Author's Response

We thank the Reviewer for their constructive comments regarding our manuscript. Our responses to specific comments are shown below in blue.

Overview of manuscript: The authors analysed model output for the period 18 ka to 6.5 ka (they use "kyr"), which corresponds to the period from the last glacial termination (i.e., the short warming period that marks the transition to from the last ice age to the current inter-glacial period) to the mid-Holocene. Two models were used: TraCE21ka (a fully coupled GCM) and LOVECLIM DGns (an intermediate complexity model). Analysis consisted of: (i) looking at time and space evolution of deglaciation in the models, and (ii) comparing model output with proxies for surface temperature, surface mass balance, coastal ocean temperatures, and sea ice. The authors' were not able to draw firm conclusions about the mechanisms that determine the regional differences that paleoclimate records indicate existed for this period. They were also not able to determine the strengths and weaknesses of the models in terms of ice sheet mass balance predictions. This inability to draw firm conclusions was because there are few climate model simulations of this deglaciation period to make comparisons between, and because there is a lack of high-resolution proxy data.

We hope that the Reviewer finds that the revised manuscript supports a number of firm conclusions regarding the mechanisms that determine regional differences in deglacial Antarctic climate and Southern Ocean changes as well as the strengths and limitations of the climate models. In particular, we demonstrate the sensitivity of coastal ocean temperatures to Southern Ocean meltwater forcing, regional differences in accumulation-temperature scaling relationships, and the strong correlation between surface air temperatures and surface albedo and sea ice coverage over the Southern Ocean. We also show that both models successfully capture the centennial-scale rates of temperature changes recorded in Antarctic ice core records, but also show key biases with regard to early Holocene SSTs and continental accumulation.

General comments: After reading the abstract, I was very interested to hear what the authors' results were, but I ended up being extremely confused by the end of the manuscript and needed to re-read it several times. My confusion was mainly for the following reasons: (1) The aims and results outlined in the abstract do not appear to be consistent with what the conclusions state at the end of the manuscript; (2) Some of the figures and their captions are missing crucial information that makes them impossible to understand in isolation from the text; (3) There are some bold assertions regarding causation that do not appear to be supported by citations of the work of others or by independent analysis in this manuscript; (4) It is not clear to me how such sparse data sets can be compared to the models used. I have elaborated on these points in the specific comments below. Specific comments: In this section, I provide specific details relating to the general comments above.

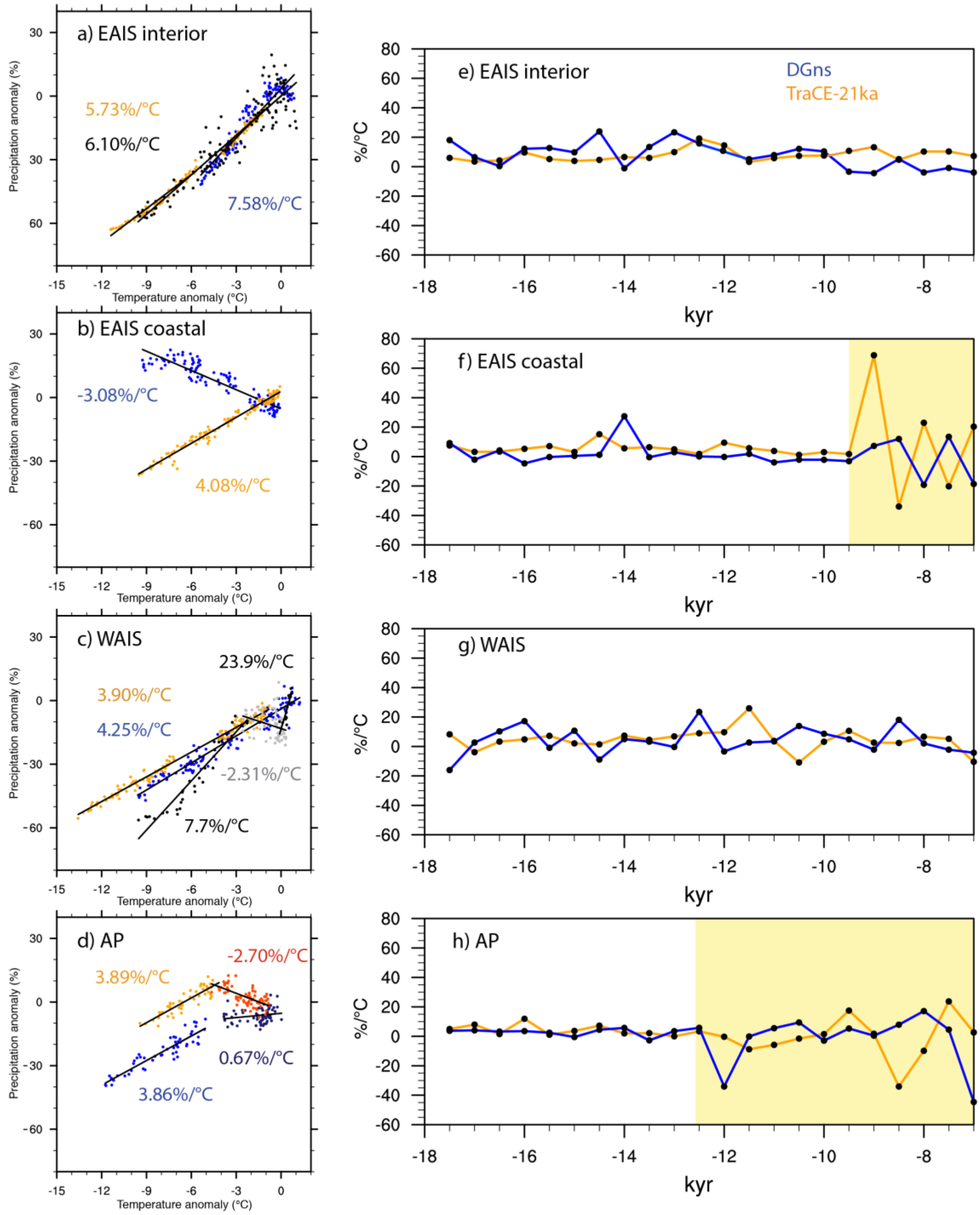
(1,2) We plan to edit the abstract and figures accordingly to avoid confusion. (3) We plan to revise the text in order to state our results more cautiously and include additional figures to better illustrate relationships between climate parameters. (4) We agree with the Reviewer that the sparse spatial and temporal coverage of the paleoclimate and Southern Ocean marine proxy records is a challenge in assessing model performance, a caveat that we plan to discuss in greater detail in the revised manuscript. In addition to climate model-proxy comparison, this paper also highlights the similarities and differences between the two model simulations for a number of parameters relevant to Antarctic ice sheet mass balance for which no proxy records are available, thereby addressing key data gaps in the observational record. Given that output of these climate model simulations continue to be applied as climate forcings in paleo-ice sheet simulations (e.g., Golledge et al., 2014; Tigchelaar et al., 2018; Petrini et al., 2018), this analysis will be useful for the community.

(1) The aims and results outlined in the abstract do not appear to be consistent with what the conclusions state at the end of the manuscript. The abstract states that the aim is to analyse results from two models to "better understand the mechanisms driving regional differences observed in paleoclimate models" and to "identify the main strengths and limitations of the models in terms of parameters that impact ice sheet mass balance". The abstract then states that the "climate simulations show" a number of results relating surface warming and accumulation rates to changes in sea ice, atmospheric circulation and ice surface elevation. The abstract also states that differences between the models and the proxy data exist, and suggested that this is because of inadequate representation of Meltwater Pulse 1A and 1B. However, in the "Summary and Conclusions" section, the ice sheet elevation effect on surface temperature is worded as if it is a specific result for TraCE-21ka, whereas in the abstract it is worded as if this is true for all simulations. In the "Summary and Conclusions" section, the accumulation rates are described as having "Strong discrepancies" between the models, which the authors suggest is related to model resolution issues, and they also note that the models do not match ice core accumulation reconstructions at the WDC and EDC sites. However, in the abstract the authors merely state that the accumulation changes in the model results are "quite distinct" and that the intermediate complexity model (which is not named in the abstract, but which is LOVECLIM DGns) had "resolution enhanced bias along the East Antarctic coast". The abstract states that variability in the relationship between accumulation and temperature has higher variability for coastal regions in the early to mid-Holocene, and state this "coincides with" atmospheric (Amundsen Sea Low) and sea ice changes. However, in the "Summary and Conclusions" section, this relationship is phrased more cautiously, with the use of "may", "appears to" and the statement for the need of a "more detailed moisture budget analysis". In the abstract, the mismatch between the models and proxies for the time and duration of the ACR and Younger Dryas/early Holocene warming is note, and states this is "suggesting that the Meltwater Pulse 1A and 1B events may be inadequately represented in these simulations." However, in the "Summary and Conclusions" section, the authors state that this mismatch "may result from model bias in large-scale ocean circulation, poorly constrained boundary conditions. . .or some combination of the two", and then mention meltwater forcing as something deglacial evolution is "highly sensitive to."

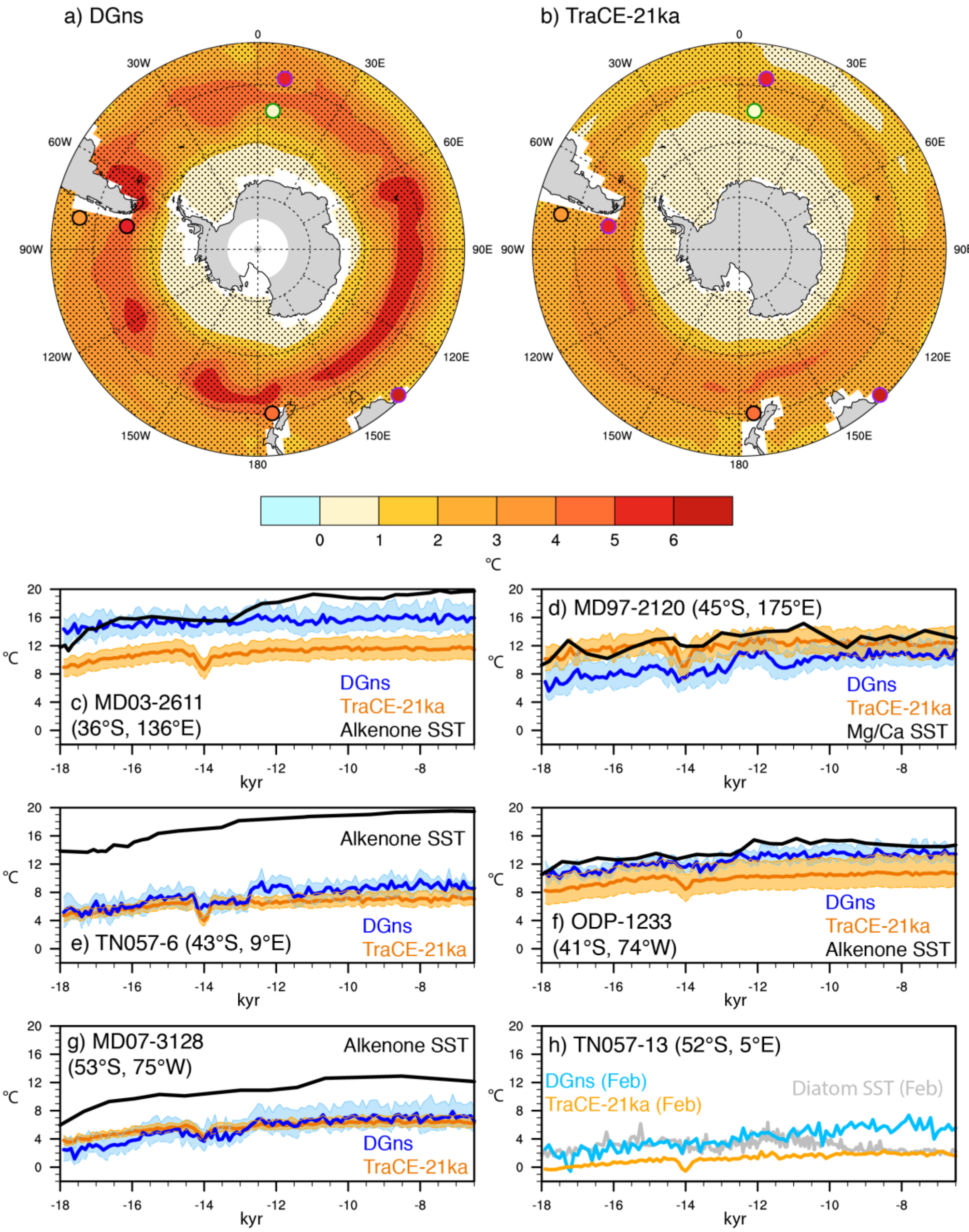
We plan to edit the abstract accordingly to avoid confusion. Specifically, we will remove the suggestion that "sea ice-albedo feedbacks likely drove regional surface temperature changes," but instead note that we observe strong correlations between surface air temperature and surface albedo over the Southern Ocean. We also plan to clarify that the decrease in ice surface elevation only influenced surface temperature in one of the two climate models (as the DG_{ns} simulation has no evolving Antarctic ice mask, which is explained in the Methods section). We can change "quite distinct" to "display large differences" with regard to modelled surface mass balance, and note the discrepancies to the Dome C and WAIS Divide ice core records. Lastly, we will add that model bias in large-scale ocean circulation as well as seasonal bias in the observational records may also have contributed to the model-proxy mismatch of the timing of accumulation rate changes in the abstract.

(2) Some of the figures and their captions are missing crucial information that makes them impossible to understand in isolation from the text: (i) The blue (DGns) and black (ice core data) lines are hard to distinguish in Figures 1-5. (ii) Figure 4 shows on the lefthand side graphs changes in snow accumulation (I think this should be "accumulation rates" because the units are "%", so presumably "% per 100 years" as in figure 3?) on vertical axes and degrees Celcius temperature change on the horizontal axes, but these axes are not labelled (they should be). The top graph on the left (a) is missing minus signs from the lower part of that graph's vertical axis. Parts of graphs (f) and (h) (which are for EAIS coastal and AP, respectively) are shaded yellow, but it is not explained why in the caption. (iii) Figure 5 shows regional SST and ocean temperatures as a time series of 100 year averages (presumably means) for "TraCE" (called "TraCE21ka" in previous graphs) and "LOVECLIM" (previous graphs called this DGns, the full title of the model is "LOVECLIM DGns"; consistency between graphs would be helpful). (iv) Figure 8 graphs are labelled (a) to (d) on both the left-hand side and the right-hand side, but the caption indicates that those on the left-hand side should be labelled (e) to (h), which is very confusing. The left-hand side graphs show 100 year averages of percentage sea ice coverage for (I presume, it does not say in the caption) the TraCE21ka model and the DGns model, while those on the right-hand side (again, I presume) show sea ice thickness. The reader needs to assume the same color-coding for model output as in previous graphs, because there is no legend, which is confusing.

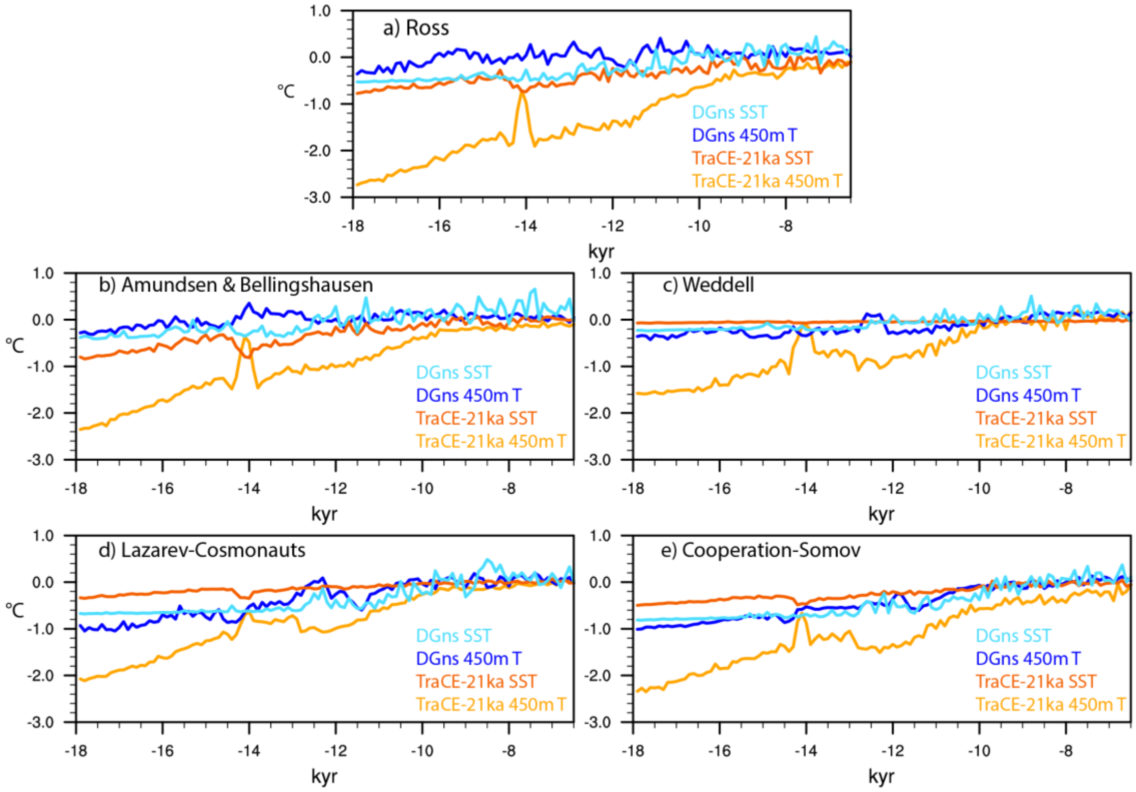
We plan to edit the figure legends and captions accordingly to avoid confusion. (i) The blue lines can be brightened to better distinguish them from the black lines. (ii) In Figure 4, the units of accumulation are % relative to the Preindustrial era. This will be added to the Figure axes and caption. We also will describe the meaning of the yellow bars, which is meant to show the shift to higher variability in accumulation-temperature scaling. (iii/iv) We plan to correct the labelling in Fig 5 and 8, and add a legend to the latter. Revised versions of Figures 4, 5, and 8 are shown below. Given comments from Reviewer 1, we plan to divide Fig 5 into two figures to show the SSTs at each individual proxy site.



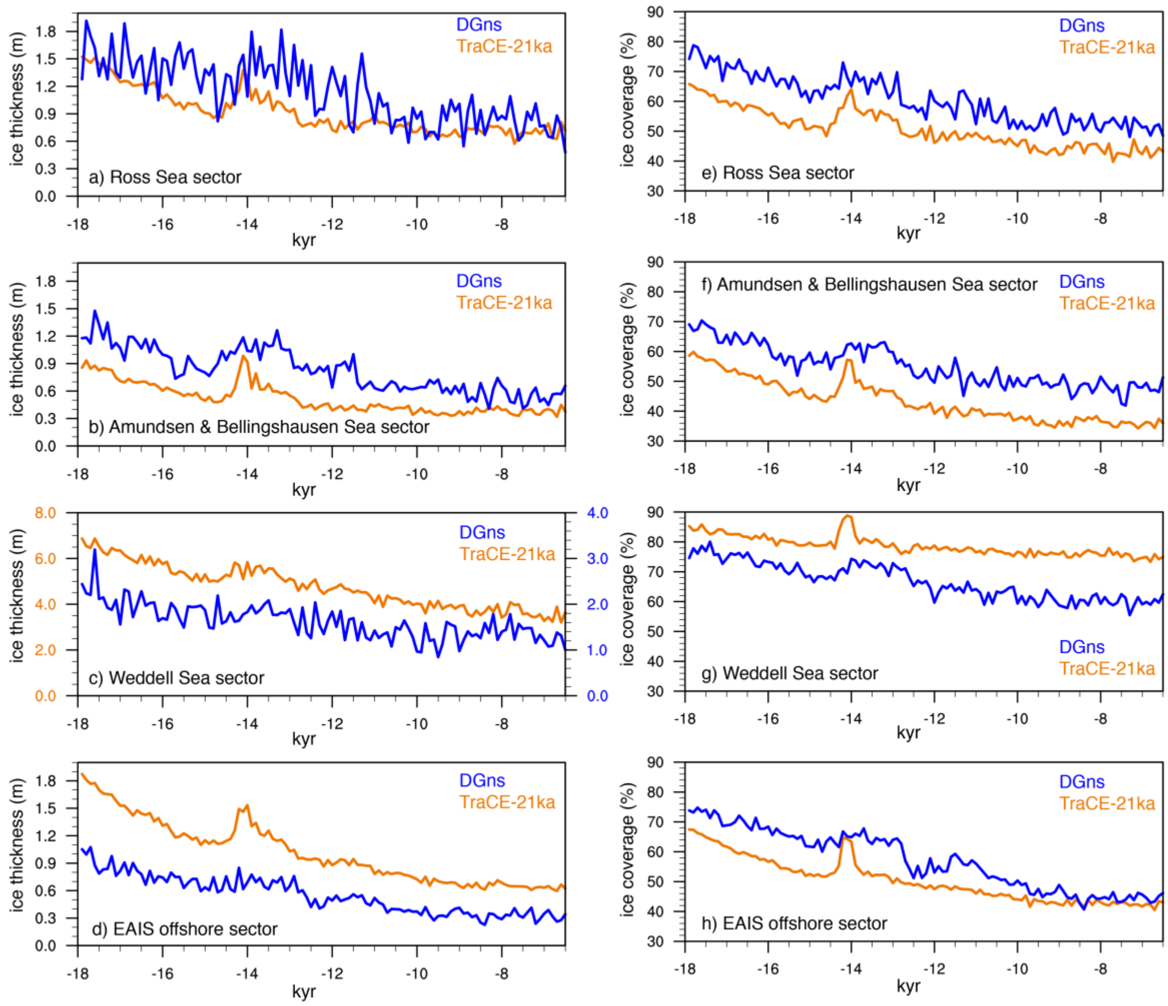
Revised Fig 4. (a-d) Scaling relationships of accumulation (% relative to PI) and temperature (°C relative to PI) in each region. Black and grey dots refer to the proxy record, blue and purple dots refer to the DG_{ns} simulation, and orange and red dots refer to the TraCE21ka simulation. (e-h) The ratio of the change in precipitation (%) to the change in temperature (°C) per 500 years. The yellow bars indicate a shift to higher variability in accumulation-temperature scaling.



Revised Fig 5-1: Sea surface temperature (SST) change (°C) as simulated in (a) DG_{ns} and (b) TraCE-21ka for the period of 18 to 6.5 kyr. Marine sediment locations are marked by open circles, with black outlines indicating a match in warming between the ice core and model simulation (i.e., the SST change estimated by the proxy from 18 to 6.5 ka is within the range of seasonal temperature changes of the climate model), and green (purple) outlines indicating an overestimation (underestimation) in warming by the models. Stippling indicates a difference between decadal output of 18.0-17.5 kyr and 7.0-6.5 kyr that is significant at the 95% confidence level. (c-h) Time series of 100-yr average mean annual SST from the models and SST proxy reconstructions (°C) at each individual marine sediment core site. The color shading represents the seasonal range calculated from the 100-yr average austral summer and winter temperature anomalies. In panel h, only a seasonal (February) proxy reconstruction is available; therefore, we only show modelled February SSTs from the climate models for this site.



Revised Fig 5-2: Time series of 100-yr mean annual average SST and 450 m depth ocean temperature anomalies relative to the Preindustrial era (°C) of the coastal seas around Antarctica, namely, the Ross Sea (70°S—62°S, 168°E—160°W), the Amundsen and Bellingshausen Seas (68°S—62°S, 135°W—60°W), the Weddell Sea (70°S—62°S, 60°W—30°W), the coastal region from Lazarev Sea to Cosmonauts Seas (67°S—62°S, 15°W—50°E), and the coastal region from Cooperation Sea to Somov Sea (67°S—62°S, 55°E—165°E).



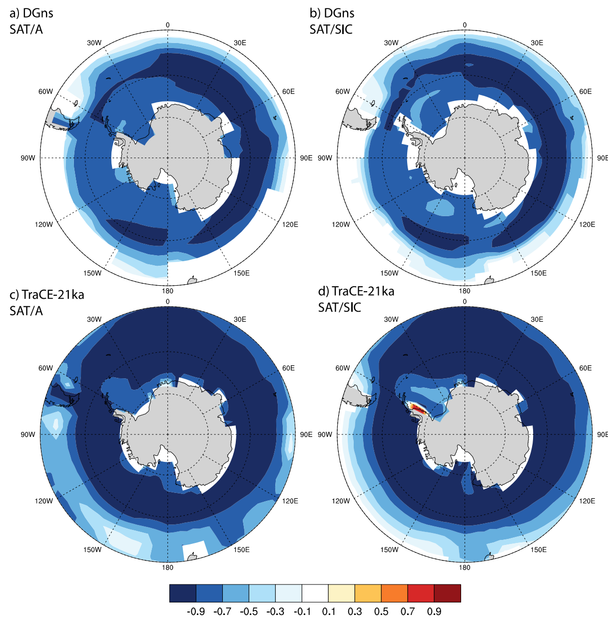
Revised Fig 8: Time series of 100-yr mean annual average (a-d) sea ice thickness (m) and (e-h) coverage (%) in the Southern Ocean, namely, the Ross Sea sector (70°S—50°S, 168°E—160°W), the Amundsen and Bellingshausen Sea sector (68°S—50°S, 135°W—60°W), the Weddell Sea sector (70°S—50°S, 60°W—30°W), and the offshore EAIS sector from Lazarev Sea to Somov Sea (67°S—50°S, 15°W—165°E). Please note the difference in scale in panel c.

(3) There are some bold assertions regarding causation that do not appear to be supported by citations of the work of others or by independent analysis in this manuscript. This is particularly the case for causation attributed to sea ice changes. Examples include: (i) Lines 200-203: Large regional temperature differences in the model results for both models are stated to be “due to decreases in annual average sea ice coverage”. How this conclusion regarding causation was reached is not explained. (ii) Lines 203-205: Differences between the results from the two models for regional temperature increases are stated to be “primarily due to differences in modelled sea ice”. How this conclusion regarding causation was reached is not explained. Figure 8(c) indicates almost no change in Weddell Sea sea ice coverage for TraCE-21ka, but this is not discussed by the authors in this context. (iii) Having made some bold assertions regarding temperatures at lines 207-221, the authors then concede at lines 222-223 that “some of the differences between the models and ice core temperature reconstructions could be due to local climate effects of the ice core sites not captured in the broad regional averages of the climate models”, which raises the question of how valid any of the comparisons between the ice cores and the models are. (iv) Lines 362-365: increases in continental surface temperature are linked with sea ice changes, with the authors stating

“regions displaying the greatest increases in continental surface temperature that are not associated with changing ice sheet topography occur along the continental margins. . .suggesting that albedo-driven radiative changes associated with sea ice coverage may be an important driver of regional warming differences”. This is more cautiously worded than the examples given in points (i) and (ii) above, but are still not physically justified. (v) Lines 369-370: similarly to point (iv) above, there is a lack of justification of the assertion “Changes in sea ice coverage may also explain the coastal warming differenced observed between DGns and TraCE-21ka.” (vi) Lines 382-386: similarly to points (iv) and (v) above, there is a lack of physical justification for the assertion “ the retreat of sea ice extent and reduced annual sea ice coverage in the early to mid-Holocene. . .may also introduce a greater variety of moisture sources of continental precipitation and alter the synoptic-scale variability, thereby weakening the SST-precipitation correlations in both models.” (vii) Lines 454-471: in this paragraph, the authors start with “It may be expected that the retreat of sea ice and increased area of open ocean may introduce additional moisture sources, thereby enhancing precipitation relative to temperature.” The authors then outline the main results from the literature, and summarize the results of their simulations which “do not exhibit a substantial increase in the scaling relationship with reduced sea ice coverage”. In other words, the bold assertion of a conceptual model in their first sentence is not supported by their modelling results. The paragraph ends with a call for “additional moisture budget analysis”.

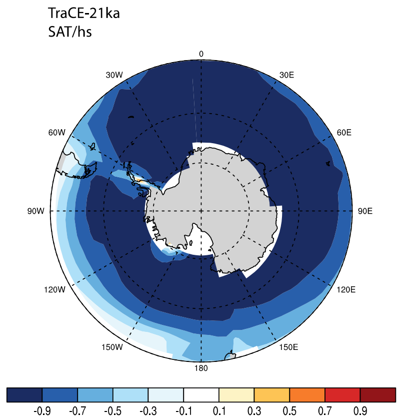
We plan to revise the text to advise more caution to our interpretations of the results. Specific responses are listed as follows:

(i) We agree with the Reviewer that we did not provide sufficient evidence to assert causality. As such, we will remove this statement. To better explore and illustrate the relationship between surface temperature and sea ice, we plan to add a figure to show the strong negative correlations that exist between surface air temperature (°C) and surface albedo and sea ice coverage (%) over the Southern Ocean in both models for the analysed period (see below figure).



Spatial Pearson linear cross-correlation coefficients (r) between decadal surface air temperature (SAT, °C), surface albedo (A), and sea ice coverage (SIC, %) for (a-b) DG_{ns} and (c-d) TraCE-21ka. DG_{ns} SAT was regridded to the same grid as DG_{ns} SIC using bilinear interpolation in panel b.

(ii) We plan to revise this clause to avoid confusion. Figure 1 shows that in both models we observe more pronounced surface warming through the analysed period in the coastal regions surrounding Antarctica than in the continental interior. The exception is the region in TraCE-21ka that is impacted by ice mask changes. We acknowledge that many factors, including the changes in greenhouse gas content, orbital forcing and oceanic/atmospheric heat transport, contribute to surface air temperature changes in the coastal regions, but we now also demonstrate the strong statistical relationship between surface air temperature, surface albedo and sea ice coverage over the Southern Ocean. Regarding the Weddell Sea, we erroneously plotted the time-average sea ice fraction rather than the areal sea ice fraction of TraCE-21ka in Fig 8 in the original submission. This has been corrected, and we now show a more substantial decrease in sea ice coverage in this model (see revised Fig 8). However, the sea ice coverage in both models shows relatively lower correlations to surface air temperature in parts of the Weddell Sea, and in the case of TraCE-21ka, an area of positive correlation adjacent to the Antarctic Peninsula (i.e., warmer surface temperatures associated with higher sea ice coverage, and vice versa). In addition to the sea ice coverage, the surface albedo also depends on the state of the surface (e.g., snow depth, snow age, bare ice, melting, lead opening), which we plan to explain in the text. Strong negative correlations are observed between snow ice thickness on the sea ice and surface air temperature in the Weddell Sea in TraCE-21ka (see Fig below), and the surface albedo decreases in both models by 0.1, an effect that is not experienced in the continental interior.



Spatial Pearson linear cross-correlation coefficients (r) between decadal surface air temperature (SAT, °C) and snow thickness on sea ice (hs, m) for TraCE-21ka. SAT was regridded to the same grid as hs using bilinear interpolation.

(iii) We plan to expand on the caveats of model-proxy comparisons in both the Methods and Discussion sections. We agree with the Reviewer that local climate effects may complicate comparisons to the broader regional averages in the climate models. However, this sentence is actually in reference to Fig 1c-f, in which we plotted time series of regionally averaged modelled temperature anomalies rather than site-specific temperature anomalies. We will clarify this further to avoid confusion.

We note that the Antarctic ice core locations were selected to be representative of global and regional climate, and with the exception of the James Ross Island ice core, the sites are located in areas that lack topographic features that would preclude model-proxy comparisons due to limitations in model resolution. Paleoclimate model simulations are often compared to ice core records as a means to evaluate climate model performance as well as to test the spatial representativeness of ice core locations (e.g., Masson-Delmotte et al., 2006).

Both models used in this analysis have previously been applied to better understand regional temperature and accumulation changes in Antarctic ice core records, as discussed in sections 3.2, 3.3 and 4.1 (e.g., Goosse et al., 2012; Freiler et al., 2015; Fudge et al., 2016). Comparisons of this nature are an important benchmark for the Paleoclimate Model Intercomparison Project 3 (PMIP3; see Bracconot et al., 2012), a sub-set of the Coupled Model Intercomparison Project 5 (CMIP5), which is used to inform the Intergovernmental Panel on Climate Change (IPCC) in terms of future climate projections.

(iv) We will revise these lines in accordance the above Figure, which shows the strong negative correlations between surface temperature, surface albedo, and sea ice coverage.

(v) We plan to remove this sentence based on the Reviewer's comments.

(vi) In this sentence, we offer a suggestion that the retreat of sea ice is a possible contributor to explain the weakening of SST-precipitation correlations at each ice core location in the Holocene in addition to the lower millennial-scale variability relative to the early deglacial period. However, in consideration of the Reviewer's concerns regarding the lack of physical justification, we plan to remove the sentence.

(vii) In this paragraph, we are not proposing a new conceptual model but rather discussing an existing one, suggested by Monnin et al. (2004), and more recently in Palerme et al. (2017) in the context of future climate. Coastal Antarctic ice core records (e.g., Law Dome, Siple Dome, Taylor Dome) do exhibit enhanced precipitation-temperature scaling in the Holocene as compared to the Last Glacial Maximum. As the Reviewer states, we demonstrate here that this behaviour is not reproduced in these climate simulations, although we do observe an increase in the variability of the precipitation-temperature scaling relationship in the Holocene. Given the implications of the possible enhancement of precipitation-temperature scaling for the future sea level contribution of the Antarctic ice sheet, we suggest that this should be explored further; however, this is beyond the scope of the present study.

(4) It is not clear to me how such sparse data sets can be compared to the models used. If I understand correctly what the authors have done, they have compared five ice cores with model output for surface temperatures from two global models, and two ice cores with model output for snow accumulation rates from two global models. As I have noted earlier, the authors concede at lines 222-223 that "some of the differences between the models and ice core temperature reconstructions could be due to local climate effects of the ice core sites not captured in the broad regional averages of the climate models", which raises the question of how valid any of the comparisons between the ice cores and the models are. There is a great deal of research on comparing model results with observations for modern day climate, and I would particularly recommend the authors read Notz (2015), titled "How well must climate models agree with observations?" (doi: 10.1098/rsta.2014.0164) and the papers cited therein. Notz (2015) uses sea ice as a particular example, so it is very relevant for what the authors' are attempting to do here. Sea ice proxies particularly lacking, so what can the authors here really say?

We agree with the Reviewer that the Antarctic paleoclimate and Southern Ocean marine proxy records are sparse, both spatially and temporally, and this is actually the main motivation of this work, as we explain in the introduction. This is of course a challenge in all paleoclimate studies, and we plan to expand on these caveats in the Methods and Discussion sections. We specifically apply these climate simulations to address some of these gaps in the observational record and to better understand mechanisms.

It is also important to consider the time-scales of this analysis. Notz (2015) describes a number of factors to be considered in model-observation comparisons in the context of modern arctic sea ice, namely, climate model internal variability, tuning of a climate model for a particular purpose (e.g., matching modern arctic sea ice trends), observational uncertainty and uncertainty of forcings and boundary conditions. Given that these are multi-millennial simulations and the physical parameters of the models were not tuned to serve a particular purpose, only the uncertainties of the latter factors are relevant in this context. In terms of the observational uncertainty, we plan to expand on the caveats of SST reconstructions and ice core isotope records, including the potential for seasonal biases, as suggested by Reviewer 1. With regard to the forcings and boundary conditions, although the greenhouse gas forcing and solar insolation applied in the simulations are well-constrained, we explain in the Methods/Discussion sections how the uncertainties related to the ice sheet topography in both hemispheres and the timing, magnitude and location of freshwater forcing resulting from deglaciation are the most uncertain aspects. As such, these boundary conditions are handled in different ways in the two simulations and lead to large differences between the models in terms of the analysed parameters.

We view the completeness of our data set and the use of two transient paleoclimate simulations, rather than one, as a main strength of our study. We offer a more comprehensive analysis of the climate parameters that impact Antarctic ice sheet mass than recent studies that have focused on a single aspect, proxy record or climate model. In addition to the assessment of climate model performance, our analysis of parameters for which no proxy records exist (e.g., coastal ocean temperatures at grounding line depths) is still highly valuable, as these models have been applied as forcings in numerous paleo-ice sheet modelling studies (e.g., Golledge et al., 2014; Tigchelaar et al., 2018; Petrini et al., 2018). As such, it is useful for the community to highlight the main differences between these two simulations, as they are consequential for ice sheet models. More specifically, we show here that the differences in timing and amount of prescribed Southern Ocean meltwater forcing lead to differences in sub-surface ocean temperature anomalies, which is highly relevant for the marine-based West Antarctic Ice Sheet.

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