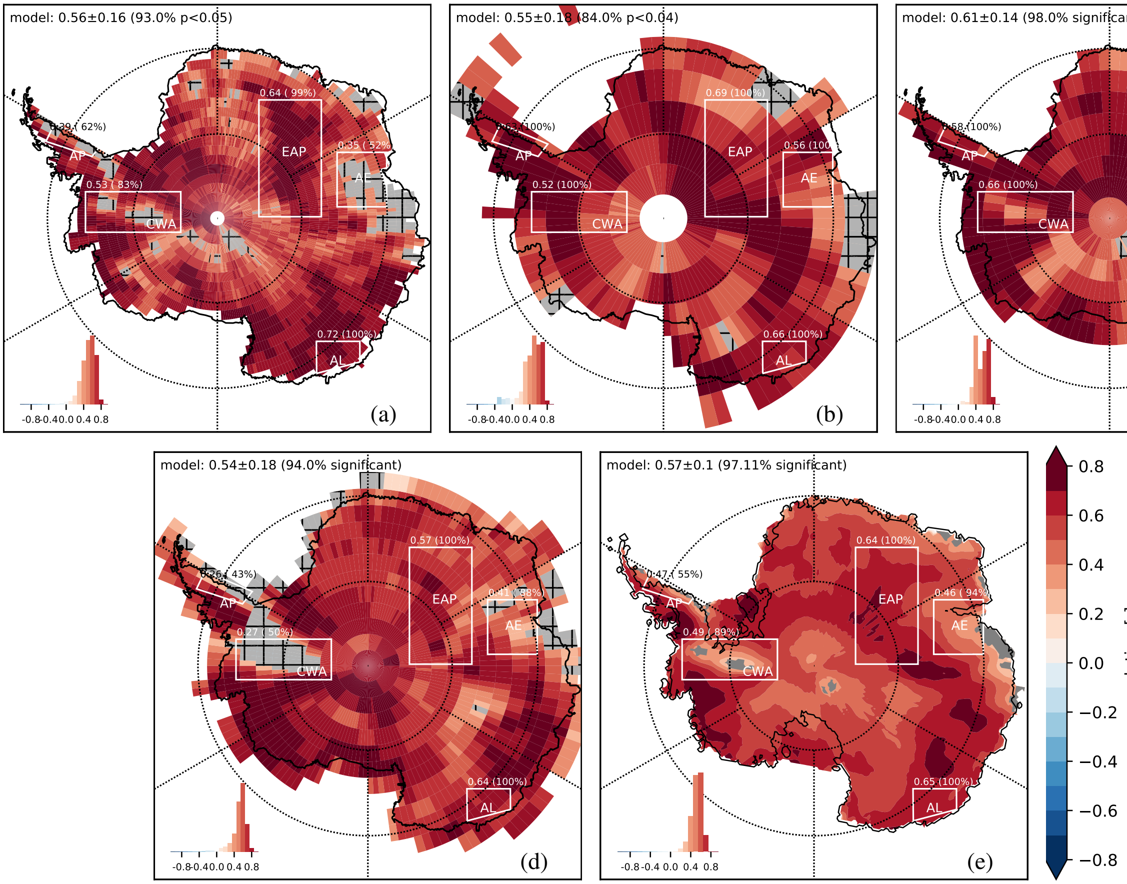

Figure S1. Annual correlation between SMB and SAT over 1961–2000 AD for each isotopic GCM: (a) ECHAM5-wiso, (b) ECHAM-MPI/OM, (c) iHadCM3 (7 simulation average), (d) iCESM1 (3 simulation average), (e) averaged over all the isotopic GCMs. Statistically insignificant areas (p > p_{FDR}, the threshold p-value calculated) are in grey. The histogram displays the distribution of correlation values. Continent-wide annual correlation mean, standard deviation and percentage of model area with p < p_{FDR} are provided on each panel (for panel e, average over all 4 isotopic GCMs).

~~Annual correlation between δ^{18}O and SMB over 1871–2000 AD for each isotopic GCM. Statistically insignificant areas (p > 0.1) are hashed in grey. The histogram displays the distribution of correlation values. Continent-wide correlation mean, standard deviation and percentage of model area with p < 0.1 are provided on each panel.~~

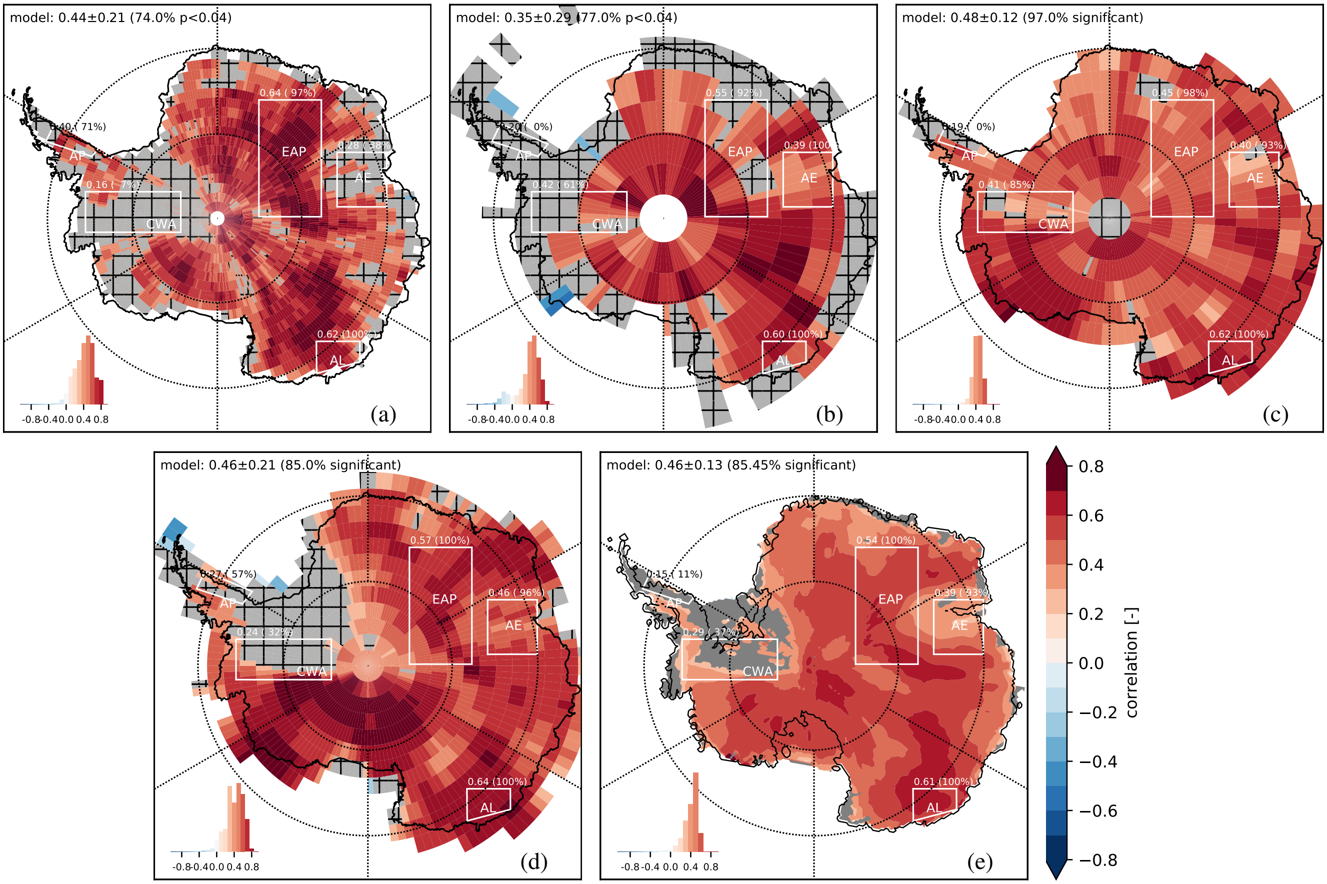

Figure S2. Annual correlation between SMB and δ^{18}O over 1961–2000 AD for each isotopic GCM: (a) ECHAM5-wiso, (b) ECHAM-MPI/OM, (c) iHadCM3 (7 simulation average), (d) iCESM1 (3 simulation average), (e) averaged over all the isotopic GCMs. Statistically insignificant areas (p > p_{FDR}, the threshold p-value calculated) are in grey. The histogram displays the distribution of correlation values. Continent-wide annual correlation mean, standard deviation and percentage of model area with p < p_{FDR} are provided on each panel (for panel e, average over all 4 isotopic GCMs).

~~Annual correlation between δ^{18}O and SMB over 1961–2000 AD for each isotopic GCM. Statistically insignificant areas (p > 0.1) are hashed in grey. The histogram displays the distribution of correlation values. Continent-wide correlation mean, standard deviation and percentage of model area with p < 0.1 are provided on each panel.~~

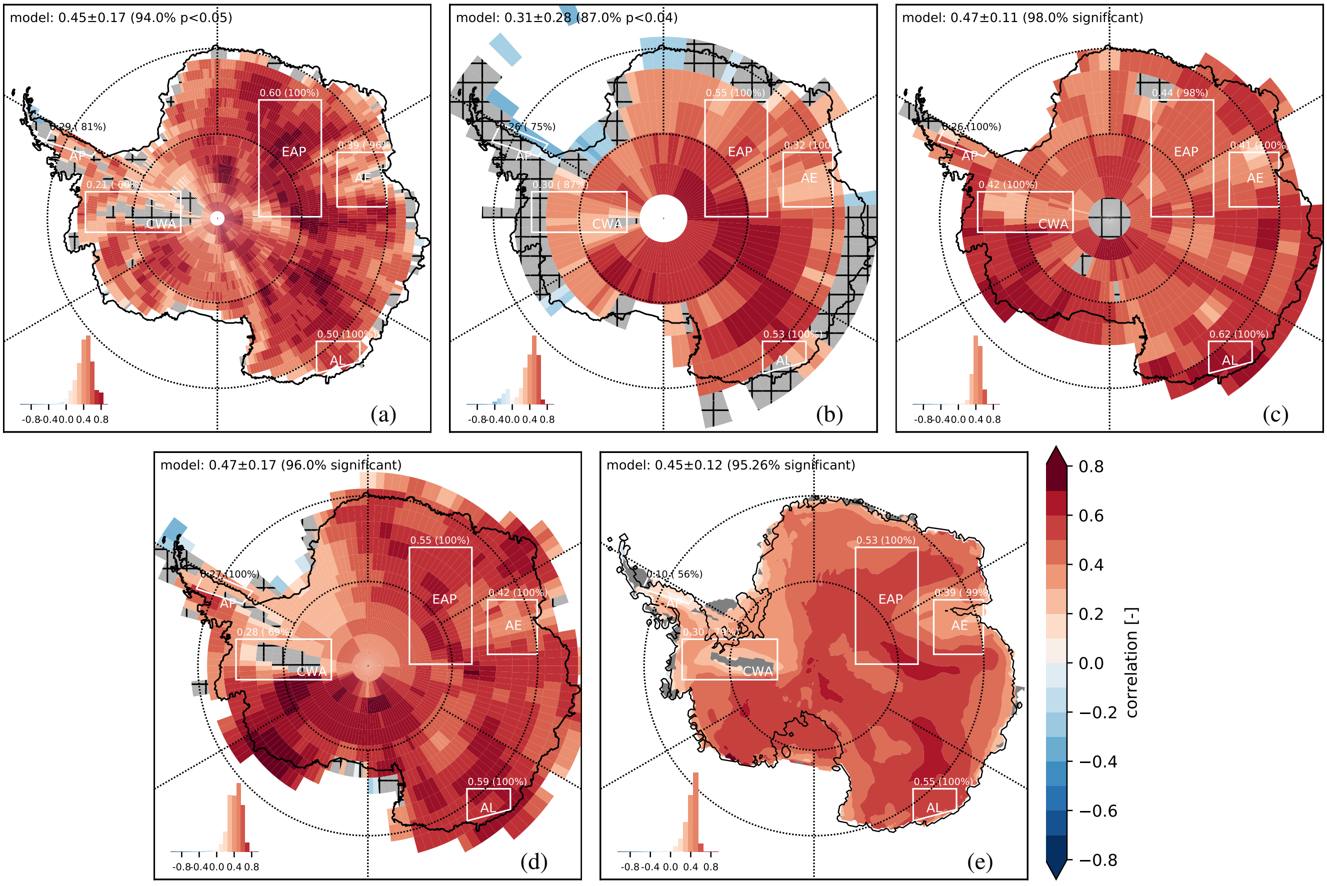

Figure S3. Annual correlation between SMB and δ^{18}O over 1871–2000 AD for each isotopic GCM: (a) ECHAM5-wiso, (b) ECHAM-MPI/OM, (c) iHadCM3 (7 simulation average), (d) iCESM1 (3 simulation average), (e) averaged over all the isotopic GCMs. Statistically insignificant areas (p > p_{FDR}, the threshold p-value calculated) are in grey. The histogram displays the distribution of correlation values. Continent-wide annual correlation mean, standard deviation and percentage of model area with p < p_{FDR} are provided on each panel (for panel e, average over all 4 isotopic GCMs).

~~Annual correlation between SMB and SAT over 1871–2000 AD for each isotopic GCM. Statistically insignificant areas (p > 0.1) are hashed in grey. The histogram displays the distribution of correlation values. Continent-wide correlation mean, standard deviation and percentage of model area with p < 0.1 are provided on each panel.~~

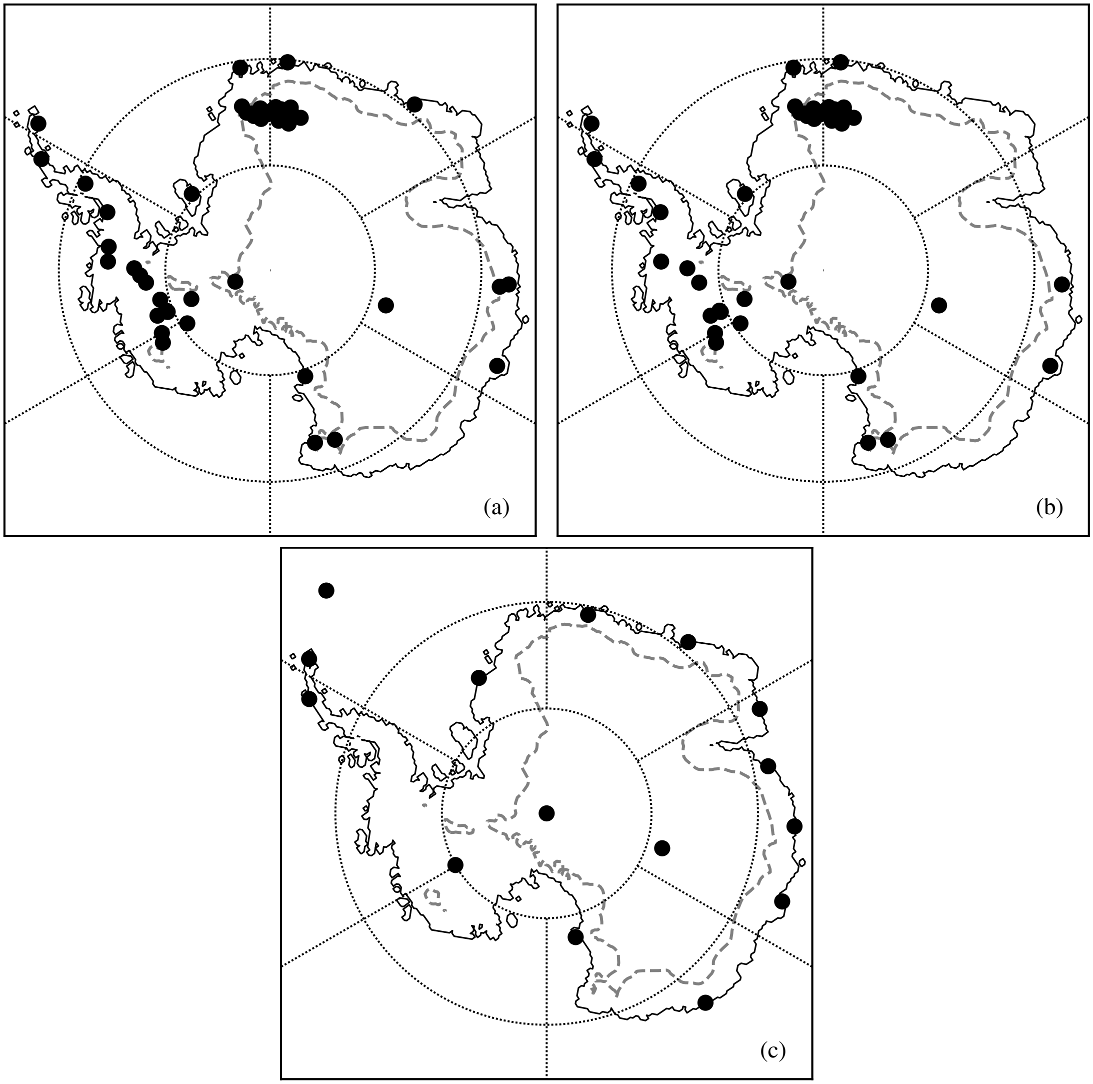

Figure S4. iCESM1Spatial distribution of the ice cores used in this study for correlations: (a) between SMB and SAT over 1958–2010 AD (total = 58) and (b) between SMB and δ^{18}O over 1871–2010 AD (total = 53), and (c) of the weather stations used in the Nicolas and Bromwich (2014) SAT reconstruction. The grey dashed line marks the line of altitude 2200 m, separating the "low elevation" and "high elevation" areas discussed in the main manuscript.

Annual correlation between SMB and SAT over 1961–2000 AD for each isotopic GCM. Statistically insignificant areas ($p > 0.1$) are hashed in grey. The histogram displays the distribution of correlation values. Continent-wide correlation mean, standard deviation and percentage of model area with $p < 0.1$ are provided on each panel.

Spatial distribution of the ice cores used in this study for correlations: (left) between SMB and SAT over 1958–2010 AD (total = 58) and (right) between δ^{18}O and SMB over 1871–2010 AD (total = 53).

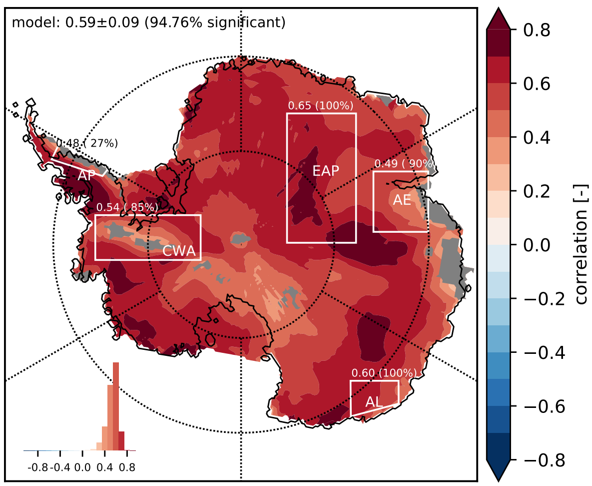

Figure S5. 5-yearly correlation between SMB and SAT ~~,~~ averaged over all four isotopic GCMs over 1871–2000 AD. Statistically insignificant areas (p > ~~0.1~~ p_{FDR}, the threshold p-value calculated) are hashed in grey. The histogram displays the distribution of correlation values for each panel. Averaged region-wide correlation mean, standard deviation and percentage of model area with p < ~~0.1~~ p_{FDR} are provided on the figure.

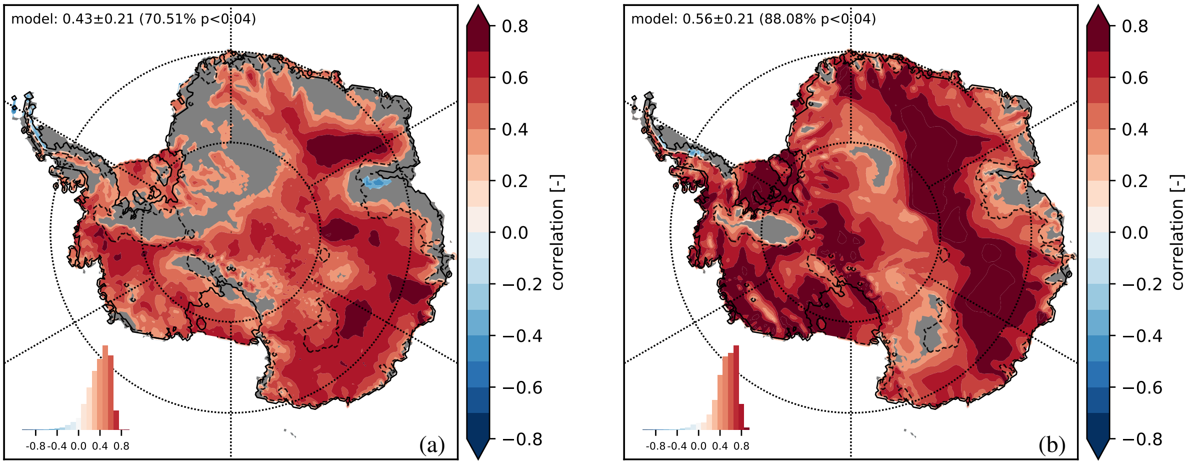

Figure S6. ~~SMB–SAT~~ Annual correlation between SMB and SAT for (a) austral summers (DJF) and (b) austral winters only (JJA) using RACMO27 model simulations over 1979–2016 AD. Statistically insignificant areas (p > p_{FDR}, the threshold p-value calculated) are in grey. Dashed black lines outline the areas with a weak SMB-SAT correlation from Fig. 2 in the main manuscript. The histogram displays the distribution of correlation values for each panel. Region-wide correlation mean, standard deviation and percentage of model area with p < p_{FDR} are provided on each panel.

~~SMB–SAT JJA Annual correlation between SMB and SAT for (a) austral summers (DJF) and (b) austral winters only (JJA) using RACMO27 model simulations over 1979–2016 AD. Statistically insignificant areas (p > 0.1) are in grey. Dashed black lines outline the areas with a weak SMB-SAT correlation from Fig.2 in the main manuscript. The histogram displays the distribution of correlation values for each panel. Region-wide correlation mean, standard deviation and percentage of model area with p < 0.1 are provided on each panel.~~

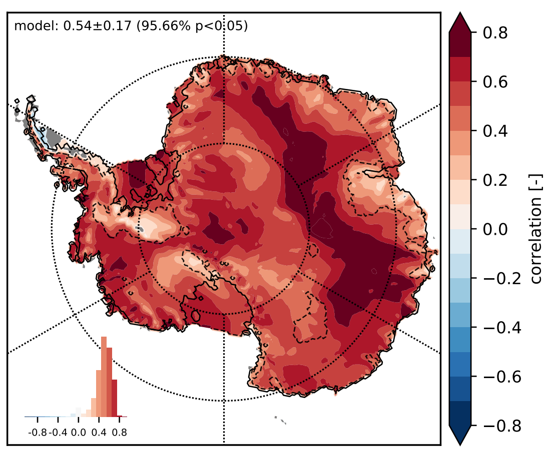

Figure S7. Monthly correlation between SMB and SAT using RACMO27 simulations over 1979–2016 AD. Dashed black lines outline the areas with a weak SMB-SAT correlation from Fig~~.2~~. 2 in the main manuscript. The histogram displays the distribution of correlation values for each panel. Region-wide correlation mean, standard deviation and percentage of model area with p < ~~0.1~~ p_{FDR} are provided on the figure.

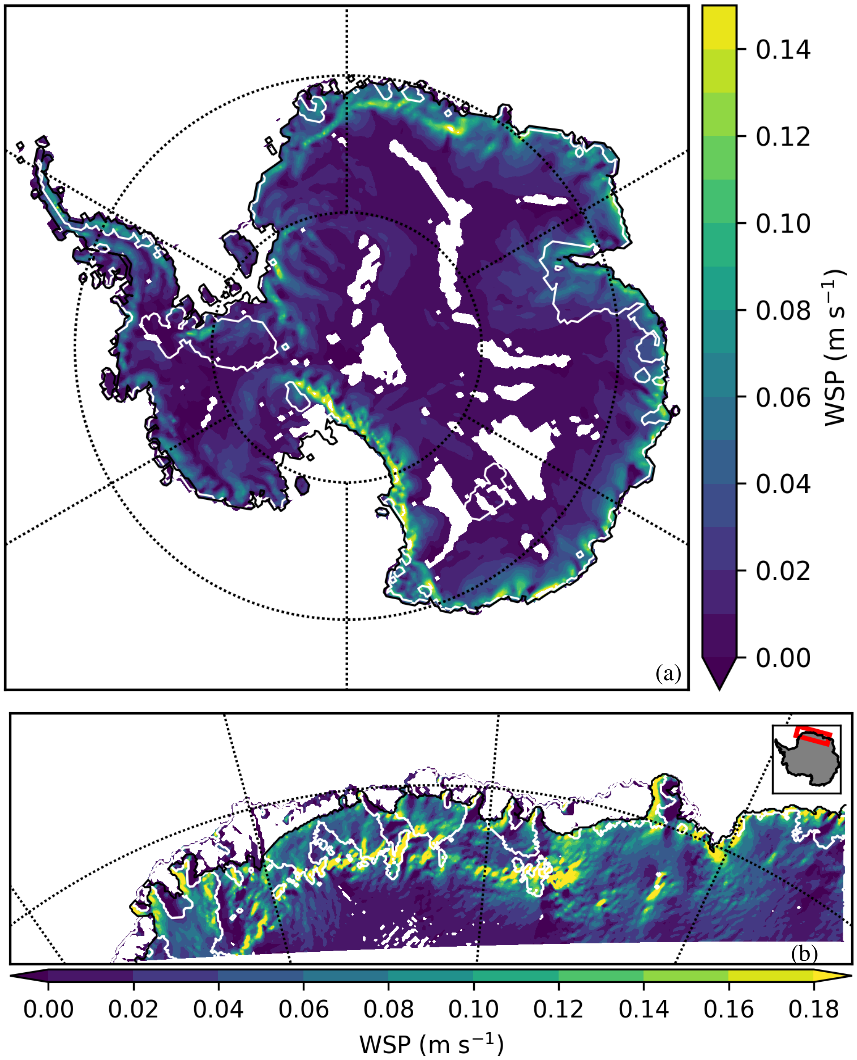

Figure S8. Mean MSWD for the AIS calculated from (a) RACMO27 and (b) RACMO5 simulations over 1979–2016 AD. White lines outline the areas with a weak SMB-SAT correlation from Fig. 2 in the main manuscript.

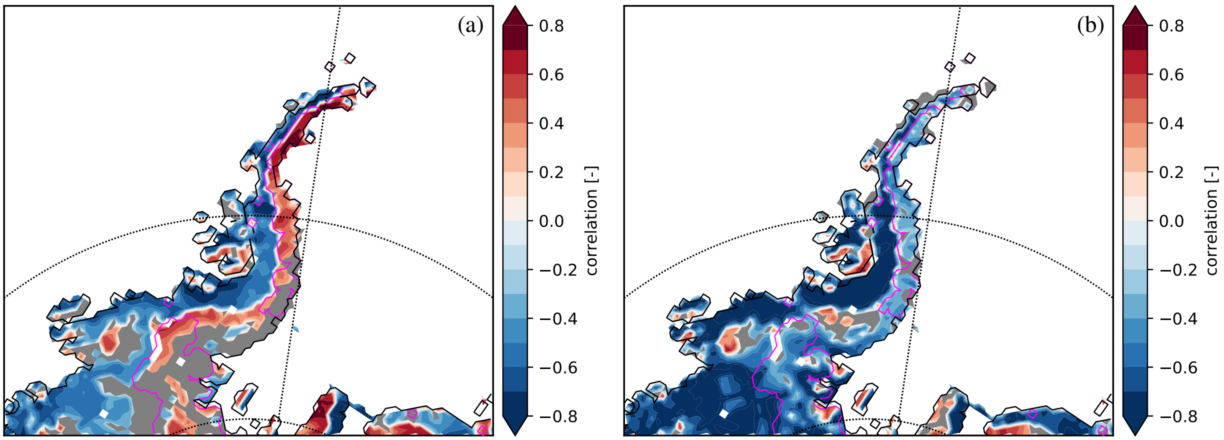

Figure S9. Zoomed-in view of the AP of the annual correlation between (a) MSWD and SAT, (b) MSWD and SMB, using RACMO27 simulations over 1979–2016 AD. Statistically insignificant areas (p > p_{FDR}, the threshold p-value calculated) are in grey. Areas with a slope smaller than 0.1% are removed and appear in white. Magenta lines outline the areas that have a weak SMB-SAT annual correlation in Fig. 1, panel f, of the main manuscript.

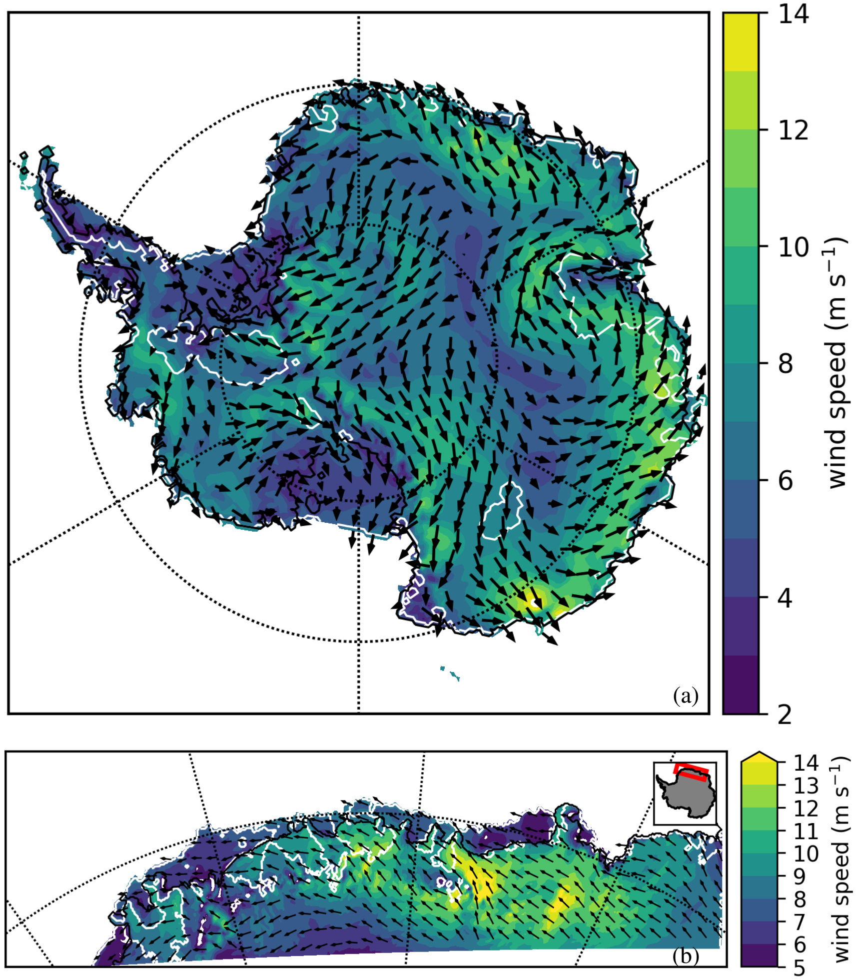

Figure S10. Mean 10 m wind speed and direction for the AIS based on (~~top~~a) RACMO27 and (~~bottom~~b) RACMO5 simulations over 1979–2016 AD. White lines outline the areas with a weak SMB-SAT correlation from Fig~~.2~~. 2 in the main manuscript.

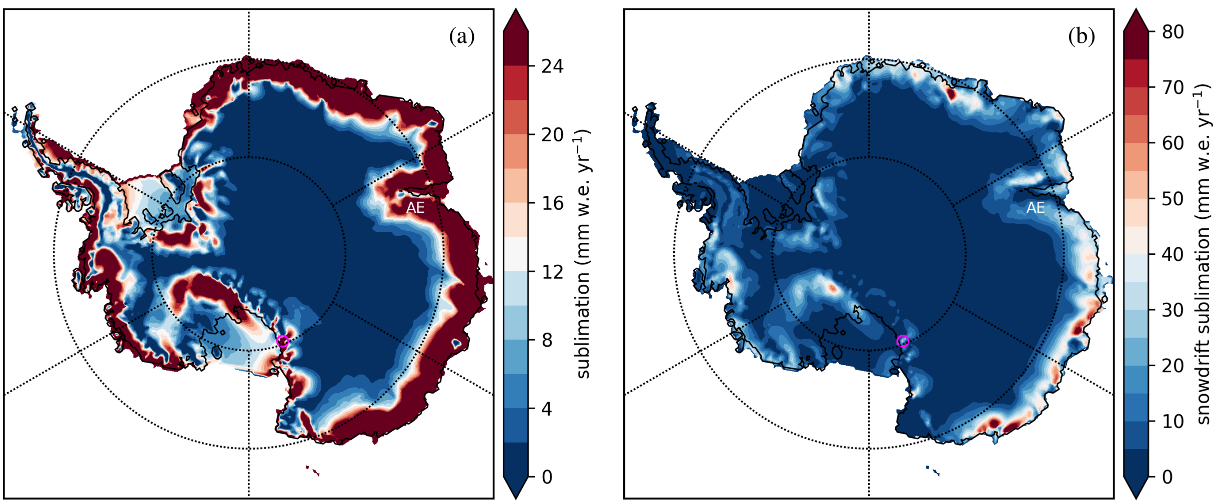

Figure S11. Mean (a) sublimation and (b) sublimation from snowdrift in mm w.e. yr^{-1} for the AIS based on RACMO27 simulations over 1979–2016 AD. The Byrd Glacier outlet is marked by a magenta circle and "AE" locates the Amery Embayment.

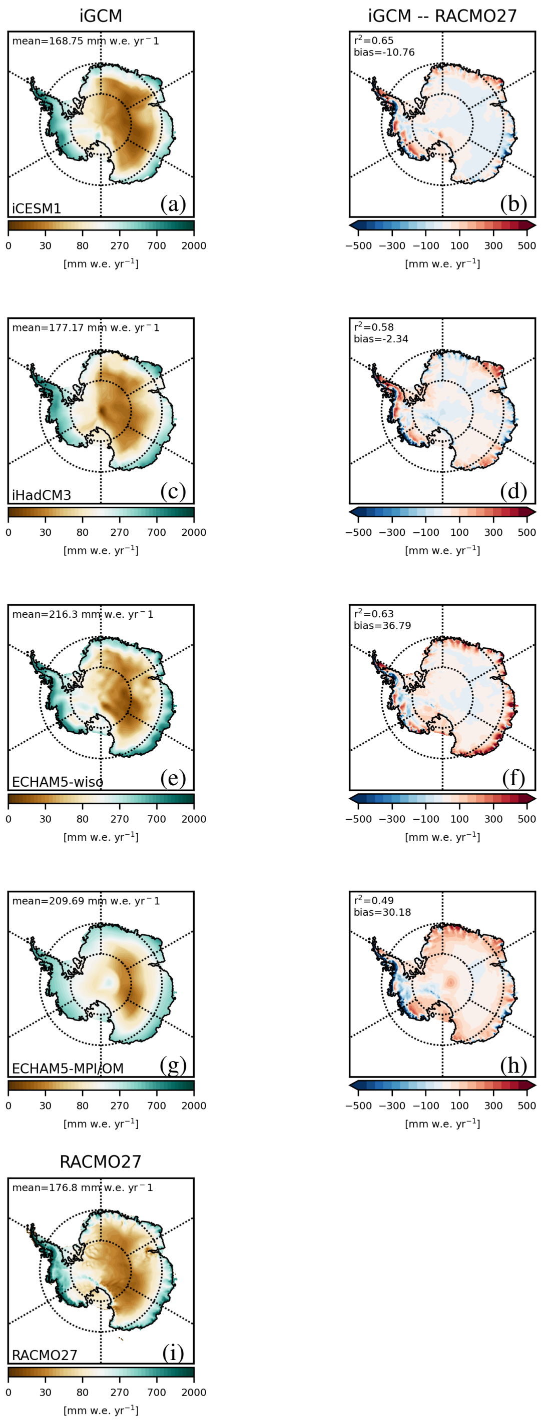

Figure S12. Mean SMB for the Antarctic continent [mm w.e. yr^{-1}] for (a,c,e,e,g) all the iGCM models used in this study and (i) RACMO27 for comparison, over the 1979–2000 AD time period. Panels (b,d,f,h) show the difference between the mean iGCM and RACMO27 SMB over the same time period, with the R^2 value and mean bias provided on each panel.

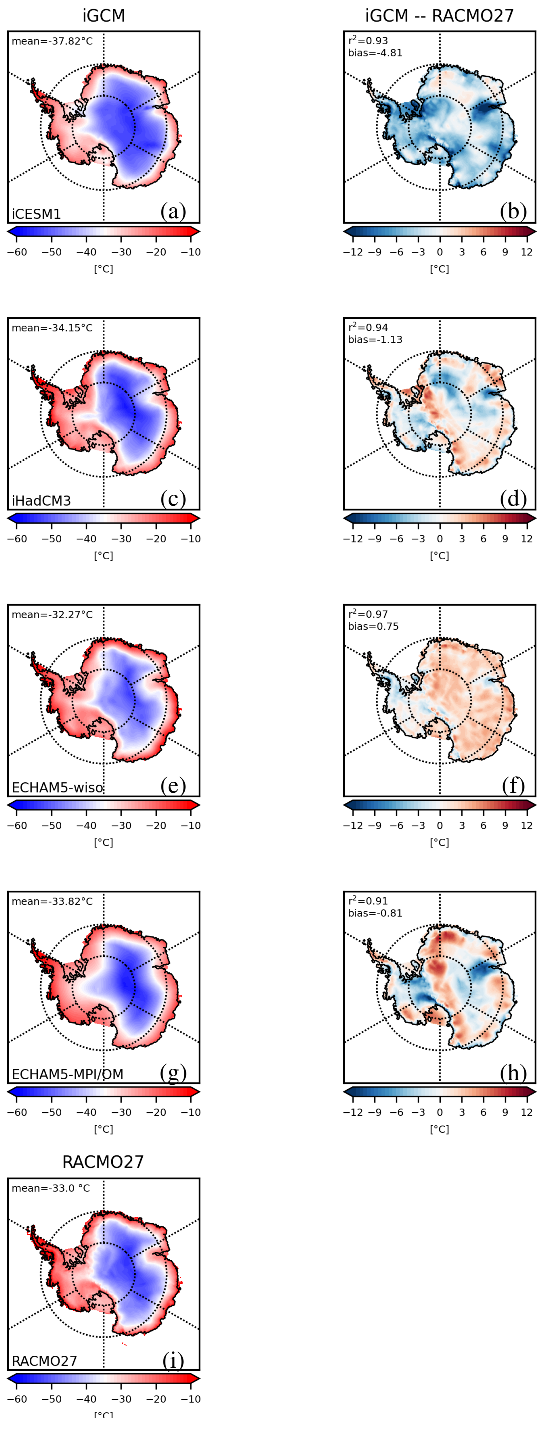

Figure S13. Mean SAT for the Antarctic continent [°C] for (a,c,e,e,g) all the iGCM models used in this study and (i) RACMO27 for comparison, over the 1979–2000 AD time period. Panels (b,d,f,h) show the difference between the mean iGCM and RACMO27 SAT over the same time period, with the R^2 value and mean bias provided on each panel.

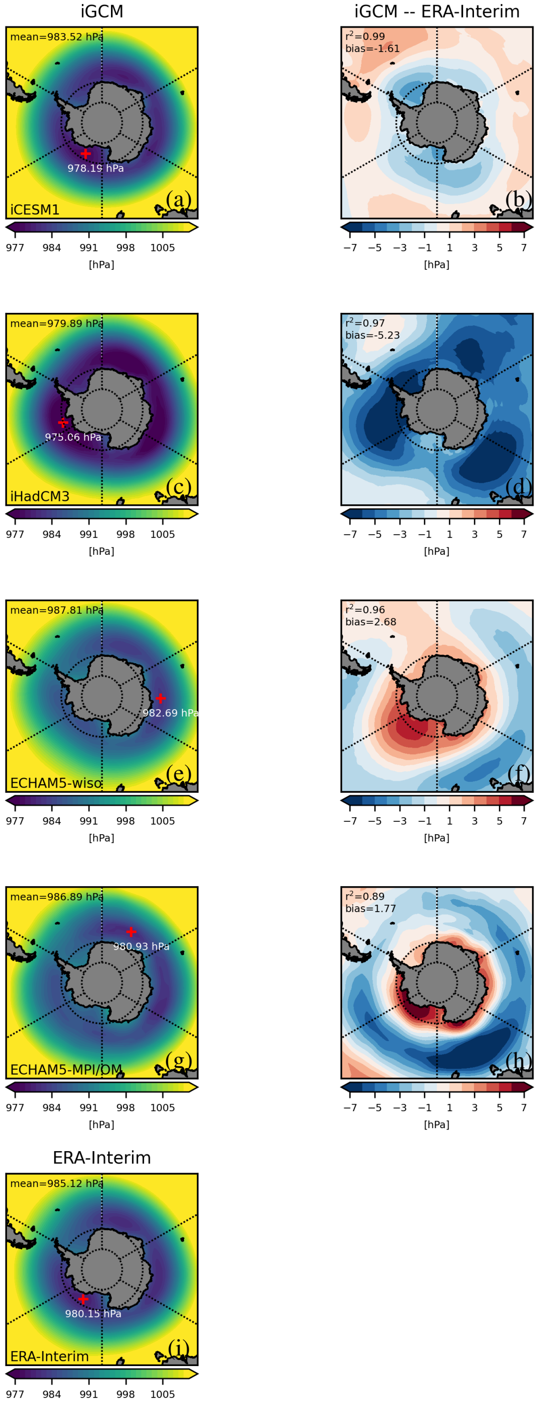

Figure S14. Mean sea-level pressure for the Southern Ocean [hPa] for (a,c,e,e,g) all the iGCM models used in this study and (i) ERA-Interim for comparison, over the 1979–2000 AD time period. The sea-level pressure absolute minimum is shown as a red cross as well as its value next to it. Panels (b,d,f,h) show the difference between the mean iGCM and ERA-Interim sea-level pressure over the same time period, with the R^2 value and mean bias provided on each panel.

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