This paper presents sensitivity studies with the atmosphere-only, stretched-grid GCM ARPEGE, forced by two present-day and strongly diverging end of 21st century sea ice and SST conditions from (bias-corrected) CMIP5 models. The results show that the Antarctic SMB is sensitive to Southern Ocean conditions, resulting from temperature and general-circulation changes. Although the paper contains some interesting results, it is very poorly written, contains factual errors, is and does not seem to come up with any clear answer to the problem posed in the title. I think it would require a very considerable effort from the authors to rewrite and strengthen the paper. I have decided not to focus on the language, but that doesn't mean that the paper needs a thorough check – it contains a lot of textual and grammatical errors! Instead, I will focus on (what I think are) the major issues with this paper, and hope the authors are able to improve the paper considerably. The only reason I decided not to reject is that I think the paper contains some interesting (but preliminary) results, but it will need to be thoroughly revised.

**Authors' reply:** We thank the reviewer for accepting to review the manuscript and for doing so rapidly. For the language, we will thoroughly check the whole paper again and have it read by (at least) one native speaker.

Major issues (in order of appearance)

√ Title: I think the title is a bit too general, and the paper does not really address it (see below for details). Something like: "Impact of two diverging scenarios of 21st century Southern Ocean surface changes on Antarctic surface climate and precipitation".

**Authors' reply:** The reviewer is right. We will change the title in « Impact of two diverging scenarios of 21st century Southern Ocean surface changes on Antarctic surface climate » or something close to this formulation. This corresponds to the actual content of the paper which was not the case for the submitted version.

Abstract: the abstract needs a few introductory and concluding sentences, introducing the problem and motivation, and giving some concluding remarks ('what did this study find, in relation to the title?')

**Authors' reply:** We will modify the abstract, add some introductory and concluding sentences and adapt it to the main findings associated with this study and its title.

√ Surface mass balance: is only one term of the mass balance; importantly, not the SMB causes a decrease in sea level, but the change (increase) in SMB, assuming solid ice discharge doesn't change. Since SMB and discharge are intimately linked, it is incorrect to describe SMB as a negative term contributor to sea level rise.

**Authors' reply:** Ok, in order to re-conciliate these considerations, we propose to rewrite this sentence in the following way "Assuming no associated response of the glaciers dynamics, the increase of the ice-sheet surface mass balance is the only significant projected negative contribution to SLR... »

√ P2, L28: ...allowing the use of cloud-resolving atmospheric model configuration. I think you mean 'preventing' instead of 'allowing'?

**Authors' reply:** No, we in-deed meant 'preventing', but we propose to rephrase this sentence in the following way in order to hopefully make it less confusing : "*The marginal importance of atmospheric deep convection for Antarctic precipitation does not require to perform dynamical downscaling at very high resolutions and the use of a cloud resolving atmospheric model configuration is therefore not particularly relevant for Antarctic climate projection. However, the added value of higher horizontal resolutions, such as for instance CORDEX-like simulations (Giorgi et al., 2016) at 0.44°, with respect to driving climate projection at coarser resolution (1 to 2°) from the CMIP5 ensemble is significant in coastal regions*".

√ P2, L33: higher horizontal resolution leads to higher estimates of snow accumulation. This is factually incorrect – actually, Genthon et al. (2009) suggest the opposite (see their Fig. 1). In addition, Lenaerts et al., 2017 do not find any significant impact of resolution on (integrated) SMB in the Amundsen region.

**Authors' reply: "** The reviewer is right, this is indeed factually incorrect for present-day snow accumulation estimation. In Genthon et al. (2009), it is also found that resolution has no significant impact for model run at sufficiently high resolution (< 3°). Using 27kms and 5.5 kms set up of RACMO, Lenearts et al., (2018) for the Amundsen region and Lenearts et al., (2012) for Adélie Land indeed found that the area integrated surface mass balance and the coastal-inland precipitation gradient were not significantly changed. One of their conclusion is that 27 kms seems to be a sufficiently high horizontal resolution to represent the coastal-inland SMB gradient in West and East Antarctica. These conclusions are possibly no longer valid when we jump from 200 kms resolution used in CMIP experiments to 30-40 kms horizontal resolution used for instance in Cordex-like experiment, our study or the work from Lenaerts and others. However, the part of this sentence about climate projection is not incorrect as Genthon et al., 2009 found a strong sensitivity of projected Antarctic precipitations increase to resolution (higher increase for higher horizontal resolution) especially for resolutions below 2° (see their figure 2). Result from Agosta et al., (2013) who used LMDZ4 model at a horizontal resolution of 60 kms and downscaled these climate projections with SMiHil model at 15 kms agree with these findings. To our knowledge, there is no publication suggesting no or opposite effect of higher horizontal resolution on Antarctic precipitation increase in a warmer climate. To be factually correct about the effect of horizontal resolution on present-day and future changes in snowfall, and re-conciliate the findings of each study cited here above, we propose to rewrite this part of the article in the following way :

"For present-day climate, Lenaerts et al., (2016,2018) found no significant differences in area-integrated SMB and coastal-inland snowfall gradient using 5.5 and 27 kms set up of RACMO model. Genthon et al., (2009) similarly found reduced impact of horizontal resolution when excluding very coarse (> 4°) model of the CMIP3 ensemble. For future climate projections however, much larger precipitation increases were reported when using climate model at higher horizontal resolutions (Genthon et al., (2009), Agosta et al., (2013)."

P3, L7: RCM. These random acronyms lead me to believe that the authors have been sloppy and have not sufficiently rechecked their manuscript prior to submission. Make sure these are defined when used for the first time.

**Authors' reply:** Ok, we have defined the RCM acronym at this place in the manuscript and checked carefully the introduction of new acronyms elsewhere.

√ P3, L18-29: This type of information does not fit in the introduction, it is far too detailed and should be moved to the methods.

**Authors' reply:**Ok, we will move the content of L18-29 and integrate it to the content of the "Data and Methods" section

Table 2: What are the units? What is the significance of these results, based on how much it varies in ERA-Interim over 1981-2010?

**Authors' reply:** Units are hectoPascals. We will perform some proper significance tests using the variability of sea-level pressure in Era-Interim, but these errors are likely to be significant as we plotted the significance (not shown) of ARPEGE sea-level pressure bias with respect to ERA-Interim and it is significant almost everywhere (at p=0.05) South of 20°S.
EDIT : They are in-deed largely significant at p=0.05 when compared to the variability in ERA-I.

√ P7, L20: 9.5 Kelvin/km. Where does this lapse rate come from? It would require a reference to back up this number.

**Authors' reply:** A dry adiabatic lapse rate of 9.8 $K.km^{-1}$ (there was indeed a small typo here) is used for instance in Bracegirdle and Marshall (2012) to correct surface temperature from meteorological reanalysis in order to compare them with in-situ observations in Antarctica. We will refer to this publication to justify to use of this lapse rate.

P9, L8 and around: This temperature bias is highly concerning, and instead of simply removing these areas, I would advise the authors to try to explain (and remedy) this bias. My intuition is that ARPEGE is not well able to represent strong surface-based temperature inversions (which not be surprising as many climate models struggle with this). Also, these simulations will likely need to be redone with ice shelves (mind the spelling) considered in the land model – that will allow the authors to analyze the effect of changing ocean conditions on ice shelves (which are a super-important component of the Antarctic glacial system – and located closest to the ocean, so should be most sensitive!). In any case, the authors will need to come up with an explanation why the ice shelves are so warm in the model, will need to remedy that bias, and apply that to new simulations. The current bias is alarming, because there is no reason why this bias wouldn't apply to other regions on Antarctica – where this bias is potentially compensated for by other model biases (radiation, clouds, albedo,...)?

**Authors' reply:** The reviewer is right in stating the fact that this temperature bias is concerning. We found it concerning as well and we tried unambiguously to identify its origin. First, we verified if ice shelves are indeed treated as land surface in the model, we plotted surface sensible and latent heat fluxes (see figures below) as well as surface albedo (SWU/SWD) and from this point of view nothing is abnormal and it compares reasonably with the same fluxes in MAR. The reviewer is also right in it is intuition that the warm bias over ice shelves (in winter) comes from ARPEGE lack of skills to represent very stable boundary layer and associated strong near-surface temperature inversions (as many climate models do). To investigate this, we plotted the difference between air temperature at 20 meters and surface temperature. We can see that the magnitude of the near-surface inversion compares reasonably well over most of Antarctica except over the ice shelves where the pattern (too weak inversion in winter and too large in summer) seems to be seasonally and spatially consistent with the biases (or difference) in near-surface temperature with MAR. The seasonality of the biases is the same over the high Antarctic Plateau. The reviewer is also right in saying that in other parts of Antarctica, ARPEGE lower skills for boundary layer are slightly compensated for by other biases (or difference with respect to MAR). In another ARPEGE experiment, in which we corrected atmospheric general circulation using nudging towards reanalyses (other paper in prep.), the warm bias over the High Antarctic Plateau increased slightly (1-2 K) as result of a decrease of a negative downward LW bias in the ARPEGE-AMIP experiment, but this warm bias in winter with respect to MAR and observations (3 - 5K) is in any case not much higher than what many other GCMs or even meteorological reanalyses are showing for the near-surface temperature of the Antarctic Plateau. It seems that the exceptional characteristics of the large ice shelves (extremely large and flat surfaces with few roughness) highlight more than anywhere ARPEGE lack of skills for extremely stable boundary layers.

Moreover, we draw the attention on the fact that a part of the large difference (10-12K) between ARPEGE and MAR over ice shelves in winter also comes from a cold bias of the MAR model as in her evaluation against 12 stations over the Ross Ice Shelf (https://zenodo.org/record/1256079#.XIuPd5zjIUF), C. Agosta found a -2.8K cold bias. This can also be seen in our comparison over the smaller ice shelves of the Dronning Maud Land region, as the comparison with MAR-ERA-I (Figure 4, left) suggest a large (5 to 9 K) warm “bias” in ARPEGE, while the warm bias of ARPEGE with respect to Halley and Neumayer weather stations are respectively only +1.2K and +0.9K. We also draw the attention on the fact that warm “biases” in winter over ice shelves is slightly reduced over Ross Ice Shelf and almost completely disappears over Ronne-Filchner Ice Shelf when RACMO2 is taken as reference (see Fig. below). This highlight how much large discrepancies can still exist over ice shelves, even between polar-oriented climate models regularly used as reference for Antarctic surface climate and mass balance such as MAR and RACMO2.

We precise that it is virtually impossible for us to redo all our ARPEGE experiment as our collaborator and co-author of the paper Michel Déqué is now retired and we therefore currently have no available computer time on the Météo-France supercomputer. Besides, fixing ARPEGE issues for stable boundary layer is a work beyond the scope of this paper and is actually the subject of a PhD thesis currently undertaken at Météo-France. Even if we agree that this bias is concerning, we think that many climate models or even meteorological reanalyses (see Freville et al., 2014, Bracegirdle and Marshall, 2012) show biases of Antarctic surface temperatures (High Plateau or ice shelves) that are the same order of magnitude as the warm bias over large ice shelves in our ARPEGE simulations. This, however did not prevent these data to be published and unfortunately sometimes widely used. So, we agree on the following for the future versions of the manuscript: avoiding to hide these biases, trying to be more explicit about their origin and warn potential users over ARPEGE reduced skills over ice shelves, being more critical about the skills of models (MAR and RACMO2) used to evaluate ARPEGE. Unfortunately, restarting the simulation while remedying the bias over the ice shelves will not be possible. To evaluate with reduced uncertainties the impact of climate change over Antarctic ice shelves, we propose to use our ARPEGE future projections to drive regional climate models (e.g. MAR or RACMO2) that are more skilled for ice shelves surface climate, which is also currently a work in progress.

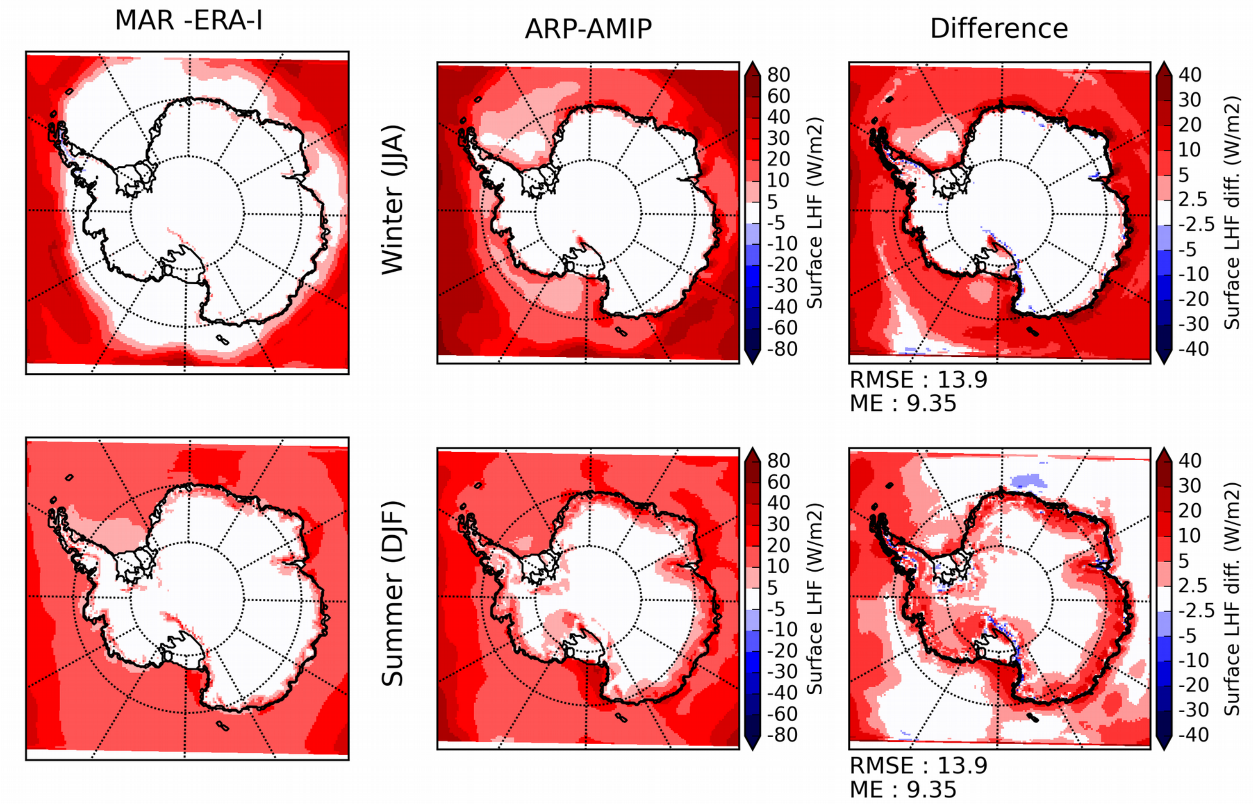


Fig 1: Surface latent heat flux (W.m$^{-2}$) for MAR forced by ERA-Interim (left), ARPEGE-AMIP simulation (centre) and ARPEGE minus MAR difference (right). Mean values for winter (JJA, bottom), mean values for summer (DJF, summer) computed for the 1981-2010 period.

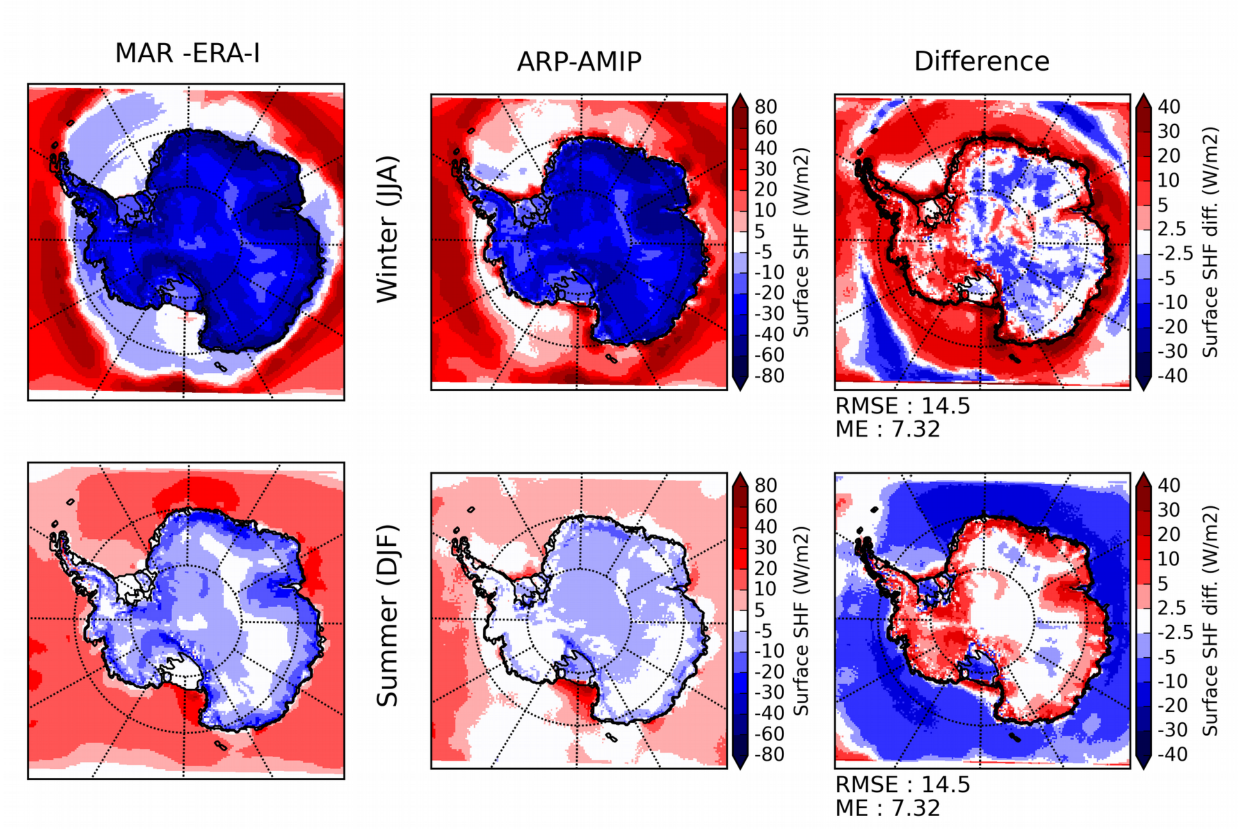


Fig 2: Surface sensible heat flux (W.m$^{-2}$) for MAR forced by ERA-Interim (left), ARPEGE-AMIP simulation (centre) and ARPEGE minus MAR difference (right). Mean values for winter (JJA, bottom), mean values for summer (DJF, summer) computed for the 1981-2010 period.

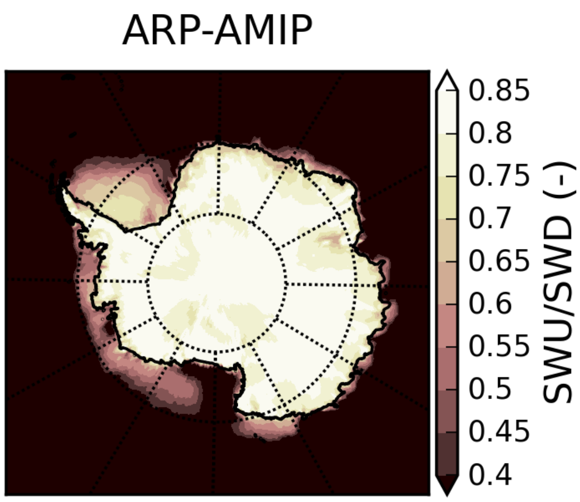


Fig 3: Mean summer (DJF) surface albedo (SWU/SWD) in the ARPEGE-AMIP simulation (1981-2010).

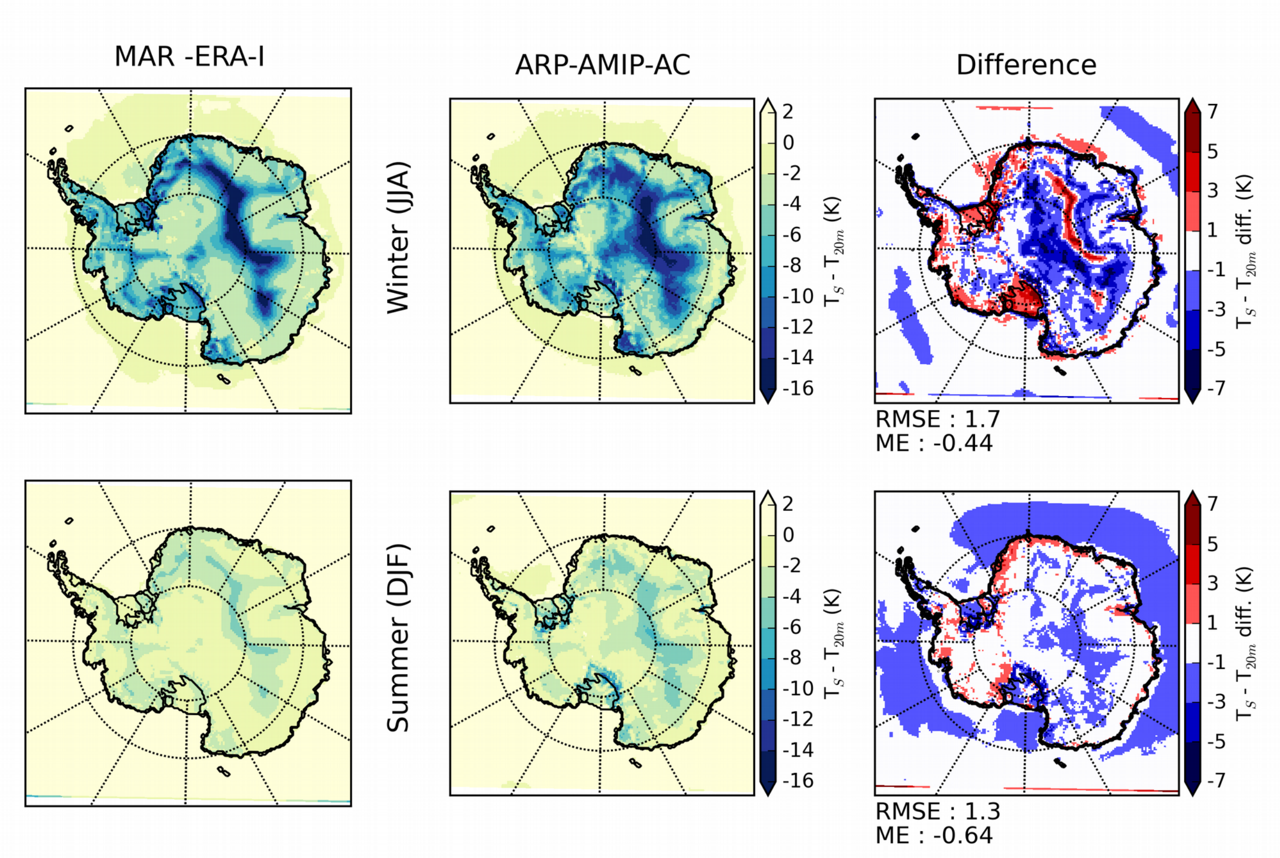


Fig 4 : Near-surface temperature inversion (T20m – Tsurf in K) for MAR forced by ERA-Interim (left), ARPEGE-AMIP simulation (centre) and ARPEGE minus MAR difference (right). Mean values for winter (JJA, bottom), mean values for summer (DJF, summer) computed for the 1981-2010 period.

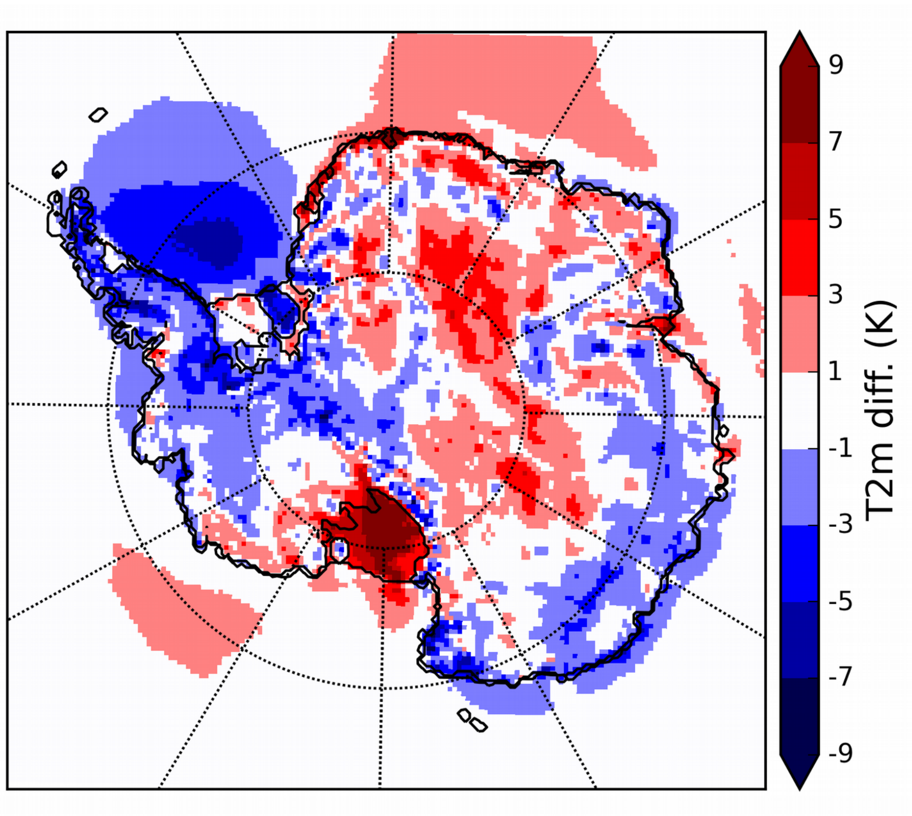

Fig 5 : ARPEGE-AMIP – RACMO2-ANT (Van Wessem et al., 2018) mean winter (JJA) 2 meters air temperatures difference over 1981-2010.

√ Table 3 is very poorly readable, enlarge and perhaps move to supplementary material. Again, don't forget to mention units. Same for Table 4.

**Authors' reply:** Ok, we will enlarge, reformat and put the units for Table 3 and 4. Table 4 will most likely be moved to the supplementary material.

√ P12, L12: this contradicts what was (falsely) mentioned in the introduction, as ARPEGE (the lower-resolution model) gives higher precipitation than MAR (the higher-resolution model)

**Authors' reply:** It is incorrect here to consider that ARPEGE is the low resolution model compared to MAR. In the set up we used, (see figure below, that will be added to the supplementary material), the horizontal resolution varies from 30 kms near the stretching pole to about 45 kms over the northern end of the Antarctic Peninsula. We can thus consider the horizontal resolution to be fairly similar to the 35 kms horizontal resolution of the MAR simulation used for comparisons.
Differences for the AIS integrated precipitation between ARPEGE and MAR are here explained by differences in precipitation physics (in parts) and mostly (as we demonstrate in another publication in prep.) by errors in atmospheric general circulation in the AMIP-style ARPEGE simulation.

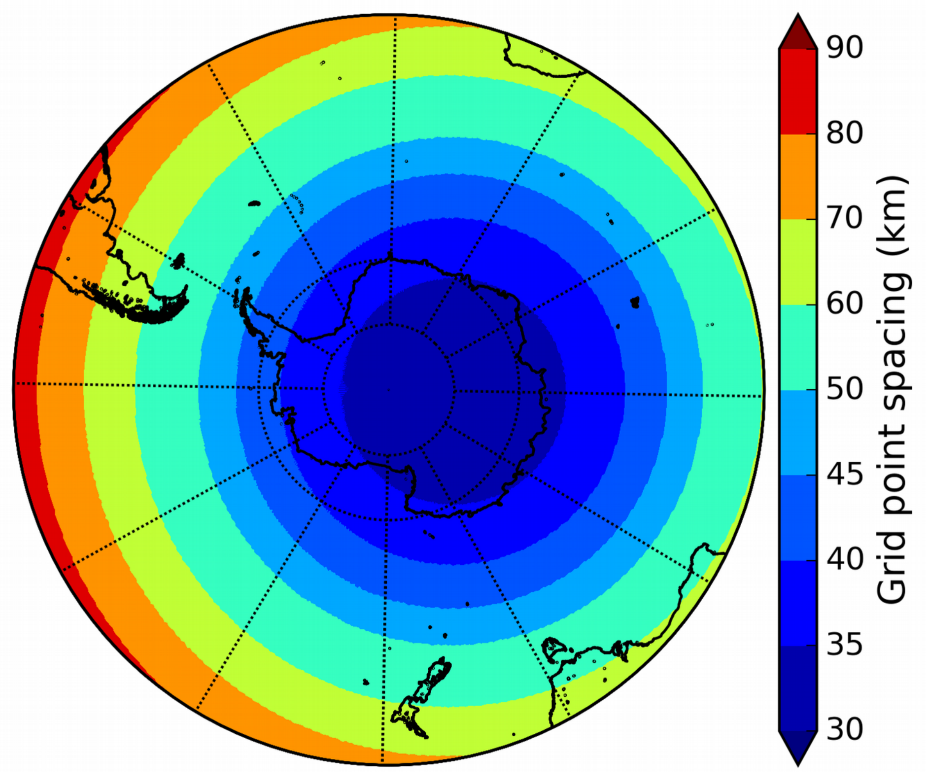

Fig 6 : Horizontal resolution (kms) of ARPEGE-T255 configuration with stretched grid over Antarctica.

P12, L18 and around: Runoff is the result of a complex interaction between atmosphere and snow conditions, and requires a sophisticated albedo and snow model, the latter which allows for percolation and refreezing of surface meltwater. The authors do not present any compelling evidence why the surface melt and runoff rates in ARPEGE are any realistic, which casts doubt on the reliability of simulated future melt and runoff rates. For example, Table 5 suggests that, on the grounded AIS, about one-third of the liquid water production (rain + melt) runs off in ARPEGE, which suggests that its snow model is not capable to retain and refreeze sufficient meltwater (for comparison: both MAR and RACMO2 produce almost no runoff with comparable liquid water production). I would therefore advise the authors to focus solely on precipitation and temperature, possibly surface melting (provided that the authors can show evidence of realistic surface melt patterns in the present-day simulation, compared to MAR for example), but refrain from analyzing future runoff changes.

**Authors' reply:**The reviewer is right in stating that ARPEGE is not able to represent the liquid water retention capacity of the Antarctic snow-pack and therefore the importance of refreezing which most likely yields an overestimation of run-off rates. This is possibly due to the fact that the first and second snow layers have an upper bound of 0.05 and 0.5m respectively as well as some possible density issues as ISBA-ES has been mostly calibrated using observations from temperate climate snow. Because of this, we agree on avoiding to analyse future runoff changes in our ARPEGE simulation. Before producing the revised version of the manuscript, we will evaluate ARPEGE ability to reproduce the spatial distribution and inter-annual variability of Antarctic surface melt as the integrated value for present-day climate (31±19 to 55±34 Gt $yr^{-1}$) seems to be at first order roughly consistent with values from MAR (34±11 Gt $yr^{-1}$) and RACMO2 (46±16 Gt $yr^{-1}$). If the results of this analysis are encouraging, we will briefly comment future melt rates in our climate projections.

Table 6: Are these changes significant at all? What is the present-day variability? What is the relative change instead of / next to the absolute changes?

EDIT : Climate signals are in-deed significant when compared to present-day variability. Differences in climate change signals when comparing the two set of SSTs (original vs bias-corrected) are mostly not significant.

Conclusions: a concluding paragraph/section is missing on the actual conclusion of this work. What is the uncertainty of Southern Ocean conditions on Antarctic SMB? What is driving it? What is the impact of changing SIC vs. SST? What are the driving forces of the change in Antarctic SMB – the thermodynamic (i.e. increase in surface temperatures) or the dynamic (large-scale atmospheric circulation)? What is the impact of the radiative and turbulent fluxes? There are many open questions that the authors do not discuss, but that can be answered if the model simulations are analyzed in more detail.

**Authors' reply:** We will largely rewrite the conclusion in order to refer more precisely to the main findings of this paper. Regarding the impact of changing SST vs SIC., this has been done in other publications (Van Lipzig et al., 2002, Krinner et al., 2014, Kittel et al., 2018). We will refer to these publications in our discussion and if relevant, reinterpret our results in light of these studies. For future projection, we propose to analyze the evolution of the different terms of the surface energy balance (radiative, turbulent, surface sensible and latent heat fluxes…) in order to discuss their relative contribution to surface warming (and possibly melt).

EDIT : We have largely modified the abstract, some part of the discussion and the conclusion and re-interpret our results in the light of the literature mentioned above. We have analyzed the changes in surface energy balance (SEB) and the relative share of the different component of the surface in this increase (see Figures below). We learn from this analysis that the increase in net longwave radiation (LWnet) and in sensible heat flux (SHF) to a lower extent are the driving fluxes responsible for increasing available energy at the surface over most of the ice sheet. Over the peripheral areas of the ice sheet, latent heat flux (LHF) and more locally net shortwave radiation (SWnet) can also be driving component of the increase in available energy at the surface. Nor large differences are found using the different set of SSC, except for a larger increase in LWnet (decrease in SWnet) over the high Antarctic Plateau in projections with MIROC-ESM SSC (large decrease in sea-ice) as a result of higher increase in atmospheric temperatures and moisture content/cloudiness (not shown). While these results are relatively interesting and could be added to the supplementarymaterial of the paper, we don't think that they are valuable informations to the papers and are a bit
out of subject. Besides, ARPEGE capability to correctly reproduces the different component of the SEB in present -day climate could not be evaluated against reliable in-situ observations. However, we are open to integrate these results in next version of the paper if this appear to be relevant for the reviewers.

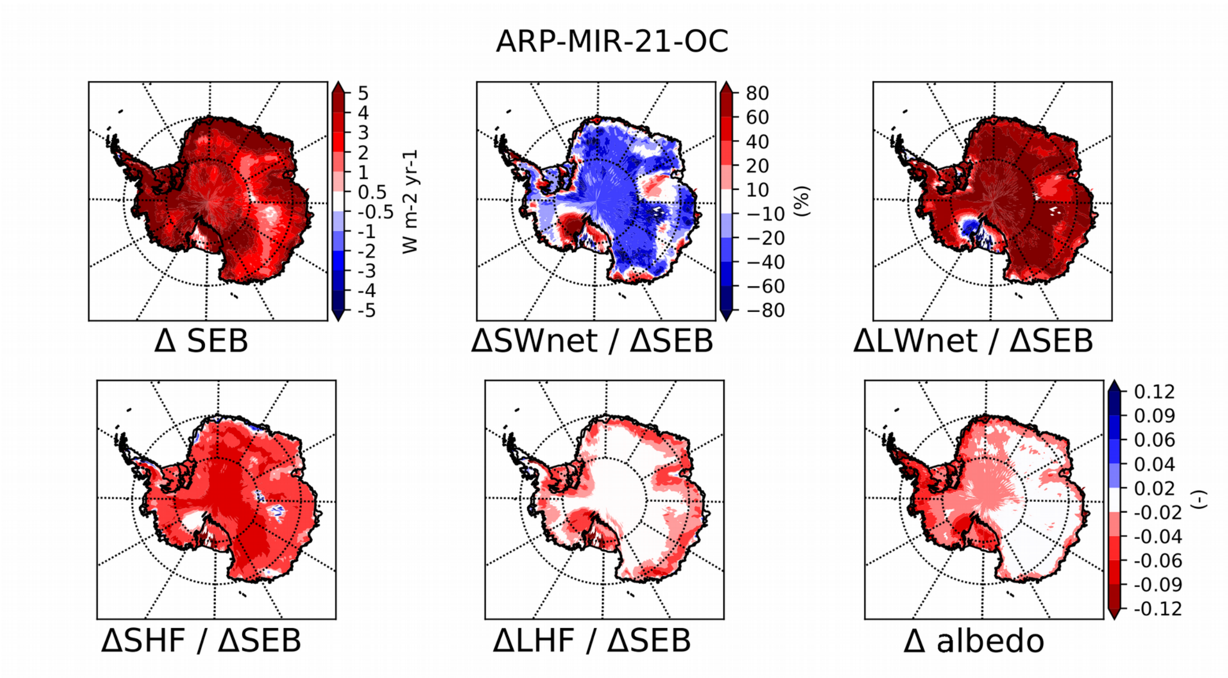


Fig : Increase in yearly mean surface energy balance (SEB) in ARP-MIR-21-OC (2071-2100) with respect to ARP-AMIP (1981-2010) and relative importance of the net shortwave and longwave radiation (Swnet and Lwnet), latent and sensible heat (LHF and SHF) fluxes in the changes in SEB. The changes in surface albedo is displayed on lower-right part of the pannel.

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# Effect of ~~uncertainties of Southern Ocean surface temperature and sea-ice change~~ prescribed sea-surface conditions on the modern and future Antarctic surface climate ~~projections~~simulated by the ARPEGE AGCM

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**Abstract.** ~~In this study, the~~ Owing to increases in snowfall due to higher air moisture holding capacity, the Antarctic Ice-Sheet surface mass balance is expected to increase by the end of current century. Assuming no associated response of ice dynamics, this will be a negative contribution to sea-level rise. However, the assessment of these processes using dynamical downscaling of coupled climate models projections still bear considerable uncertainties due to poorly represented Southern Ocean surface conditions and southern high-latitudes atmospheric circulation.

This study evaluates the Antarctic surface climate simulated by a high-resolution atmospheric model, and assess the effects of two diverging sea surface conditions (SSC, i.e. sea surface temperature and sea-ice concentration) projections from coupled climate models on the simulated Antarctic surface climate. The two coupled models from which SSC are taken, MIROC-ESM and NorESM1-M, show opposite antarctic sea-ice trends among the CMIP5 RCP8.5 projections ensemble. The atmospheric model ARPEGE is used with a stretched grid in order to ~~reach a~~ achieve an average horizontal resolution of 35 kilometers over Antarctica. Over the historical period (1981-2010), ARPEGE is ~~forced~~ driven by the historical ~~sea surface conditions (SSC , i.e. sea surface temperature and sea-ice concentration) from MIROC and~~ SSC from MIROC-ESM, NorESM1-M CMIP5 historical runs, and by observed SSC (AMIP-experiment). These three simulations are evaluated against the ERA-Interim reanalyses for atmospheric general circulation~~and against~~ , the MAR regional climate model, and *in-situ* observations for surface climate. ~~As lower boundary conditions for simulations for the period~~

For the 2071-2100 ~~, we use SSC from coupled climate model CMIP5 simulations of the same models following~~ period, SSC from the same coupled climate models forced by the RCP8.5 emission scenario ~~. We use these output~~ are used both directly and with an anomaly method based on quantile mapping. We ~~assess the uncertainties linked to the choice of the coupled model and the impact~~ evaluate the effects of driving the atmospheric model by the different choice of SSC from coupled models as well as the effects of the method (direct output and anomalies) used. For the simulation using SSC from NorESM1-M, ~~we do not find significant changes in~~ no significantly different climate change signals over Antarctica ~~when using~~ as a whole are

found when bias-corrected SSC are used. For the simulation ~~using~~ driven by MIROC-ESM ~~output~~SSC, an additional increase of +185 Gt.yr$^{-1}$ in precipitation and of +0.8 K in winter temperatures for the ~~grounded Antarctic ice-sheet was obtained when using~~ Antarctic Ice-Sheet is obtained with bias-corrected SSC.

Antarctic warming and precipitation increase obtained in this study fall within the range of the CMIP5 ensemble RCP8.5 projections. For the range of Antarctic warming found (+3 to +4 K), we confirm the much larger importance of snowfall increase compared to increases in melt and rainfall expected. Using the end members of sea-ice trends from the CMIP5 RCP8.5 ensemble projection, the difference in warming obtained ($\sim$ 1 K) is clearly smaller than the spread of the CMIP5 Antarctic climate projections. This confirms the importance of the representation of the South Hemisphere general circulation by atmospheric models and associated late 21$^{st}$ century projected circulation changes.



## 1 Introduction

~~Dominated by precipitation increase, the~~ Projected 21$^{st}$ century increases of the Antarctic surface mass balance (SMB)~~of the Antarctic ice sheet is the only projected negative contributor to the global~~ , due to higher precipitation rates, are expected to partly compensate for eustatic sea level rise (SLR) ~~over the course of the 21$^{st}$ century (????)~~due to opposite changes in almost all other components affecting global sea level (**???**). However, the acceleration of ice ~~dynamics~~ flow and the interactions between oceans and ~~ice-shelfs~~ ice shelves are expected to ~~yield~~ lead to an overall positive Antarctic contribution to SLR (**??**). ~~For these reasons, it is~~ Uncertainties ice dynamics and surface mass balance trends are large and influence each other (e.g., **??**). It is therefore crucial to produce ~~downscaled Antarctic climate scenarios~~ high-quality Antarctic climate projections for the end of the current century with reduced uncertainties~~in order to provide i) better~~ , yielding trustworthy estimates of the contribution of the ~~ice-sheet SMB and ii) better accumulation or atmospheric forcings~~ Antarctic Ice Sheet (AIS) SMB and useful driving data for ice dynamics and ~~ocean-ice-shelfs interactions~~ ocean-ice shelf interaction model studies.

~~The attribution of recent evolutions of the Antarctic climate to the current anthropic climate change~~

Detection of an anthropogenic climate change signal is more challenging ~~compared to~~ than in the Arctic. ~~Indeed, while~~ While some parts of West Antarctica and of the Antarctic Peninsula (AP) have experienced one of the world's most dramatic warming in the second part of the 20$^{th}$ century (**??**), there was no significant ~~trend in the evolution of the temperatures of~~ recorded temperatures trend in East Antarctica as a whole (**?**) except for some coastal regions that experienced a cooling in autumn over the 1979-2014 period (**?**). Moreover, the observed strong warming trend in the ~~Antarctic Peninsula~~ AP has shown a pause or even a reversal for 13 years in the beginning of the 21$^{st}$ century (**?**). Contrary to the dramatic sea ice loss observed in the Arctic (e.g., **?**), significant positive trends have been observed in the antarctic sea-ice ~~around Antarctica~~ extent (SIE) since the 1970s (**??**, e.g.), although recently record sea ice loss was observed in 2016/7 (**?**). Most of the Coupled Atmosphere-Ocean Global Circulation Models (AOGCM or CGCM), such as those participating the Coupled Model Intercomparison Project, Phase 5 (CMIP5, **?**) struggle to reproduce the seasonal cycle of ~~Sea-Ice Extent (SIE )~~ SIE around Antarctica, and very few of them ~~was~~ were able to reproduce the positive trend observed in the end of the 20$^{\text{th}}$ century (**?**). This is ~~a major issue as the evolution~~ problematic because **?** have shown that atmospheric model simulations of the Antarctic climate ~~by the end of the current century was shown to be more~~ are very sensitive to the ~~evolution of the~~ prescribed sea surface conditions (SSC) ~~, i.e.~~ such as sea surface temperatures (SST) and sea-ice concentration (SIC)~~, than to the evolution of greenhouse gases concentration (?). Besides~~. Additionally, the amount of sea-ice present in ~~the~~ historical AOGCM climate ~~simulation~~ simulations is strongly correlated to the absolute ~~decrease in~~ sea-ice decrease in the projections for the 21$^{\text{st}}$ century ~~(?), which is itself~~ (**??**). This itself is strongly linked to the strengthening of the westerly ~~winds~~ wind maximum (**?**).

~~So far, it~~ It is expected that the signal due to the current ~~anthropic~~ anthropogenic climate change will take over the natural variability of Antarctic climate by the middle of the twenty-first century (**?**). A more complete review of the current understanding of the regional climate and surface mass balance of Antarctica and of the key-processes that need to be taken into account in order to assess their evolution can be found in **?**.

The dynamical downscaling of climate ~~scenarios~~ projections such as those provided by coupled models from the CMIP5 ~~experiment is generally performed using regional climate models~~ ensemble is generally produced using Regional Climate Models (RCM). The marginal importance of atmospheric deep convection for Antarctic ~~precipitations~~ precipitation does not require ~~to perform~~ dynamical downscaling at very high resolutions~~allowing~~ , thus the use of a cloud resolving atmospheric model configuration ~~. The~~ is therefore not necessarily particularly relevant for Antarctic climate projections. However, the added value of ~~simulations at a higher resolution, for instance~~ higher horizontal resolutions, such as the CORDEX-like simulations (**?**) at 0.44°, with respect to ~~original climate scenario at a~~ driving climate projections at coarser resolution (1 to 2°) from the CMIP5 ensemble is significant in coastal regions near the ice-sheet margins or on the ~~Antarctic Peninsula~~AP, as the steep topography induces a strong precipitation gradient between wet coastal regions and dry inland ~~Antarctic Plateau~~East Antarctic Plateau (EAP). Below 1000 m above sea level (a.s.l), the origin of ~~precipitations~~ precipitation on the Antarctic continent is mostly orographic (e.g., **?**). ~~As a consequence, model ran at a higher horizontal resolutiontend to produce higher estimates of the snow accumulation at the continent scale over Antarctica and higher accumulation increases in a warming climate (??). Modelling~~ For present-day climate, **??** found no significant differences in area integrated SMB and coastal-inland snowfall gradient between simulations with the RACMO model run at 5.5 and 27 km horizontal resolution. **?** similarly found reduced impact of the model grid resolution when excluding very coarse ($> 4°$) model of the CMIP3 ensemble. For future climate projections however, much larger precipitation increases were reported when using climate models at higher horizontal resolutions (**??**). The modelling of strong katabatic ~~winds that blow~~ wind flows blowing at the ice sheet surface is also generally improved with a better representation of the topography (e.g., **?**).

In this study, we use ~~CRNM-ARPEGE~~CNRM-ARPEGE, the atmosphere general circulation model (AGCM) from Météo-France, with a stretched grid allowing a horizontal resolution of about 40 km over the ~~whole Antarctic continent~~ , entirety of the Antarctic continent to dynamically downscale ~~different climate scenarios~~multiple coupled climate simulations. As a global atmospheric model, ARPEGE is driven by prescribed SSC, but does not require any lateral boundary conditions. This method has some advantages over the more commonly used limited-area RCM method. More details on the ARPEGE model setup are given in section 2.1. ~~This method has some advantages over the more commonly use of RCM.~~ It is possible to use observed SSC at the present and model-generated SSC anomalies for projections (e.g., **?**). When such an anomaly method is used, the results do not absolutely require the AOGCM used as ~~driver for sea surface conditions to represent~~ a driver for SSC to represent realistically the atmospheric general circulation and its variability in the region of interest~~realistically in every respect~~. Using a stretched grid GCM also allows ~~better taking~~ us to better take into account potential ~~feedbacks~~ feedback and teleconnections between the high-resolution region ~~which the focus lies on~~we are interested in, and other regions of the world. ~~Rather unsurprisingly, several~~ Several studies showed that AGCMs produce a better representation of atmospheric general circulation and a better ~~repartition~~ spatial distribution of precipitation when forced by observed ,instead of simulated SSC (**???**). ~~These~~ Consistently, these studies also showed that ~~bias correction of SSC before the downscaling of future climate scenarios gives~~ AGCM runs for future climate with bias-corrected SSC yielded significantly different results ~~with respect to original scenarios. For these reasons, we performed a~~ than runs with SSC directly taken from coupled model output.

In this work, the bias-correction of SSC using a quantile mapping method for SST and an analog method for SIC is achieved following the methods and recommendations described in **?**. ~~We reduced our ensemble of possible simulations to the choice of two AOGCMs from the CMIP5 experiment : MIROC-ESM and NorESM1-M. As they are~~ We drive the ARPEGE AGCM (**?**) with both observed and simulated (from coupled models) SSC for present-time. For future climate projections (late 21$^{st}$ century), we drive the model with SSC directly taken from two coupled models and with corresponding bias-corrected ~~in a second step, the main criterion was the amplitude of the climate change signal in the oceanic forcings coming from these two models, not the realism of the simulated present-day~~ SSC. One aim of this paper is to evaluate the capability of ARPEGE at high resolution to represent the current Antarctic climate. Additionally, we quantify the sensitivity of present and future simulations with this AGCM to the prescribed SSC. The ~~short analysis on which we based our model choice is described in section 2.2. We also performed an AMIP-style control simulation for the period 1981-2010 in which CNRM-ARPEGE is forced by observed SST and SIC coming from PCMDI data set (?). CNRM-ARPEGE was also forced by the original oceanic SSC coming from the historical simulations of MIROC-ESM and NorESM1-M (1981-2010) and from projections under the radiative concentration pathway RCP8.5 (?) carried out with the same two models (2071-2100)~~results are compared to those of similar previous studies. This study also differs from **??** as the ARPEGE AGCM is run at a substantially higher horizontal resolution (35 km) than the LMDZ model, which was used in these previous studies aiming at analyzing the impact of prescribed SSC on the Antarctic climate simulated by AGCMs.

Section **??** presents a short analysis of CMIP5 SST and SIE in the Antarctic region that was used as a basis to select the coupled model providing the SSC used here. This section also presents the ARPEGE model set-up used in this study. In section~~3.1, we present~~ **??**, we assess the ability and limitations of CNRM-ARPEGE to represent current Antarctic climate~~as well as the differences between the AMIP experiment and the experiments forced by oceanic forcings coming from historical simulations of CMIP5 GCMs. In section 3.2, we present modelled climate at the end of the 21$^{st}$ century by CNRM-ARPEGE~~

~~and the differences in climate change signal between scenarios realized with bias-corrected and original SSC from the RCP8.5 scenarios of MIROC-ESM and NorESM1-M~~. Results and comparisons for Antarctic future climate projections are shown in section **??**.

## 2 Data and Methods

### 2.1 Sea Surface Conditions in CMIP5 AOGCMs

~~SSC forcings~~ Sea surface conditions have been identified as key ~~forcings~~ drivers for the evolution of the Antarctic climate of the continent (**??**). In this study, SSC obtained from CMIP5 projections are bias-corrected using recommendations and methods from **?** before being used as surface boundary conditions for the atmospheric model. Therefore, the importance of the ~~bias~~ realism of each CMIP5 model for the reconstruction of oceanic conditions around Antarctica in their historical simulation is reduced. There is however a limitation in the previous statement, as the analog method used to bias-correct SIC runs into trouble when the bias is so large that ~~sea ice~~ sea-ice completely disappears over wide areas for too long. Besides this caveat, ~~however,~~ the choice of CMIP5 AOGCMs used in this study was guided by compliance to desired characteristics of the climate change signal rather than by the skills of the models in reproducing SSC in the historical periods.
Therefore, we identified CMIP5 models with the highest and lowest climate change signal by the end of the 21$^{\mathrm{st}}$ century considering only SSC in the Southern Ocean, in order to span the uncertainty range associated with model response. We computed the relative evolution of integrated winter SIE over the whole Southern Ocean between the historical simulation (reference period: 1971-2000) and the RCP8.5 scenario (reference period: 2071-2100) for 21 AOGCMs from CMIP5 experiment. The CMIP5 ensemble was reduced to 21 because some models sharing the same history of development and high code comparability as others have been discarded. The model list is the same as in **?** and can be seen in the Fig. **??** legend. We also looked at the mean summer SST increase South of 60°S for the same reference periods. In order to be consistent with periods of maximum (minimum) SIE, seasons considered in this analysis are ~~slightly~~ shifted, and winter (summer) ~~correspond~~ corresponds here to the period August-September-October, ASO (February-March-April, FMA).
The results of the computation can be seen in ~~Figure~~ Fig. **??**, which displays the relative ~~decrease of SIE in~~ late winter (ASO) decrease in SIE in the RCP8.5 ~~scenario~~ projections as a function of the value of the ~~mean~~ late winter SIE in the historical simulation. The four models with the highest decrease in SIE are CNRM-CM5 (-62.4 %), GISS-E2-H (-53.4 %), inmcm4 (-47.9%) and MIROC-ESM (~~-45,2~~-45.2 %). Because of the above-mentioned limitation of the bias-correction method, the first three GCMs cannot be selected due to a large negative bias of winter and spring SIE. We therefore selected MIROC-ESM as representative for models projecting a large climate change signal for ~~sea~~ sea- ice around Antarctica. If we consider weak climate change signals, MIROC5 shows the lowest decrease (~~-1,5~~-1.5%) followed by NorESM1-M (-13,6%). For the same reasons of limitations of the bias correction method, we dismissed MIROC5 and kept NorESM1-M as representative for a weak climate change signals in the SSC around Antarctica. The impact of primarily considering changes in winter SIE rather than in late summer SST is limited as the climate change signal for these two variables are strongly ~~linked~~ correlated ($R^2$=0.96). For late summer SSTs, MIROC-ESM shows the 6$^{\mathrm{th}}$ largest increase(+1.8 K) while NorESM1-M exhibits the second lowest (+0.4 K).

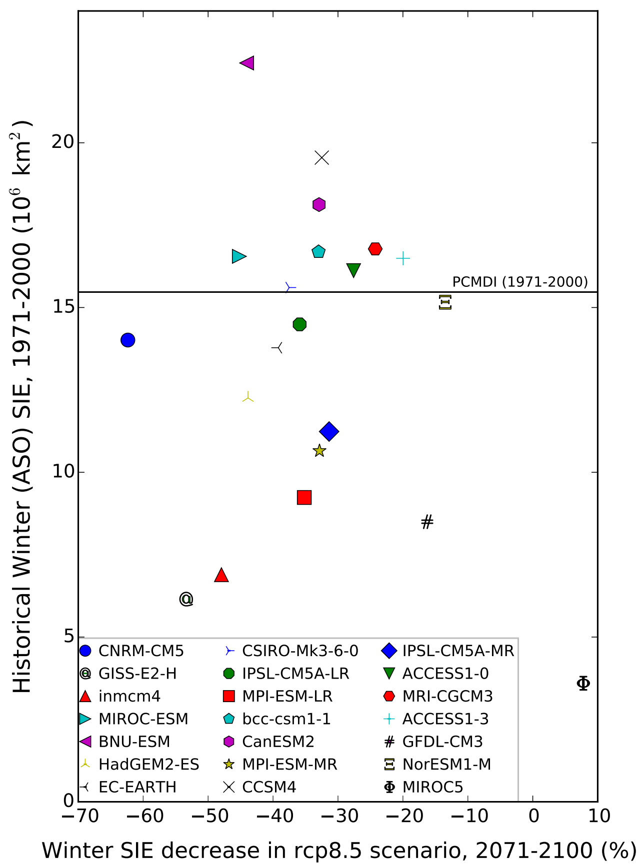



**Figure 1.** Historical Antarctic ~~Winter~~ winter (August-September-October: ASO) Sea-Ice Extent (SIE, in millions of km$^2$) as function of the relative decrease of ~~Winter~~ winter SIE in the RCP8.5 ~~scenario~~ projection for the period 2071-2100 with respect to the reference period 1971-2000. The mean ~~Winter~~ winter SIE in the observations for the historical reference period is indicated by the horizontal black line (PCMDI 1971-2000).

**Table 1.** Summary of the period, sea surface conditions, greenhouse gazes (GHG) concentration and reference historical simulation (for ~~each future scenarios~~ climate projections) for each ARPEGE simulation presented in this paper

| Simulations | Period | SSC | ~~GES~~ GHG Concentration | Reference for hist. climate |
|---|---|---|---|---|
| ARP-AMIP | 1981-2010 | Observed | historical | - |
| ARP-NOR-20 | 1981-2010 | NorESM1-M historical | historical | - |
| ARP-MIR-20 | 1981-2010 | MIROC-ESM historical | historical | - |
| ARP-NOR-21 | 2071-2100 | NorESM1-M RCP8.5 | RCP8.5 | ARP-NOR-20 |
| ARP-MIR-21 | 2071-2100 | MIROC-ESM RCP8.5 | RCP8.5 | ARP-MIR-20 |
| ARP-NOR-21-OC | 2071-2100 | Bias-corrected NorESM1-M RCP8.5 | RCP8.5 | ARP-AMIP |
| ARP-MIR-21-OC | 2071-2100 | Bias-corrected MIROC-ESM RCP8.5 | RCP8.5 | ARP-AMIP |

### 2.2 CNRM-ARPEGE set-up

We use version 6.2.4 of AGCM ARPEGE, a spectral primitive equation model from Météo-France, CNRM (**?**). The model is run at T255 truncation with a 2.5 zoom factor and a pole of stretching at 80°S and 90°E. With this setting, the horizontal resolution in the Antarctic ranges from ~~35~~ 30 km near the stretching pole on the Antarctic Plateau to 45 km at the Northern end of the ~~Antarctic Peninsula~~AP. At the Antipodes, near the North Pole, the horizontal resolution decreases to about 200 km. In this model version, the atmosphere is discretized into 91 sigma-pressure vertical levels. The surface scheme is SURFEX-ISBA-ES (**?**) which contains a three-layer snow scheme of intermediate complexity (**?**) that takes into account the evolution of the surface snow albedo, the heat transfer ~~trough~~ through the snow layers and for the percolation and refreezing of liquid water in the snow pack. Over the ocean, we use a 1D version of sea-ice model GELATO (**?**) which means that no advection of sea-ice is possible. The sea-ice thickness is prescribed following the empirical parametrization used in **??** and described in **?**. The use of GELATO is therefore limited to the computation of heat and moist fluxes in sea-ice covered regions and also allows taking into account for the accumulation of snow on top of sea-ice.

We performed an AMIP-style control simulation for the period 1981-2010 in which CNRM-ARPEGE is driven by observed SST and SIC coming from PCMDI data set (**?**). CNRM-ARPEGE was also forced by the original oceanic SSC coming from the historical simulations of MIROC-ESM and NorESM1-M (1981-2010) and from projections under the radiative concentration pathway RCP8.5 (**?**) carried out with the same two models (2071-2100). In section **??**, we present modelled climate at the end of the 21st century by CNRM-ARPEGE and the differences in climate change signal between projections realized with bias-corrected and original SSC from MIROC-ESM and NorESM1-M RCP8.5.

In each ARPEGE simulation, the first two years are considered as a spin-up phase for the atmosphere and the soil, and are therefore discarded from the analysis. The characteristics of the different ARPEGE simulations presented in this paper are summarized in the table**??**.

## 3 Results

### 3.1 Simulated Present Climate

### 3.2 ~~Evaluation for Present Climate~~

The ability of ARPEGE model to reproduce atmospheric general circulation of the Southern Hemisphere is assessed by comparing sea level pressure (SLP) and 500 hPa geopotential height (Z500) ~~South of~~ below 20°S to those of ERA-Interim reanalysis (ERA-I). For surface climate of the Antarctic continent, several studies have shown that (near)~~surface~~ -surface temperatures from ERA-I are not reliable (**???**), as the reanalysis is not constrained by enough observations and because the boundary layer physics of the model fails to successfully reproduce strong temperature inversions near the surface that characterize the climate of the ~~Antarctic Plateau~~EAP. As a consequence, near-surface temperatures in Antarctica from ARPEGE simulations are evaluated using observations from the SCAR READER data base (**?**) as well as temperatures from a MAR RCM simulation in order to increase the spatial coverage of the model evaluation. Modèle Atmosphérique Régional (MAR, **?**) has been one of the most successful RCMs in reproducing the surface climate of large ice-sheets such as Greenland (**??**) and Antarctica (**???**). For Antarctica, outputs of the MAR simulation (version 3.6 of the model) driven by ERA-I haven been rigorously evaluated against *in-situ* observations for surface pressure, 2 m temperatures, 10 m wind speed and surface mass balance in (**??**). Skills of MAR model for temperatures and SMB are generally excellent for most of Antarctica. Although, a systematic 3-5 K cold bias over large ice shelves (Ross and Ronne-Filchner) throughout the year and a 2.5 K warm bias over the Antarctic Plateau in winter are worth mentioning.

In this evaluation, we compare ARPEGE ~~near surface~~ near-surface temperatures to those of an ERA-I driven MAR simulation (hereafter MAR-ERA-I) at a similar horizontal resolution of 35 kilometres (**?**). The SMB of the grounded ~~Antarctic Ice Sheet~~ AIS and its components from ARPEGE simulations are compared to outputs of the same ERA-Interim driven MAR simulation from **?**. Statistical significance of the errors is assessed using a double-sided t-test and pvalue of 0.05.

#### 3.1.1 Atmospheric General Circulation

~~Difference~~ The differences between mean SLP from the ARPEGE simulation (1981-2010) ~~forced~~ driven by observed SSC (called ARP-AMIP in the remainder of this paper, see ~~table~~ Table **??**) and mean SLP from ERA-I reanalysis can be seen in Fig. **??**. The general pattern is an underestimation of SLP around 40°S, especially in the Pacific sector and an overestimation around Antarctica, especially in Amundsen/Ross sea sector. Mean SLP differences for ARPEGE simulations ~~forced~~ driven by NorESM1-M (ARP-NOR-20) and MIROC-ESM (ARP-MIR-20) historical SSC can be seen respectively in Fig. **??** and Fig. **??**. The pattern and the magnitude of the errors are similar to those of the ARP-AMIP simulation in summer (DJF). The root mean square errors (RMSE) per seasons for each simulations are summarized in Table **??**. In winter (JJA), spring (SON) and autumn (MAM) the errors are substantially larger in ARP-NOR-20 and ARP-MIR-20 than in ARP-AMIP. The patterns of the errors and the ranking of ~~simulations~~ simulation scores are similar for the 500hPa geopotential height~~than for SLP~~ (*not shown*) and SLP.

**Table 2.** Seasonal root mean square error (RMSE, in hPa) on mean SLP South of 20°S with respect to ERA-Interim for the different ARPEGE simulations over the 1981-2010 period. Each error is significant at p=0.05

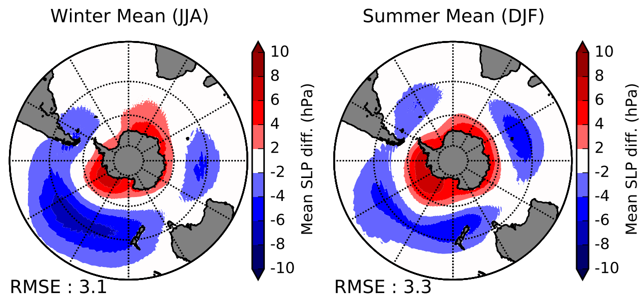
| Simulations | DJF | MAM | JJA | SON |
|---|---|---|---|---|
| ARP-AMIP | 3.3 | 2.7 | 3.1 | 3.0 |
| ARP-NOR-20 | 3.5 | 4.3 | 4.8 | 4.6 |
| ARP-MIR-20 | 3.2 | 4.0 | 4.6 | 3.2 |

The mean atmospheric general circulation in each simulation has also been compared and evaluated against ERA-I by analyzing the 850 hPa eastwards wind component (referred to as westerly winds in the following) latitudinal profile, as well as the strength (m/s) and position (°Southern latitude) of the zonal mean westerly wind maximum ~~or westerly "jet"~~ (Fig. **??**). In this figure, results are only presented for the annual average, as the differences between simulations or with respect to ERA-I do not depend much on the season considered (*not shown*). ~~When compared with ERA-I,~~ ARP-AMIP and ARP-MIR-20 are closer to ERA-I when the westerly winds maximum strength is considered~~, and~~. The position of the westerly wind maximum is closest to ERA-I in ARP-NOR-20~~when it is its position~~. With respect to ARP-AMIP, ARP-NOR-20 displays a much weaker and ~~poleward surface westerly jet in all seasons~~polewards shifted surface westerly wind maximum, while ARP-MIR-20 is characterized by a lower latitude westerly wind maximum of comparable strength.

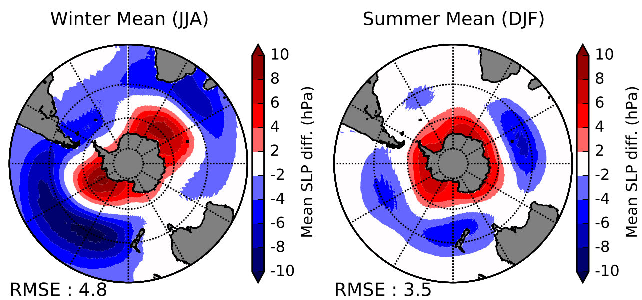
### 3.1.2 ~~Near Surface~~ Near-surface Temperatures

Screen level (~~2m~~2 m) air temperatures ($T_{2m}$) from ARP-AMIP simulation are compared to those ~~of the ERA-Interim driven MAR simulation~~ from MAR-ERA-I simulation and READER data base in winter (JJA) and summer (DJF) for the reference period 1981-2010 ~~. Differences are shown in~~ (Fig. **??**~~. On the same figure, circles represent $T_{2m}$ differences between ARP-AMIP and weather~~ ). In this analysis, stations from the READER data base ~~. In this analysis, weather stations where~~ for which less than 80% of valid observations were recorded for the reference period were not used for the computation of the climatological mean. Altitude differences between corresponding ARPEGE grid point and ~~weather~~ stations have been ~~taken into account~~ accounted for by correcting modelled temperatures with a ~~9.5~~ 9.8 K km$^{-1}$ ~~vertical gradient~~dry adiabatic lapse rate, such as done for instance in **?**. Errors on $T_{2m}$ in ARP-AMIP simulation for each weather station and each season are presented in ~~Tab. **??**. A~~ the supplementary material (Table **??**) as well as a map showing the location of these stations ~~can be seen in the supplementary material~~ (Fig. **??**).

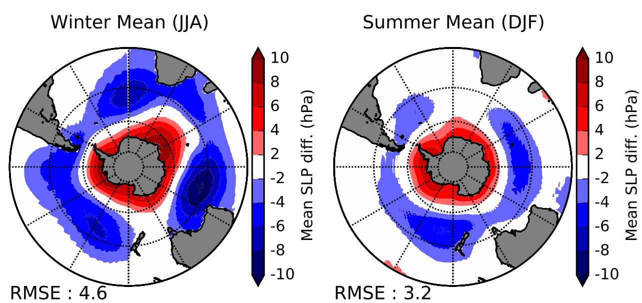
The ARP-AMIP $T_{2m}$ are much warmer than MAR-ERA-I on the ridge and the western part of the Antarctic Plateau in winter as ~~wall~~ well as on on the large Ronne and Ross ~~ice-shelves.~~ ice shelves. Consistently with its atmospheric circulation errors in this area, ARPEGE is colder than MAR-ERA-I on the Southern and Western part of the Antarctic Peninsula, especially in winter~~, which is consistent with atmospheric circulation errors. Finally, we~~. We can also mention a moderate (1 to ~~3K~~3 K) but widespread warm bias on the slope of the ~~East Antarctic Plateau~~ EAP and on the ~~West~~ west side of the West Antarctic Ice Sheet (WAIS) in summer. Except for some coastal stations of East Antarctica, $T_{2m}$ ~~error~~ errors in the ARP-AMIP simulation




(a) ARP-AMIP




(b) ARP-NOR-20




(c) ARP-MIR-20

**Figure 2.** Difference between ARPEGE simulations and ERA-I mean SLP for the reference period 1981-2010 in winter (JJA) and summer (DJF). Value of the RMSE are given below the plots.

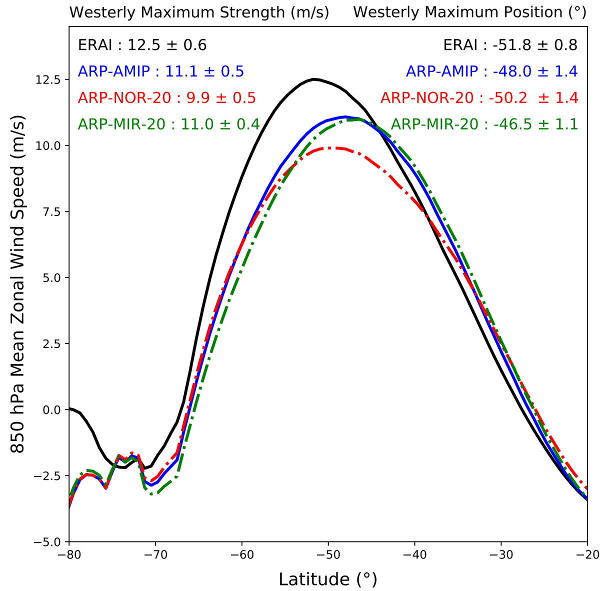



**Figure 3.** Mean latitudinal profile of 850 hPa ~~Eastwards~~ eastwards wind component (reference period : 1981-2010) for ARP-AMIP (grey), ARP-MIR-20 (dashed green), ARP-NOR-20 (dashed red) and ERA-Interim (black). ~~Upper left : yearly~~ Yearly mean ± one standard deviation of strength (m/s~~)~~, ~~Upper right :~~ upper left) and latitude position (°~~)~~, upper right) of the ~~westerlies~~ 850 hPa westerly wind maximum~~or "jet"~~.

are very similar in the comparisons with MAR-ERA-I and READER data base.

Considering errors on ~~surface~~ near-surface temperatures of the Antarctic Plateau as large as 3 to ~~6K~~ 6 K for ERA-I reanalysis in all seasons (**?**), ~~the magnitude of the errors~~ skills of the ARP-AMIP simulation in this region ~~in ARP-AMIP simulation is encouraging. The~~ is comparable to those of many AGCM or even climate reanalyses. The systematic error for Amundsen Scott station is ~~even insignificant at~~ for instance not significant at the p=0.05 level in all seasons but autumn (MAM). The ~~warm bias on the large ice-shelves is due to the fact that ice-shelves are not considered as land in the ARPEGE version used. In order to correct this weakness, we prescribed an SIC of 100% and a thickness of 40 m in grid points corresponding to ice-shelves. Even if this reduced the initial bias by about 5K, it did not prevent the warm bias from still being as high as 12K in~~ large discrepancies between ARPEGE and MAR over large ice shelves are further investigated in section **??**. Although a part (3-5K) of this large discrepancy in winter (ARPEGE up to 12 K warmer than MAR over the center of ~~the Ross Ice-Shelf in Winter. Part of the errors on this ice-shelf are also likely due atmospheric general circulation errors, but this issue will require further investigation. As a consequence of these large biases in temperatures and~~ Ross Ice Shelf) comes from a cold bias in MAR identified in the comparison with the in-situ observations (**?**), the majority of ARPEGE errors on large ice shelves appears to come from specificities in the representation of stable boundary layers over these large and flat surfaces. As a consequence, the surface climate over ~~large ice-shelves, surface mass balance and temperatures changes at the continent scale are only~~ the

**Table 3.** ~~Error on READER weather station~~ Mean seasonal $T_{2m}$ differences (in K) for the GIS with respect to the ARP-AMIP simulation~~for the reference period 1981-2010~~. ~~Errors~~ Differences significant at p=0.05 are presented in ~~**bold**~~**bold**.

~~Stations DJF MAM JJA SON *EAP* Amundsen Scott 0.5 **2.4** 1.1 0.9 Vostok **-1.5 3.2 3.2 1.9** *Mean error* -0.5 2.8 2.1 1.4 *RMSE* 1.1 2.8 2.4 1.5 *Coastal EA* Casey **-3.9 -5.7 -6.9 -5.4** Davis **-1.6 -4.2 -5.9 -3.3** Dumont Durville -0.5 **-2.8 -4.1 -2.2** Mawson **-2.2 -4.3 -5.7 4.3** McMurdo **-7.1 -6.5 -8.1 -8.4** Mirny **-1.2 -2.2 -3.0 -2.0** Novolazarevskaya **2.5** 0.6 -1.0 0.6 Scott Base **-5.0 -3.2 -4.5 -5.0** Syowa -0.2 -0.6 **-1.5** 0.0 *Mean error* -2.1 -3.3 -4.5 -3.3 *RMSE* 3.4 3.8 5.0 4.2 *Ice shelves* Halley **1.2 2.4** 1.2 0.8 Neumayer **2.1 1.2** 0.9 **1.4** *Mean error* 1.7 1.8 1.0 1.1 *RMSE* 1.7 1.9 1.0 1.1 *Peninsula* Bellingshausen **-1.0** -0.4 -0.2 -0.0 Esperanza **-1.1** 0.5 -1.3 -0.8 Faraday **-2.6 -4.6 -5.7 -3.6** Marambio **-1.8** 1.0 -1.3 -1.6 Marsh **-0.8** -0.3 -0.3 -0.0 Orcadas **-1.1** -0.0 0.6 -0.7 Rothera **-5.5 -7.9 -8.7 -6.1** *Mean error* -2.0 -1.7 -2.4 -1.9 *RMSE* 2.5 3.5 4.0 2.8 *Southern Ocean* Gough **-1.O** -0.34 0.02 **-0.79** Macquarie **-0.7** -0.4 0.2 **-0.4** Marion **-1.2 -0.4** -0.0 **-0.7** *Mean error* -0.9 -0.4 0.1 -0.6 *RMSE* 0.9 0.4 0.1 0.7~~

~~Mean seasonal $T_{2m}$ differences for the GIS with respect to the ARP-AMIP simulation. Differences significant at p=0.05 are presented in bold.~~

| Simulations | DJF | MAM | JJA | SON |
|---|---|---|---|---|
| ARP-NOR-20 | ~~-0.09~~ -0.1 | ~~**0.41**~~**0.4** | ~~**1.16**~~**1.2** | ~~**0.95**~~**0.9** |
| ARP-MIR-20 | ~~**-1.48**~~**-1.5** | ~~-0.22~~ -0.2 | ~~0.25~~ 0.3 | ~~**-0.65**~~**-0.7** |

large ice shelves simulated by ARPEGE should at this stage be used with circumspection. Considering the model lower skills on the floating ice shelves, integrated SMB and temperature changes are preferably presented and discussed for the grounded ice sheet (GIS) in the remainder of the paper.

~~The large negative bias that~~ Large negative biases in ARP-AMIP ~~shows~~ for some coastal stations of East Antarctica (Casey, Davis, Mawson, Mc Murdo), especially in winter, are likely partly due to ~~site-effects. First~~site effects. Indeed, ARPEGE temperatures are representative for a 40x40 km$^2$ inland grid point, whereas many weather stations are located very close to the shoreline. ~~Second, ARPEGE underestimates 10m wind-speed in these stations in winter. An underestimate of the strength and frequency of katabatic winds reduces the adiabatic heating of the air masses flowing down from the Plateau to the coasts and favors the stratification of the air masses in these areas. Finally, a~~ The large cold bias at Rothera station on the ~~Antarctic~~ Peninsula is likely a combination of site ~~effect and errors on~~ effects and errors of the simulated atmospheric general circulation.

Regarding $T_{2m}$ in ARPEGE simulations forced by NorESM1-M and MIROC-ESM historical SSC, the skills of the ARPEGE model are particularly ~~decreased~~ impacted over the AP and over the EAP to a lesser extent (see Fig. **??**). Over coastal East Antarctic stations, most of the errors in $T_{2m}$ are likely due to site-scale effects, topography differences or inadequacies of the physics of the atmospheric model~~and~~ , as the skills of the atmospheric model shows few variations in the three simulations. The use of SSC from NorESM1-M and MIROC-ESM instead of observed SSC also leads to modified temperatures at the continental scale. Differences for ARP-NOR-20 and ARP-MIR-20 in $T_{2m}$ for the Antarctic GIS with respect to the ARP-AMIP simulation are presented in Tab. **??**. For the ARP-MIR-20, differences of -0.7 K in spring and -1.5 K in ~~Summer~~ summer were found significant~~at p=0.05 level. For the~~ . For ARP-NOR-20, differences ranging from ~~0,4K to 1,2K~~ 0.4 K to 1.2 K in autumn, winter and spring are significant as well.

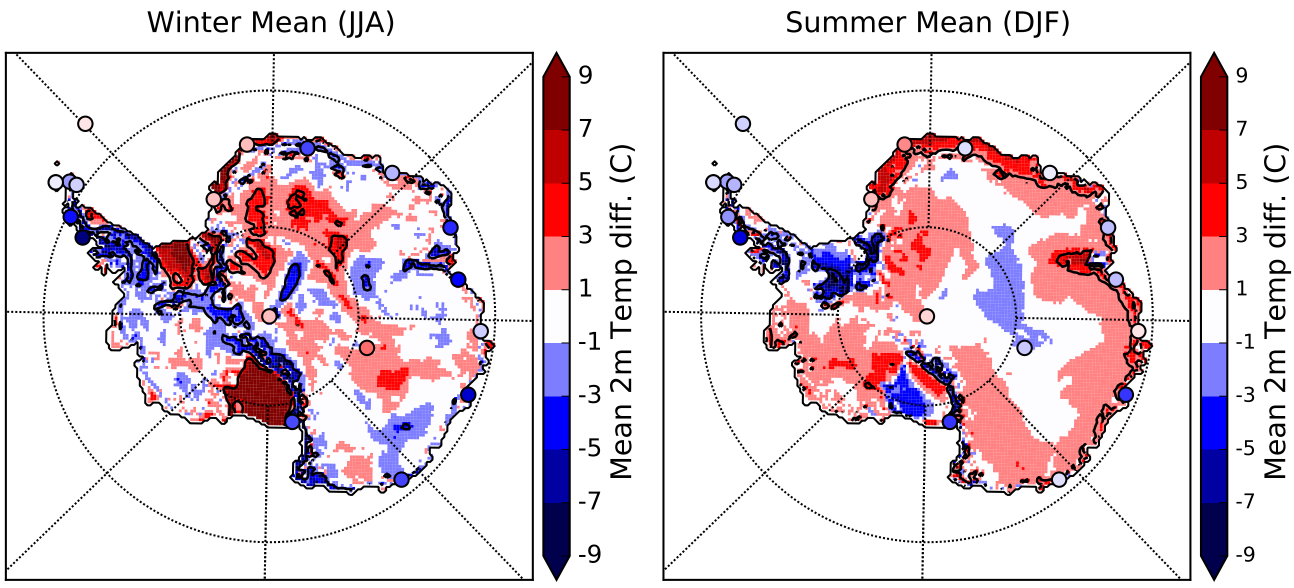



**Figure 4.** $T_{2m}$ differences between ARP-AMIP and MAR-ERA-I (??) simulations in winter (JJA, *left*) and summer (DJF, *right*) for the reference period 1981-2010. Circles are $T_{2m}$ differences between ARP-AMIP and weather stations from the READER data base. Black contour lines represent areas where ~~$|ARPEGE - MAR| > 1.MAR\sigma$~~ $|\,\mathrm{ARPEGE} - \mathrm{MAR}\,| = 1\mathrm{MAR}\sigma$.

### 3.1.3 Surface Mass Balance

In this study, SMB from ARPEGE simulations is defined as the total precipitation minus the surface snow sublimation/evaporation minus run-off. Differences between ARP-AMIP and MAR-ERA-I total precipitation, snow sublimation and SMB (in mm of water equivalent per year) for the reference period 1981-2010 can be seen in Fig. **??**. As differences in run-off are restricted to the ~~ice-shelfs~~ ice shelves and some very localized coastal areas, their spatial distribution is not displayed in this figure. Yearly mean SMB, total precipitation, surface sublimation, run-off, rainfall and melt, integrated over the whole Antarctic GIS for the different ARPEGE simulations, for MAR-ERA-I and from other studies are presented in Table **??**.

At the continental scale, we can see that estimates of the SMB of the ice-sheet from the ARP-AMIP simulation resemble those from state of the art polar-oriented RCM MAR and RACMO2. However, higher total precipitation values in ARPEGE-AMIP are compensated for by much higher values of sublimation/evaporation of surface snow and, to a lesser extent, higher run-off. Total precipitation in ARP-AMIP simulation is 274 Gt yr$^{-1}$ higher than in the MAR-ERA-I simulation, corresponding to about 2.8 interannual standard ~~deviations~~ deviation ($\sigma$). Precipitation is generally higher in ARPEGE over most of the coastal areas. The largest precipitation overestimates with respect to MAR are found in the Ross sector of ~~Marie-Byrd~~ Marie Byrd Land, in Dronning Maud and ~~Coats Land and in the Northern and Eastern~~ in the northern and eastern part of the ~~Antarctic~~

~~Peninsula~~AP. On the other hand, precipitation is lower in ARP-AMIP in the ~~Southern and Western~~ southern and western part of the Peninsula, in the inland part of central WAIS and in the interior and lee-side of the Transantarctic Mountains. Sublimation ~~/evaporation of snow~~ integrated over the ~~whole ice-sheet~~ grounded ice sheet is about four times higher in ARP-AMIP than in MAR-ERA-I. Differences mostly come from coastal areas and the ~~lower slopes of the ice-sheet~~peripheral ice sheet. This is consistent with ARP-AMIP being systematically 1 to ~~3K~~ 3 K warmer than MAR-ERA-I in summer in those areas. Run-off at the continent scale is eight times higher in ARP-AMIP than in MAR-ERA-I, which is also ~~most~~ likely a consequence of warmer coastal areas in ARPEGE in summer. ~~However,~~ The inter-annual variability is very high in the simulated ARPEGE ~~run-off~~runoff, and so it is in MAR-ERA-I~~($\sigma$ is at least 50% of the mean)~~. If we ~~have~~ take a closer look at the values of rainfall, surface ~~sow~~ snow melt and run-offs in the three present-day ARPEGE simulations in Table **??**, the ratio between inputs of liquid water into the snow pack (rainfall + surface snow melt) and the water run-off that finally leaves the snow-pack is about 1/~~4.~~ 3. In MAR-ERA-I and in RACMO2-ERA-I, this ratio is about 1/~~20.~~ 50. This means that although the snow surface scheme SURFEX-ISBA used in ARPEGE is by its construction able to model storage and refreezing of liquid water in the snow-pack, the retention capacity of the Antarctic ~~snow pack underestimated with respect to~~ snow-pack appears to be largely underestimated following the comparisons with MAR and RACMO2. For these reasons, projected changes in melt rates are preferably presented and discussed in section **??**, while changes in run-off are *not shown* due to ARPEGE lower skills for this variable and strong non-linearities generally expected in changes in surface run-offs in a warming climate.

In ARP-MIR-20 simulation, snow sublimation and evaporation, run-off and melt were found significantly lower than in ARP-AMIP, which is consistent with this simulation being 1.5 K cooler in summer (DJF). The effect of driving ARPEGE by biased SSC for the modelling of Antarctic precipitation is discussed in the supplementary material (see Sec. **??**).

### 3.2 Climate change signal

In this section, we present the climate change signal obtained ~~for the~~ in ARPEGE RCP8.5 ~~scenarios coming~~ projections driven by SSC from NorESM1-M and MIROC-ESM SSC. For ARPEGE ~~scenarios~~ projections realized using original SSC from the two coupled models (ARP-NOR-21 and ARP-MIR-21), the reference simulations for the historical period are the ARPEGE simulations performed with historical SSC coming from the respective coupled model (ARP-NOR-20 and ARP-MIR-20). For scenarios realized with ~~bias correction of the~~ bias-corrected SSC (ARP-NOR-21-OC and ARP-MIR-21-OC), the reference simulation for the historical period is ARP-AMIP (observed SSC). The primary goal here is to evaluate the ~~uncertainty~~ effect in climate change signals for Antarctica associated with ~~oceanic forcing~~ diverging oceanic forcings coming from coupled models and the changes coming from the bias correction of the SSC.

#### 3.2.1 Atmospheric General Circulation

Climate change signals in mean SLP for the different RCP8.5 ~~scenarios~~ projections realized with ARPEGE can be seen in Fig. **??**. ~~All scenarios show~~ Each one shows a pressure increase at mid-latitudes (30-50 °S) and a decrease around Antarctica. This corresponds to a shift and a strengthening of the circum-antarctic low pressure belt towards the continent (positive phase of the SAM)~~and is a generally~~ , which is generally the expected consequence of 21$^{st}$ century climate forcing (**??**). This pattern

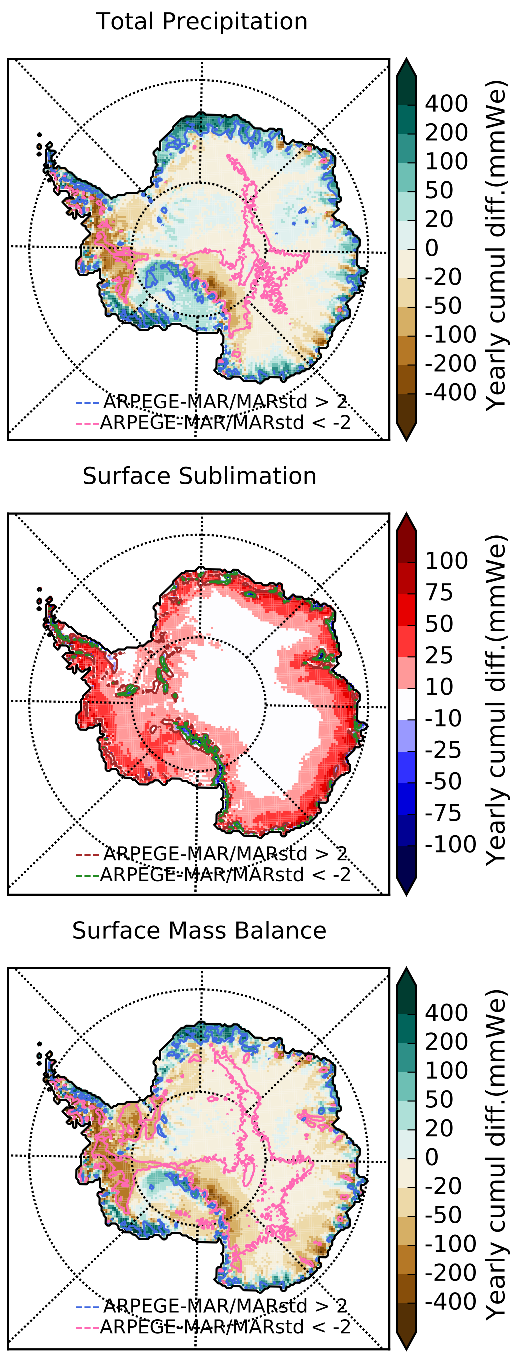



**Figure 5.** Total ~~Precipitations~~ precipitation (*top*), Sublimation/Evaporation (*centre*) and ~~Surface Mass Balance~~ SMB (*bottom*) for ARP-AMIP minus MAR-ERA-I ~~yearly cumul~~ difference (~~mmWe~~mm.we yr$^{-1}$) for the reference period 1981-2010. Pink (brown) and blue (green) contour lines represents areas where ARPEGE-MAR differences are respectively smaller than -2 or bigger than 2 MAR standard deviation of annual values ($2\sigma$).

| Simulation | SMB | Tot. PCP | Surf Subl. | Run-Off | Rainfall |
|---|---|---|---|---|---|
| ARP-AMIP | 2192±107 | 2529±105 | 316±19 | 21±13 | 11±2 |
| ARP-NOR-20 | **2436±112** | **2771±111** | 314±14 | 20±11 | 11±2 |
| ARP-MIR-20 | 2228±94 | 2532±103 | **294±21** | **10±6** | 10±~~2~~ 3 |
| MAR-ERA-I[1] | 2125±104 | ~~2204~~2205±~~100~~ 101 | 79±9 | ~~0.5~~1±~~0.5~~ 1 | 12±2 |
| RACMO2-ERA-I[1] | 2085±91 | 2213±97 | 128±~~3~~ 4 | 1±1 | 2±1 |
| RACMO2-ERA-I[2](entire ice sheet) | 2596±121 | 2835±122 | 228±11 | 5±2 | 6±2 |
| CESM-hist[3] | 2280±131 | 2433±135 | 68±6 | 86±21 | 5±2 |
| (?) | 1811 | | | | |

**Table 4.** Mean Grounded Antarctic Ice-Sheet ~~Surface Mass Balance~~ SMB (area = 13.4 $10^6$ $km^2$) and its component (Gt $yr^{-1}$) ± one standard deviation of the annual value for the reference period 1981-2010. Variables from ARP-NOR-20 and ARP-MIR-20 that are significantly different from the value in ARP-AMIP at p=0.05 level are in ~~bold~~**bold**. [1]MAR and RACMO2 forced by ERA-I statistics for 1981-2010 for Antarctic GIS (area = 12.3 $10^6$ $km^2$) using the same ice-masks such as in **?**, sublimation values for RACMO2 include drifting snow sublimation.[2]RACMO2 statistics are given for the total Ice-Sheet and the period 1979-2005 from **?**, sublimation includes drifting snow sublimation. [3]Community Earth System Model historical simulation (1979-2005), values for the total ice-sheet from **?**

(increase at mid-latitude, decrease around Antarctica) is sharper in ~~scenarios~~ projections realized with MIROC-ESM SSC. Differences in the climate change signal for ARP-NOR-21-OC and in ARP-NOR-21 with respect to their corresponding references in historical climate are ~~small. The ASL deepens more in the scenario realized with non bias-corrected SSC (ARP-NOR-21) in winter while it is the opposite in summer.~~ smaller. Differences in SLP climate change signal are ~~more obvious in the scenarios~~ larger in the projections realized with MIROC-ESM SSC ~~. In the scenario realized~~ ; in those with non bias-corrected SSC (ARP-MIR-21), the intensification of the low pressure systems around Antarctica in winter is clearly organized in a 3-wave pattern (Fig. ~~??~~**??**b). In ARP-MIR-21-OC, the JJA pressure decrease is rather organized in a dipole with one maximum of pressure decrease centered the ~~Eastern~~ eastern side of the Ross Sea and another one ~~West~~ west of the Weddell Sea. As a result, the 3-wave pattern is clearly noticeable in the difference between the two ~~scenarios~~ climate change signals (Fig. ~~??~~**??**b, *right*). ~~In summer, the differences between the two simulations are weaker and mainly consist of a sharper pressure increase at mid latitudes in ARP-MIR-21-OC.~~ Late 21$^{st}$ century changes in westerly wind maximum latitude position and strength at 850 hPa are shown in Table **??**. When compared to variability in the reference historical simulations, each climate change signal is significant at p=0.05. Regarding the changes in westerly ~~wind maximum strength(Table ??), the differences~~ winds maximum strength, the difference between the two ~~scenarios~~ projection using NorESM1-M SSC are ~~once again~~ limited. We can however mention a -1.4° higher decrease (poleward movement) in westerly winds maximum position in the ~~scenario~~ projection using bias-corrected SSC (significant at p=0.05). Differences in changes in position and strength are

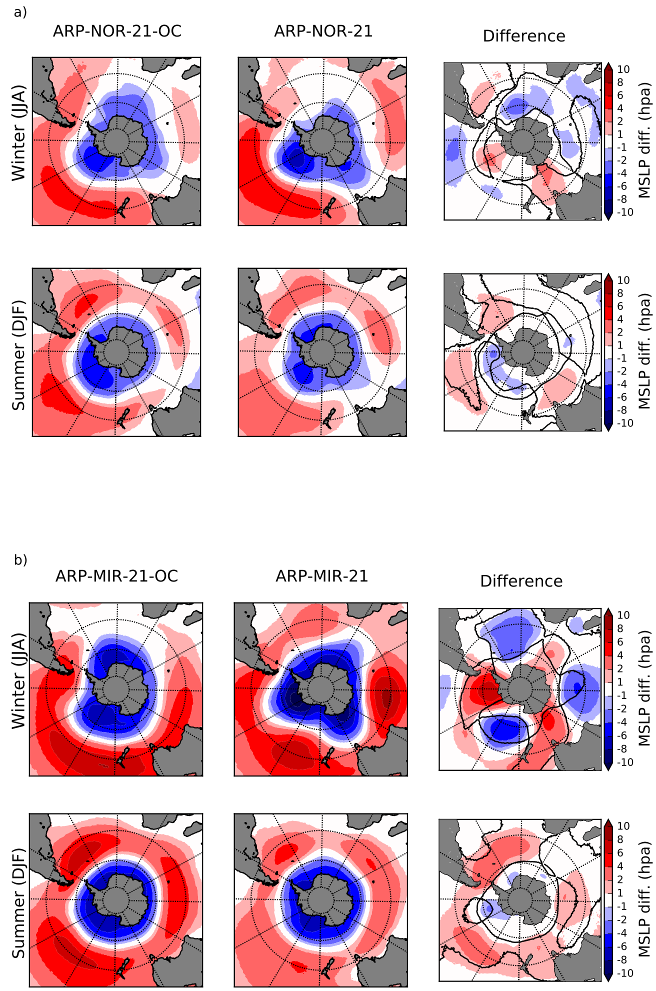



**Figure 6.** Climate change signal in SLP for ARPEGE RCP8.5 ~~scenarios~~ projections with bias corrected SSC (*left*), original SSC (*center*) and difference (*right*). Climate change signal for winter (JJA) are displayed at the *top* of the subfigures and for summer (DJF) at the *bottom*. Results for scenarios with SSC from NorESM1-M are presented in ~~subfigure~~ upper (a) and from MIROC-ESM in ~~subfigure~~ lower (b) part of the figure. *Black contour lines* represent areas where differences in climate signal is 50% of the climate signal in the simulation with non bias-corrected SSC.

not ~~substantial~~ significant between ARP-MIR-21 and ~~APR-MIR-21-OC~~ARP-MIR-21-OC. Compared to ~~scenarios~~ projections realized with SSC from NorESM1-M, these ~~scenarios~~ projections show a slightly larger increase in ~~jet~~ westerlies maximum strength and a much larger poleward shift, although this difference is reduced when comparing ~~scenarios with bias corrected~~ projections with bias-corrected SSC.

**Table 5.** Changes in mean yearly Southern westerly wind maximum ~~or "jet"~~ strength ($\Delta$~~WMSTR~~JSTR, m/s) and position ($\Delta$~~WMPOS~~JPOS, °) for the different ARPEGE ~~scenarios~~projections. Changes significantly different using bias-corrected SSC are shown in **bold**.

| Simulations | $\Delta$~~WMSTR~~ JSTR (m/s) | $\Delta$~~WMPOS~~ JPOS (°) |
|---|---|---|
| ARP-NOR-21 | 1.7 | -0.8 |
| ARP-NOR-21-OC | 1.5 | ~~-2.2~~ **-2.2** |
| ARP-MIR-21 | 1.9 | -3.7 |
| ARP-MIR-21-OC | 2.0 | -3.8 |

**Table 6.** Mean season $T_{2m}$ increase (K) for the Antarctic GIS for the different ARPEGE RCP8.5 scenario at the end of $21^{st}$ (reference period: 2071-2100) with respect to their historical reference simulation (reference period: 2071-2100). Climate change signal in scenarios with bias-corrected SSC significantly different at p=0.05 level are presented in bold.

| Simulations | DJF | MAM | JJA | SON |
|---|---|---|---|---|
| ARP-NOR-21 | 3.5±1.4 | 2.7±1.4 | 2.6±2.0 | 2.7±1.4 |
| ARP-NOR-21-OC | 3.0±1.4 | 2.6±1.4 | 3.1±1.4 | 2.6±1.0 |
| ARP-MIR-21 | 3.9±0.9 | 4.1±1.3 | 3.8±1.4 | 3.5±1.2 |
| ARP-MIR-21-OC | 3.6±1.5 | 4.6±1.7 | **4.6±1.4** | 3.8±1.5 |

### 3.2.2 Near-surface ~~Temperatures~~temperatures

The mean yearly $T_{2m}$ increase for the Antarctic GIS using SSC from NorESM1-M ~~rep8~~RCP8.5 ~~scenario~~ projection is 2.9±1.0 K using original SSC (ARP-NOR-21) and 2.8±0.8 K using bias-corrected SSC (ARP-NOR-21-OC). For scenarios using SSC from MIROC-ESM, these temperatures increases are respectively 3.8±0.7 K and 4.2±1.0 K. The differences in yearly $T_{2m}$ increase using bias-corrected SSC are found non significant at p=0.05 level in both cases. $T_{2m}$ increase per season can be seen in Tab. **??**. Only a +0.8 K difference in winter ~~temperature~~ temperatures increase in ARP-MIR-21-OC with respect to the ~~scenario with~~ projection driven by original SSC is found significant. At the regional scale (Fig. ~~**??**~~**??**b), this is materialized by large areas of 1 to ~~2K~~ 2 K stronger warming in the centre of the East Antarctic Plateau, Dronning Maud Land, Byrd Land, and the Ross ~~ice shelf~~Ice Shelf. The difference in warming in ARP-MIR-21-OC is the highest in Marie-Byrd Land (+~~2K~~2 K). For ~~scenarios~~ projections using SSC from NorESM1-M, no seasonal ~~difference was~~ differences were found significant at the scale of the ice-sheet although a 0.5 K weaker temperature increase in summer for ARP-NOR-21 is close to the significance threshold. ~~However, if we look at regional warming (Fig. ??), we can see that for large areas covering the center of East Antarctic Plateau and coastal areas, the regional warming is 0.5 to 1K higher in winter and 0.5 to 1K lower in summer in the scenario with bias-corrected SSC.~~

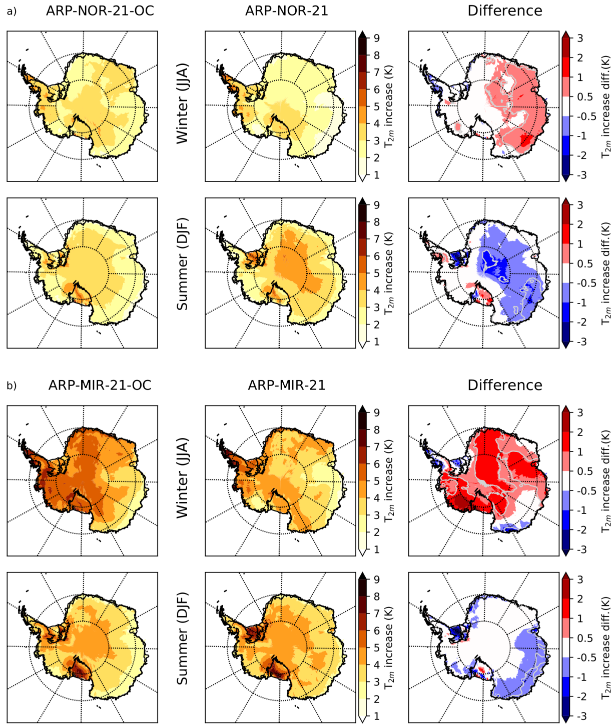



**Figure 7.** Climate change signal in $T_{2m}$ for ARPEGE RCP8.5 ~~scenarios at the end of~~ projections for the late 21~~$^{st}$~~ $^{st}$ century (~~reference period :~~ 2071-2100) with ~~bias corrected~~ bias-corrected SSC (*left*), original SSC (*center*) and difference (*right*). Climate change signal for austral winter (~~JJA~~summer) are displayed at the ~~*top*~~ ~~of the subfigures and for summer~~ *upper* (~~DJF~~*lower*) ~~at~~ part of the ~~*bottom*~~figure. Results for ~~scenarios~~ projections with SSC from NorESM1-M are presented in ~~subfigure~~ (a) and from MIROC-ESM in ~~subfigure~~ (b). *Grey contour lines* is where differences in climate change signal is 25% of the climate change signal using non ~~bias corrected~~ bias-corrected SSC

### 3.2.3 ~~Precipitations~~ Precipitation and Surface Mass Balance

~~Statistics of~~ Absolute values and changes in Antarctic GIS SMB and its component for the ~~reference period 2071-2100 at the scale of the Antarctic GIS are presented in Tab.~~late 21$^{st}$ are shown in Table **??**. For the experiment realized with NorESM1-M SSC, precipitation and SMB changes (in both cases increases) are very similar, while there is about 250 Gt.yr$^{-1}$ more precipitation and therefore accumulation in ARP-NOR-21 absolute values. For both total precipitation and SMB, absolute values were found significantly different at p=0.05 level in ARP-NOR-21-OC with respect to ARP-NOR-21, while climate changes signals were not. No significant ~~difference~~ differences in absolute values or climate change signals were found for the other components of SMB for scenarios with NorESM1-M SSC.

For ~~scenarios~~ experiment performed with MIROC-ESM SSC, absolute values and increase in precipitations are about 185 Gt.yr$^{-1}$ stronger in the ~~scenario~~ projection with bias-corrected SSC. ~~The difference in SMB between the two scenarios is slightly reduced by a larger run-off in ARP-MIR-21-OC simulation.~~ The total precipitation increase is as high as +8.8%

$K^{-1}$ in ARP-MIR-21-OC, compared to a 6.1% $K^{-1}$ increase in ARP-MIR-21. For SMB and ~~precipitations~~precipitation, both absolute values and climate changes signals were found significantly different in ARP-MIR-21-OC than in ARP-MIR-21. ~~As for the ARP-MIR-20 reference, absolute value in yearly run-off is found significantly different than in the corresponding non bias-corrected simulation.~~

In each ~~scenario~~projection, the sublimation increases by about 20 to 25% with respect to the corresponding references in the historical period. ~~Run-off and melt increase~~ Surface melt increases by about a factor 4 in scenarios with NorESM1-M SSC and by factors ranging from 6 to ~~10~~ 9 in scenarios with MIROC-ESM SSC. ~~This, however, does not prevent these components to remain one order of magnitude smaller than total precipitation. As a consequence, increases in SMB are~~ Increases in SMB remain essentially determined by the increases in ~~total precipitation. In future climate simulated by ARPEGE, the ratio between liquid water inputs (rainfall + melt) and liquid water leaving the snow-pack (run-off) remains around 1/3. As the change in SMB is mainly the result of change in total precipitation~~precipitation. As a consequence, we only present here the spatial distribution of changes in precipitation in Antarctica in Fig. **??**. In all ~~scenarios~~projections, the strongest absolute precipitation increases occur in the coastal regions of West Antarctica and in the ~~West~~ west of the Peninsula. In simulations with MIROC-ESM SSC, precipitation increase is also very strong in the Atlantic sector of coastal East Antarctica. The difference between total precipitation increases in ARP-NOR-21 and ARP-NOR-21-OC (Fig. ~~**??**~~**??**a) is small in most regions of Antarctica, except for a stronger increase (or lower decrease) in Marie-Byrd Land, and a lower increase in Adélie Land in ARP-NOR-21-OC. For the simulations with MIROC-ESM SSC (Fig. ~~**??**~~**??**b), we can clearly identify an alternation of three regions of higher or lower precipitation increases. This tri-pole pattern can easily be linked with the 3-wave pattern in SLP change in ARP-MIR-21, clearly different than the pattern in MSLP change in ARP-MIR-21-OC (Fig. ~~**??**~~**??**b). Here again, Marie Byrd Land and Adélie Land are among the areas where large differences are found between simulations with or without bias-corrected SSC. ~~Here, substantial differences are also found in Dronning Maud and Wilkes Land, as well as on the western flank of the East Antarctic Plateau, south of Dronning Maud Land.~~ Winter and spring (and to a lesser extent autumn) are the seasons mostly responsible for differences in precipitation changes between the simulations with MIROC-ESM original SSC. The relative mean precipitation changes (in %) and the associated standard deviation for the four RCP8.5 ~~scenarios~~ projections realized in this study can be seen in Fig. **??**.

## 4 Discussion

### 4.1 Reconstruction of the historical climate

The atmospheric model ARPEGE correctly captures the main features of the atmospheric circulation around Antarctica. The three local minima in SLP and ~~500hPa geopotential , generally present~~ 500 hPa geopotential heigh located around 60°W, 90°E and 180 °E ~~,~~ are well reproduced in the ~~ARPEGE-amip~~ ARP-AMIP simulation (see Fig. **??**). However, there is a positive SLP bias in the seas around Antarctica, particularly in the ASL sector, and a negative bias ~~in~~ at mid-latitudes (30-40 °S), especially in the Pacific sector. This bias structure in the Southern Hemisphere is present in many coupled and atmosphere-only GCMs. Its consequence is an ~~equator-ward bias in~~ equatorward bias of the position of the surface jet associated with westerly winds

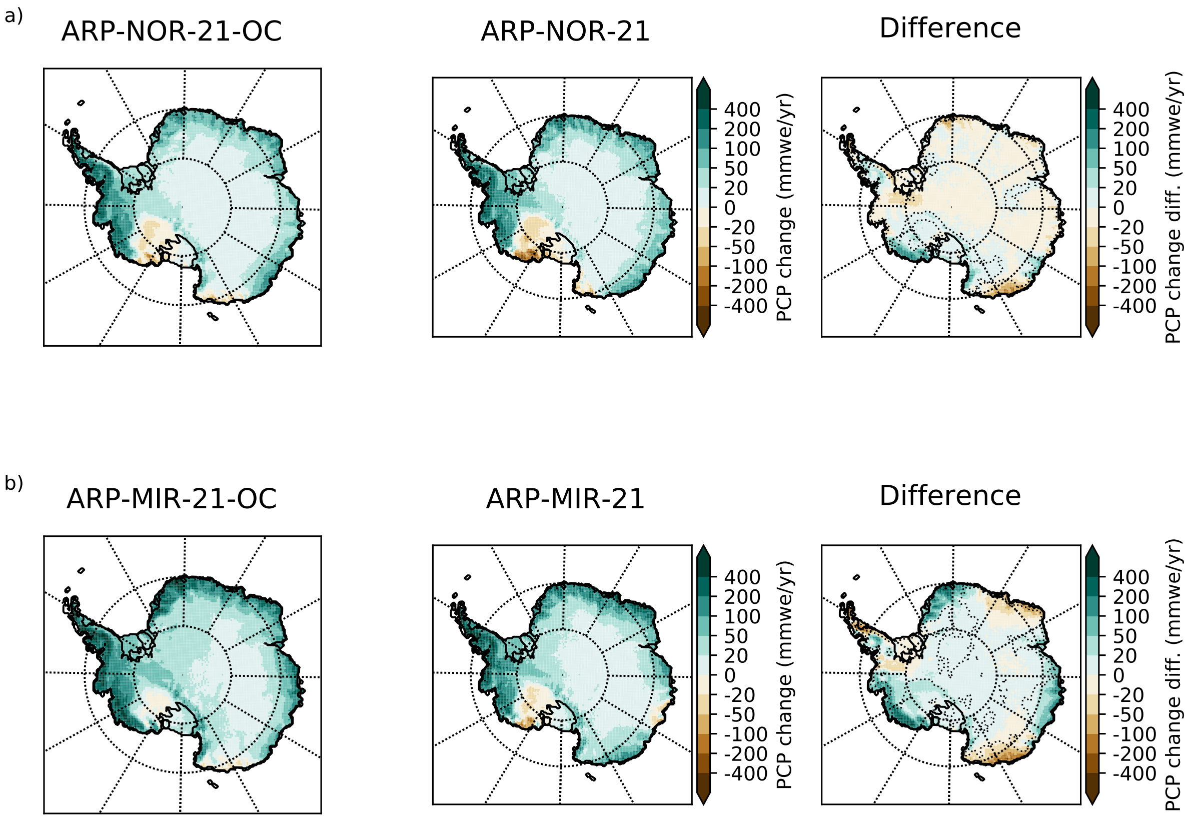



**Figure 8.** Climate change signal in ~~Total Precipitations at the end of the~~ total precipitation for late 21$^{st}$ century (reference period: 2071-2100) ~~for~~ in ARPEGE RCP8.5 ~~scenarios~~ projection with bias corrected SSC (*left*), original SSC (*center*) and difference (*right*). Results for scenarios with SSC from NorESM1-M are presented in subfigure (a) and from MIROC-ESM in subfigure (b). ~~Black contour line indicates~~ *Dotted lines* indicate where difference is 50% of the precipitation change in the non bias-corrected SSC ~~scenario~~projection.

**Table 7.** Absolute ~~value~~values, absolute (Gt yr$^{-1}$) and relative climate change signal (in %) for Mean SMB and components ~~(Gt yr$^{-1}$)~~ for the Antarctic GIS for the different ARPEGE RCP8.5 ~~scenario~~ projection (~~reference period:~~ 2071-2100). Climate change signals and absolute values significantly different at p=0.05 level in ~~scenarios~~ projections with bias-corrected SSC are displayed in bold.

| Simulations | SMB | Tot. PCP | Surf. Sublim. | ~~Run-Off~~ Rainfall | Melt |
|---|---|---|---|---|---|
| **ARP-NOR-21** | 2817±~~156~~ 158 | 3311±~~185~~ 186 | ~~386~~387±32 | ~~107±46~~ 29±7 | 260±136 |
| *CC change (Gt yr$^{-1}$)* | 381±211 | 540±220 | 72±29 | ~~86±38~~ 17±8 | 203±114 |
| *Rel. change* | 16% | 20% | 23% | ~~423%~~ 152% | 360% |
| **ARP-NOR-21-OC** | **2585±201** | **3060±196** | 377±24 | ~~99±41~~ 29±~~7~~ 8 | 241±~~120~~121 |
| *CC change (Gt yr$^{-1}$)* | ~~393~~393.1±~~209~~ 210 | 531±~~200~~ 201 | 60±28 | ~~78±35~~ 18±8 | ~~1856~~186±94 |
| *Rel. change* | 18% | 21% | 19% | ~~379%~~ 161% | 336% |
| **ARP-MIR-21** | 2784±109 | 3288±~~145~~ 146 | 378±27 | ~~126±51~~ ~~49~~50±13 | 321±156 |
| *CC change (Gt yr$^{-1}$)* | 556±143 | 756±152 | 84±20 | ~~116±46~~ 39±13 | 290±140 |
| *Rel. change* ~~25~~*(%)* | ~~30~~20% | ~~20~~23% | ~~117~~022% | 381% | 936% |
| **ARP-MIR-21-OC** | **2914±172** | **~~3469~~3467±~~224~~225** | 392±33 | **~~162±63~~ ~~54~~55±16** | 403±190 |
| *CC change (Gt yr$^{-1}$)* | **723±219** | **940±254** | 76±26 | ~~142±54~~ 43±15 | 347±161 |
| *Rel. change* | 33% | 37% | 24% | ~~688%~~ 386% | 627% |

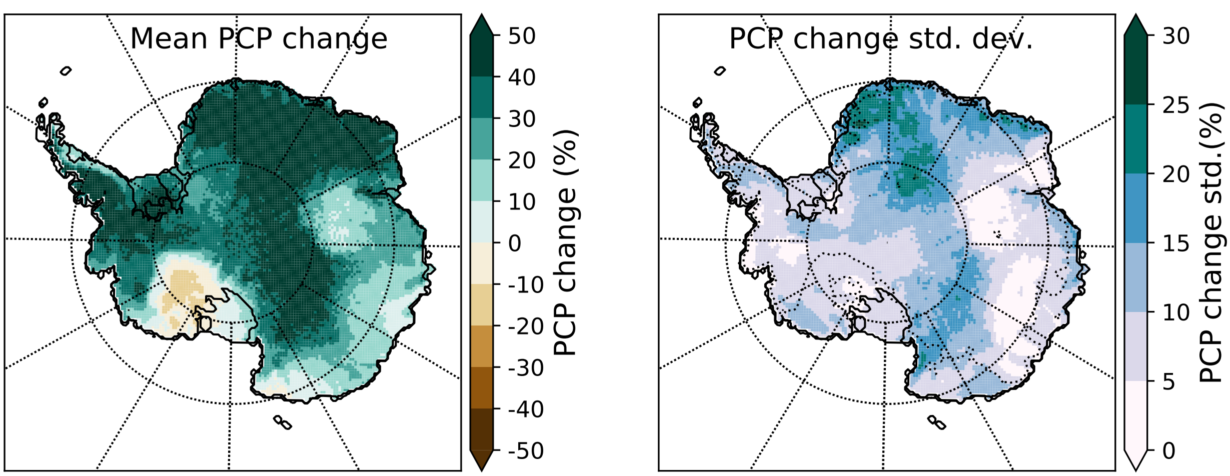



**Figure 9.** Mean (*left*) relative precipitation change (%) for late 21$^{st}$ century from the four ARPEGE RCP8.5 ~~scenario~~ projections and associated standard deviation (*right*). ~~*Black contour line* indicates~~ *Dotted lines* indicate where standard deviation is 50% of the mean change.

(**?**). The use of observed SSC (ARP-AMIP) rather than SSC from NorESM1-M and MIROC-ESM substantially improves the simulated mean SLP in the Southern Hemisphere in all seasons but summer. This unsurprisingly confirms results from previous studies which have shown that the use of observed rather than modeled SSC to drive atmosphere-only model clearly improves the skill of the atmospheric models (**???**). ~~In ARP-NOR-20, the use of modeled SSC yields a better comparison with ERA-I in terms of westerly winds maximum position while its strength is much largely underestimated. In ARP-MIR-20, the strength of the westerlies maximum is similar to ARP-AMIP, but the equatorward bias on the position is much larger.~~ The equatorward bias found in the ~~850hPa~~ 850 hPa westerly wind maximum position ($\sim$3°) in ARP-AMIP is very similar to the bias found by **?** for the surface westerly wind maximum in CMIP5 and AMIP ~~simulation~~ simulations from CNRM.

Regarding surface climate, ARPEGE also ~~correctly~~ reasonably reproduces Antarctic $T_{2m}$ except over ~~the large ice-shelfs~~large ice shelves. The $T_{2m}$ ~~error~~ errors with respect to ~~MAR is generally lower than 3K~~ MAR-ERA-I is generally below 3 K over most of the GIS. There is a substantial warm bias on the ~~ridge of~~ top the Antarctic Plateau in winter. However, ~~the magnitude of~~ these errors (+1.5 K at Amundsen-Scott, +3.4 K at Vostok) ~~is~~ are to be compared with ~~much larger biases~~ errors sometimes much larger in other GCMs or even in ~~reanalysis, as most~~ reanalyses. These errors are due to the fact that many climate models usually fail to capture the strength of the near-surface temperature inversion. The cold bias of ARPEGE on the Antarctic Peninsula, especially in the winter, can largely be explained by atmospheric circulation errors, as ~~an underestimate of the depth and/or recurrence of the ASL leads to an underestimate~~ these lead to an underestimation of mild and moist ~~flux from the North-West onto~~ fluxes from the north-west towards the Peninsula.

The ~~GIS SMB in~~ grounded AIS SMB in the ARP-AMIP simulation (2191±106 Gt yr−1) falls within the ± 1-standard deviation (1$\sigma$) uncertainty range with respect to estimates using the MAR RCM, and ~~concurs with~~ is similar to studies using other RCMs~~and GCMs~~, GCMs, or independent estimates. However, ~~it has to be mentioned that~~ the higher precipitation rates in the ARP-AMIP simulation ~~than in~~ compared to MAR and RACMO2 (about 2.5$\sigma$) are compensated for by ~~a~~ much stronger surface snow sublimation rates in the ARPEGE ~~simulations.~~ simulation.

Some of the differences ~~with MAR-ERA-I~~ in the spatial distribution of precipitation rates ~~in~~ between the ARP-AMIP simulation and MAR-ERA-I can also be linked to errors in atmospheric general circulations. These ~~errors are certainly part of the explanation for ARPEGE being wetter~~ are for instance ARPEGE higher precipitation rates in Marie-Byrd Land, ~~in the Eastern and Norther~~ the eastern and norther part of the Peninsula, and in Dronning Maud Land as well as ~~for ARPEGE being drier~~ with ARPEGE lower precipitation in central West Antarctica~~and in~~ , and the western part of the Peninsula.

When ~~forced~~ driven by SSC from NorESM1-M, ARPEGE ~~simulated~~ simulates significantly higher precipitation rates at the scale of the ~~ice-sheet~~ ice sheet (+243 Gt yr$^{-1}$, 2.3 $\sigma$). When ~~forced~~ driven by MIROC-ESM SSC, ~~run-off~~ runoff and snow sublimation were found significantly lower due to cooler temperatures in spring and summer.

### 4.2 Climate change signals

~~As described above,~~ NorESM1-M and MIROC-ESM ~~have been chosen~~ were chosen in this study because they display very different RCP8.5 ~~scenarios~~ projections in terms of ~~change~~ changes in sea-ice around Antarctica ~~by the end of the~~ (respectively -14% and -45% of winter SIE) for late 21$^{st}$ century. The increase in SST below 50 °S is much larger in MIROC-ESM (+ 1.8 K) than in NorESM1-M (+ 0.4 K). The separate effects of decreases in sea-ice cover and increases in SST on Antarctic SMB has been assessed in **?** using MAR RCM. Both result in an increase in Antarctic SMB (precipitation) that mostly takes places over coastal areas, as a result of increases in evaporation, air moisture content (capacity), and decrease of the cover effect of sea-ice. **?** found similar results using RACMO RCM. These authors have also investigated the separated effect of surface warming of the ocean and of homogeneous warming of the atmospheric column at the border of the domain of integration, the latter being more important as a result of increased moisture advection towards the ice-sheet over a thicker atmospheric column. These two studies carried out with RCMs driven by climate reanalyses do not account for the response of the atmospheric general circulation to changes in oceanic surface conditions and changes in radiative forcing as expected for the current century. This was done in **?** using LMDZ AGCM in a stretched-grid configuration who found that the effects of changes in oceanic surface conditions on Antarctic precipitation is much larger than the effect of changes in radiative forcings. It was also found in this study that the thermodynamic component (changes in precipitation for a given type of atmospheric circulation patterns) was larger that the dynamic one (changes in precipitation due to changes in frequencies of atmospheric circulation patterns) in the projected increase in Antarctic precipitations.

In the projections presented in this study, the Antarctic increase in annual mean $T_{2m}$ and the relative increase in precipitation for late $21^{st}$ century ~~. Indeed, these two models suggest a decrease of respectively -14%~~are within the range of the CMIP5 ensemble RCP8.5 (see **?**, e.g.,). Unsurprisingly, the warming obtained with projections using SSC from NorESM1-M (around +2.8K) belongs to the lower end of the values for RCP8.5 CMIP5 projections, a consequence of weaker changes in the Southern Ocean SSC in this projection. In projections using MIROC-ESM SSC, the increase in annual $T_{2m}$ is around +4 K. The relative increase in precipitation in ARP-MIR-21-OC (+37%) belongs to the upper limit of the CMIP5 ensemble. As suggested by **?**, the choice of the AOGCM providing SSC strongly influences the warming and precipitation increases obtained at the Antarctic-continent scale. Using NorESM1-M and original SSC from MIROC-ESM, the SMB (precipitation) increase obtained with ARPEGE ranges from 5.2 to 6.3 %.K$^{-1}$ (6 and ~~-45%of winter SIE around Antarctica between 1091-2010 and 2071-2100~~7.4 %.K$^{-1}$). This is within the range of values obtained in previous studies (**??????**). Using bias-corrected SSC from MIROC-ESM, the sensitivity of the precipitation to temperature increase (8.8%.K$^{-1}$) is slightly above the higher end values of previous studies. Yet, this value is consistent with upper values of the CMIP5 ensemble (see **?**, Fig. 3) which mostly come from AOGCMs with large SIE in their historical simulations, and consequently larger decrease in sea-ice in their future climate projections (**??**). This suggests that there is some non-linearities in the sensitivity of Antarctic precipitation change to regional warming, as it is also sensitive to the rate of sea-ice loss and the consequent reduced cover effect of sea-ice. Consistent with findings from **?**, we found that for regional warming within the + 3 to 4 K range, the increase in SMB is still largely dominated by precipitation increases, which remain much larger than the increase in surface melt and rain.

For the RCP8.5 simulation using SSC from NorESM1-M, the use of bias-corrected SSC has not yielded significantly different climate change signals with respect to the simulation using uncorrected SSC. The changes in SLP and ~~850hPa~~ 850 hPa westerlies maximum strength are very similar in both cases and so ~~is the increase~~ are the increases in mean annual temperature ~~(around 2.8±1K). The $T_{2m}$ changes are not significantly different in any season, and neither are changes of SMB and its individual components~~and total precipitation. For future ~~scenarios~~ projections with SSC from MIROC-ESM, ~~the use of~~

using bias-corrected SSC ~~induced a~~ led to significantly different climate change signals for ~~most~~ many variables, especially in winter. In the ~~scenario~~ projection with original MIROC-ESM SSC, the deepening of the low pressure zone around Antarctica is mainly organized in a three-wave pattern in JJA~~. In the scenario with bias-corrected SCC, this SLP decrease is rather~~ , while it is organized following a dipole in the projection with bias-corrected SCC. These differences in changes in atmospheric general circulation ~~have yielded~~ lead to significantly different changes in atmospheric temperatures (0.8 K greater in ARP-MIR-21-OC in winter), the most dramatic difference being ~~a 2K bigger~~ the larger (2 K) increase in west Marie-Byrd Land using ~~bias corrected~~ bias-corrected SSC. Differences in atmospheric circulation are also unsurprisingly associated with significantly different changes in total precipitation~~(and SMB)~~. At the ~~continent~~ continental scale, the increase in moisture advection approximated trough P-E is 9% larger in ARP-MIR-21-OC than in ARP-MIR-21. The consequences of the three-wave pattern ~~in ARP-MIR-21~~ decrease in SLP around Antarctica in ARP-MIR-21 are obvious with three regions of higher ~~(lower)~~ precipitations increases with respect to ~~the~~ ARP-MIR-21-OC~~scenario~~. At the regional scale, it is noteworthy that all ~~scenarios~~ projections agree on a (slight) precipitation decrease in Marie-Byrd Land and ~~western Ross ice shelf~~ the western Ross Ice Shelf (see Fig. **??**). ~~Victoria, Adélie, and Wilkes Land as well as the eastern side of the AP are also regions of lower precipitation increase compared to the rest of the continent. All these regions show high uncertainty in future changes in precipitation estimated in this study (Fig. **??**, high value of standard deviation when compared to mean change). Lower increase or slight decrease in precipitation in Marie-Byrd~~ A lower increase or a slight precipitation decrease in Marie Byrd Land are also ~~present~~ found in other studies (**??**). These results however bear uncertainties as ~~lot of~~ many free AGCM (including ARPEGE) struggle to reproduce the depth and the variability of the Amundsen Sea Low currently located at the east side of the Ross Sea in winter. The decrease in precipitation in this region is mitigated when using both set of bias corrected SSC. ~~The increase in annual mean~~ $\sout{T_{2m}}$ ~~at the end of the~~ $\sout{21^{st}}$ ~~century for the Antarctic ice-sheet with the different ARPEGE scenarios are in good agreement with the CMIP5 RCP8.5 outputs (**?**). Unsurprisingly, the warming obtained with scenarios using SSC from NorESM1-M (around +2.8K) belongs to the lower end of the values for RCP8.5 scenario reported in this previous study, as a consequence of weak changes in Antarctic sea-ice in this projection, whereas in scenarios using MIROC-ESM SSC, the increase in annual~~ $\sout{T_{2m}}$ ~~is around +4K. As suggested by **?**, the choice of the AOGCM providing SSC is determinant in the warming obtained at the Antarctic-continent scale. Using NorESM1-M and original SSC from MIROC-ESM, the SMB (precipitation) increase obtained with ARPEGE range between 5.2 and 6.3~~ $\sout{\%.K^{-1}}$ ~~(6 and 7.4~~ $\sout{\%.K^{-1}}$~~). This is in the range of values obtained in previous studies (**?????**). Only the SMB increase obtained with bias-corrected SSC from MIROC-ESM, 7.9%.~~$\sout{K^{-1}}$ ~~is above the higher end values of previous studies.~~ As in **?**, we found that regional precipitation increases depend on the ~~AOGCM chosen as~~ SSC source and on ~~their bias-correction~~ whether they are bias-corrected or not. ~~For a weaker climate change signal such as the one coming from NorESM1-M SSC, we found no significant difference in climate change signals at the continent scale over Antarctica using bias corrected or original SSC to drive ARPEGE. However, for a more dramatic change in SSC such has the one coming from MIROC-ESM, we found a +14% higher precipitation increase using bias-corrected SSC.~~

Climate change signals for temperature and precipitation over large ice shelves (Ross and Ronne-Filchner) do not seem to substantially differ those from adjacent areas. Yet, as for the reconstruction of recent climate, projected climate change over these areas should be considered with circumspection, especially for near-surface temperatures. Finally, we draw the attention on the fact that when considering absolute values rather than climate change signals, both annual total precipitation ~~rates~~ and SMB are significantly different ~~than when using bias corrected SSC~~ when bias-corrected SSC are used to drive ARPEGE. In the scenarios with original SSC, the annual ~~GIS~~ AIS SMB at the end of current century is slightly higher in ARP-NOR-21 than in ARP-MIR-21, which is ~~a bit~~ surprising considering the very weak decrease in sea-ice around Antarctica in NorESM1-M RCP8.5 scenario. When using bias-corrected SSC, the order is reversed and SMB values are respectively 2585 Gt yr$^{-1}$ and 2914 Gt yr$^{-1}$, which is more intuitive considering much larger decrease in sea-ice in MIROC-ESM RCP8.5 scenario.

### 4.3 Consistency of atmospheric model responses

The late winter (August to October, ASO) and late summer (February to April, FMA) differences between historical SST and SIC from NorESM1-M~~and~~ , MIROC-ESM, and the observations, ~~as well as~~ and the same differences between SSC of their RCP8.5 ~~scenario~~ projection and their bias-corrected equivalent are displayed in the ~~annex~~ supplementary material (Fig. **??** and **??**). The differences in SSC used to drive the atmospheric model are, unsurprisingly, extremely similar between historical and future climate experiments.~~For the SST, the similarity is almost perfect and for SIC, the patterns are the same, but given the decrease in SIC in future climate, they are shifted poleward.~~

Has the introduction of the same SSC "biases" with respect to the observed or bias-corrected references yielded the same responses of the atmospheric model in the historical and future climates? ~~This~~ The consistency of the response of the atmospheric model is considered here as being the key for having the same climate change signals between experiments using original ~~SSC from the CMIP5 model and experiments considering the climate change signal between the AMIP experiment and the corresponding~~ or bias-corrected ~~projected~~ SSC.

For simulations using SSC from the NorESM1-M model, the consistency of the response of the atmospheric model is ~~obvious. The similarity~~ clear. The similarities in the differences between ARP-NOR-20 and ARP-AMIP with differences between ARP-NOR-21 and ARP-NOR-21-OC is ~~strong for most climate variables , e.g.SLP~~clear for many climate variables (SLP, see Fig. **??**, 500 hPa ~~geopotentials~~geopotential, stratospheric temperatures, 500hPa zonal wind ~~,~~ and near-surface atmospheric temperatures~~...(an example for SLP can be seen in Fig. **??**). The~~ ). In this perspective, the most interesting feature ~~in this perspective~~ is that in both historical and future climate, the ARPEGE simulations forced by NorESM1-M original SSC are about 10% wetter and significantly warmer in winter and spring at the Antarctic continental scale than their bias-corrected reference. The link here between the dynamical response of the atmospheric model and the SST biases of the NorESM1-M AOGCM seems physically consistent. NorESM1-M SSTs are indeed characterized by a warm bias in Southern hemisphere mid-latitudes (40-60°S) and a cool bias in the Southern Tropics (except for large upwelling areas, see Fig. **??**), having as a consequence a decrease of the meridional SST gradient. These biases are stronger in winter and spring. The response of the atmospheric model ~~is here~~ here is a decrease in the westerly winds (which is confirmed by a weaker surface westerly winds in the historical simulation), which allows an increase in the moisture transport towards Antarctica (P-E larger by about 10% in present and future climate) and explains the additional 200 to 300 Gt.yr$^{-1}$ (1.5 to 2 $\sigma$) of precipitation on the ice-sheet in the ARPEGE simulations realized with NorESM1-M SSC. The warm SST bias in the 40-60°S region, which is a large part of the moisture source region for Antarctic precipitation (**?**), is certainly also part of the explanation for larger ~~precipitations~~precipitation rates. The consistency of the response of the atmospheric model in historical and future climate explains the absence of significant differences in the climate change signals between experiments with the original NorESM1-M SSC and their bias-corrected reference.

~~For the simulations realized with oceanic forcings from MIROC-ESM, the~~ The consistency of the response of the atmospheric model is less ~~generalized~~clear for the projections realized with SSC from MIROC-ESM. Some changes in the differences between simulations forced with original SSC and those forced by their bias-corrected references are noticeable in winter and autumn SLP and zonal wind speed (an example for SLP can be seen in Fig. **??**). The main result here, as a consequence of these differences, is a total precipitation difference in the RCP8.5 experiment with bias-corrected SSC of about +200 Gt $yr^{-1}$ ($1\sigma$), while there was almost no difference in total precipitation in the historical period between ARP-AMIP and ARP-MIR-20. In both historical and RCP8.5 experiments, simulations with original SSC from MIROC-ESM model are cooler over most of Antarctica in spring and summer. Here, the link between biases in Southern Hemisphere SST from MIROC-ESM (see Fig. **??**) and the response of ARPEGE appears less clear. SSTs from MIROC-ESM are mainly characterized by a cold bias at mid-latitudes and a warm bias around Antarctica, especially in summer and autumn, as well as a cold bias in the Tropics throughout the years. ARPEGE ~~simulation forced~~ simulations driven by these SSTs are characterized by an equatorward surface ~~westerly winds~~ westerlies maximum in the historical simulation but not in the future scenario. Changes in the latitude of the maximal SST gradient might explain the equatorward position of the westerlies maximum. However, with respect to the ARP-AMIP simulation, ARP-MIR-20 is also characterized by cooler temperatures throughout the tropical troposphere, higher tropical stratospheric temperatures in spring~~and~~ , much lower upper tropospheric and stratospheric temperatures in Antarctica. This suggests that interactions between SST biases, tropical convection, and stratospheric meridional temperature gradients could also explain the response of the atmospheric model when forced by MIROC-ESM SSC.

### 4.4 Implication of Sea Surface Conditions selection

In many cases, it has been reported that selecting the best skilled models for a given aspect of the climate system ~~helped~~ helps in better constraining the associated uncertainties on the climate change signal (e.g., **?**). Here, because we use bias-correction of the SSC ~~,~~ this aspect has reduced importance. ~~Our aim is to cover as much as possible, while~~ While performing a limited number of climate projections, ~~the range of~~ we cover a large range of the uncertainties associated with the evolution of the Southern Ocean surface condition for the Antarctic climate ~~projection as~~ because it was shown to be its primary driver (**?**). ~~The~~ This approach is supported by the fact that biases on large-scale atmospheric circulation of coupled climate models were shown to be highly stationary under strong climate change (**?**), and that the response of the ARPEGE atmospheric model to the introduction of the same SSC “bias” was shown to be mostly unchanged in future climate~~support this approach~~.
The warming signal for the Antarctic ~~ice-sheet~~ Ice-Sheet in the CMIP5 model ensemble RCP8.5 ~~scenario~~ projection is evaluated to be 4±1 ~~°C~~ K (**?**). Interestingly, by picking NorESM1-M and MIROC-ESM~~which show some of the more opposite climate change signal on~~ , which show the end values of the Southern Hemisphere SIE changes among the CMIP5 ensemble, we still have warming differences much smaller than the CMIP5 ensemble spread and cover in our ~~scenario~~ projections (2.8 to 4.2 ~~°C~~K) mostly the lower half of this uncertainty range on Antarctic warming. **?** found that about half of the variance of the CMIP5 projection in RCP8.5 scenario for Antarctic temperature and precipitation is explained by historical biases and sea-ice ~~decrease~~

~~by~~ decreases by the late 21 $^{st}$ century. Obviously, a non negligible part of the uncertainties ~~on Antarctic climate changes~~ of Antarctic climate change is linked to the representation of general circulation in the atmospheric model (**?**) and these should be assessed in future work.

## 5 Summary and Conclusion

~~In this study , we present a~~ This study presented the first general evaluation of the capability of the AGCM ARPEGE to reproduce ~~the~~ atmospheric general circulation of the high southern latitudes and the surface climate of the Antarctic ice-sheet. ARPEGE is able to correctly represent the main features of atmospheric general circulation, although we have shown a negative bias in sea-level pressures at mid-latitudes and a positive bias around Antarctica especially in the Amundsen ~~sector is to be reported~~Sea sector. Unsurprisingly, the use of observed sea surface conditions (ARP-AMIP simulation) rather than SSC from NorESM1-M and MIROC-ESM helped to improve the representation of sea-level ~~temperatures~~ pressures in the southern latitudes in all seasons but summer. ARPEGE is also able to correctly reproduce surface climate of Antarctica except for large ~~ice-shelves~~ice shelves. The differences in $T_{2m}$ with ~~polar~~ polar-orineted RCM MAR and *in-situ* observations is encouraging, especially given the large biases that ~~can exhibit~~ are exhibited in other GCMs or even ~~reanalysis when surface climate of Antarctica~~ reanalyses when antarctic surface climate is considered (**??**). Regarding SMB, our estimates at the continental scale ~~concur~~ agree with estimates from other studies such as those using ~~polar RCM~~ MAR or RACMO2, even though higher precipitation rates in ARPEGE tend to be compensated for by higher ~~surface snow~~ total sublimation rates (+200 Gt yr$^{-1}$). Concerning regional patterns, the distribution of precipitation in the ARP-AMIP simulation differs from the one in the MAR RCM ~~,~~ mainly as a consequence of errors in atmospheric general circulation.

The future climate projections presented in this study belong to the first antarctic climate projections realized at a “high” (Cordex-like) horizontal resolution using a global atmospheric climate model. Concerning climate change signals, we evaluate the impact of using original and bias-corrected sea surface conditions from MIROC-ESM and NorESM1-M, which display ~~very different changes in winter SIE in their~~ diverging RCP8.5 ~~scenario : respectively~~ projections for the Southern Ocean’s late 21$^{st}$ century SIE (respect. -45% and -14% ~~at the end of the 21$^{st}$ century (2071-2100~~for winter SIE). Using SSC from NorESM1-M model, ~~we found a $T_{2m}$ increase of +2.8K and a precipitation increase of about 20%. No~~ no significant differences in yearly or seasonal mean $T_{2m}$ increase, ~~in precipitation~~precipitation, or SMB changes were found when using bias-corrected SSC. When using SSC directly from MIROC-ESM model, the increase in ~~$T_{2m}$ is around +4K in both cases, but the increase in~~ precipitation is +23%~~when using directly SSC from MIROC-ESM, while~~ , and it reaches +37% when using the corresponding bias-corrected SSC. This difference is ~~found~~ statistically significant and is ~~to be~~ linked with clearly different dynamical and thermodynamical changes in SLP around Antarctica, occuring mainly in winter and spring~~when using bias-corrected SSC~~. At the regional scale, large differences in $T_{2m}$ and ~~precipitations increase~~ precipitation increases are found when using bias-corrected SSC both from NorESM1-M and MIROC-ESM. ~~In this study, we have shown~~ The analysis of the climate projections is further evidence the potential of the ARPEGE model for the study of Antarctic climate and climate change. ~~Unsurprisingly, the representation of present climate, especially atmospheric general circulation is improved when using observed SSC.~~ When using SSC from

NorESM1-M, we found a 10% higher precipitation accumulation at the Antarctic-continent scale (which is detrimental to the model skills for precipitation) with respect to the bias-corrected reference in both historical and future climate. ~~With respect to the observations, NorESM1-M SST are characterized by a weaker meridional gradient in the Southern Ocean, which decreases the strength of Westerlies around Antarctica and favor the meridional transport of moisture towards the Pole~~These findings advocate once more for the use of bias-corrected SSC to drive climate projections using an AGCM. Additionally, this method reduces the uncertainty of the baseline (historical) climate and the need for computational resources as only one historical simulation using observed SSC in needed.

~~Concerning climate change signals~~In this study, we confirm the importance of the ~~choice of the coupled model~~ coupled model choice from which SSC scenario is taken. By performing bias correction of SSC, we showed that not only the regional pattern of temperature and precipitation changes can be different ~~. Indeed, in the case of~~ but also the integrated changes in SMB and seasonal temperatures at the ice-sheet scale. Unsurprisingly, projections using climate changes signal from MIROC-ESM SSC ~~, we found significantly higher precipitation increase and larger~~ projections (larger decrease in sea-ice) show higher increases in temperature and precipitation that the one using NorESM1-M SSC. This confirms the effect of sea-ice decreases and SST increases on Antarctic temperatures and SMB in a "realistic" climate projection experiment. For the range of antarctic warming obtained (+3 to +4 K), we confirm results from previous studies showing that the increase in ~~winter $T_{2m}$ when using bias-corrected SSC. These results are another argument in favor of the bias correction of SSC when performing future climate scenarios, as it reduces the uncertainty of the baseline (historical)climate and the need for computational resources as only one historical simulation using observed SSC in needed. However, this method still bears some uncertainties for the study of the climate change in Antarctica, mainly coming from the errors of the atmospheric model ARPEGE. We have seen that the errors on atmospheric general circulation remain substantial even when using observed SSC. Therefore~~SMB is largely dominated by increases in snowfall which remain much larger that the increase in melt and rainfall at the ice-sheet scale. Considering changes in SIE at the two extreme end values from the CMIP5 ensemble, differences in Antarctic warming obtained ($\sim$ 1 K) are clearly smaller than the spread of CMIP5 projections for the AIS. This confirms that a large part of the CMIP5 diversity for Antarctic climate projections comes from atmospheric model (errors) and associated uncertainties. Climate projections presented in this study still bear considerable uncertainties. These mostly come from ARPEGE errors (even when driven by observed SSC) on southern high latitudes general atmospheric circulation, which casts some doubt on the reliability of the projected Southern Hemisphere atmospheric circulation changes. As a consequence, in future work, we will assess the uncertainties associated with ~~the~~ errors of the atmospheric model by performing an ARPEGE simulation nudged towards the reanalysis and use the statistics of the model drift in this nudged simulation such as done in **?** to perform an atmosphere bias-corrected ARPEGE historical simulation. Bias-corrected projections such as done in **?** can then also be assessed using the ~~methods presented here~~method presented in this study.

*Competing interests.* The authors have no competing interests.

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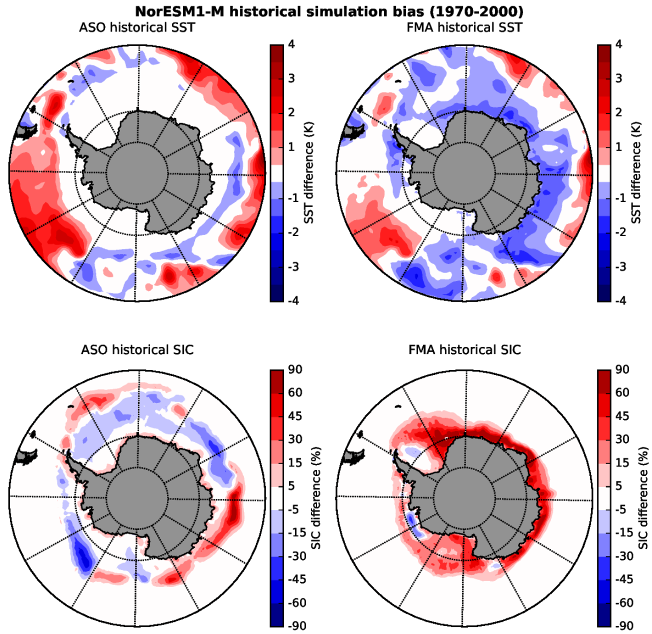
## Appendix A: Sea Surface Conditions

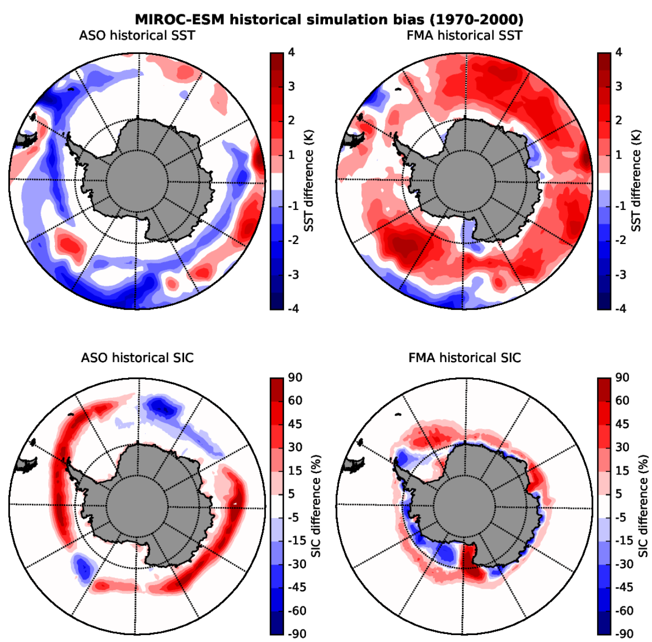
In this section, we present the historical bias in SSC in MIROC-ESM and NorESM1-M (Fig. **??**) used to force ARPEGE model as well as the differences between SSC in rcp8.5 scenarios in these model and their bias-correction (Fig. **??**). ~~These first two figures illustrate the efficiency~~ The skills of the bias-correction ~~methods fro SSC~~ method for SSC can be appreciated as the similarity between differences in futures SST is striking. For SIC, the ~~patterns~~ pattern of the model bias in historical climates can easily be identified in the differences between original and bias-corrected SSC (Fig. **??**), but because there is a decrease of SIE, these patterns are shifted poleward. Yearly and seasonal ~~Southern hemisphere~~ South Hemisphere SIE in MIROC-ESM, NorESM1-M and observations (Table **??**) and in the two AOGCM original and bias-corrected ~~rcp8~~RCP8.5 ~~scenario~~ projection (Table **??**) are also presented in this supplementary material. Here again, the efficiency of the bias-correction methods to reproduce the climate change signal in hemispheric SIE from the coupled model ~~can be~~ is confirmed. In Figure **??**, SST historical bias for both coupled ~~model for each seasons on the whole Southern~~ models for each season in the southern hemisphere are displayed in order to support the discussion on how the atmospheric model has responded to the same SST biases or perturbations in present and future climate.
In Table **??**, the climate change signals in SIE in scenarios from MIROC-ESM and NorESM1-M can be evaluated, with the decrease in sea-ice being three ~~time more important~~ times importanter in MIROC-ESM ~~scenarios~~projection. It can also be noted that both AOGCM hemispheric SIE are ~~quite~~ relatively close to the observations. Only an underestimate of about 20% ~~of Summer and Fall~~ in summer and autumn SIE in MIROC-ESM can be mentioned. ~~As a consequence, there are few differences in both absolute and relative changes as well as in absolute values in bias-corrected and original projected SIE.~~

## Appendix B: Near-surface temperature

In this section, we present additional material for near-surface temperatures ($T_{2m}$). The difference between $T_{2m}$ from the ARP-AMIP simulation and those from the MET READER data base and corresponding evaluation statistics can be seen in Table **??**. A map showing the location of the different research stations including those of the MET ~~reader~~ READER data base used for the comparison with ARPEGE ~~presented in Tab. ??~~ can be seen in Fig. **??**.

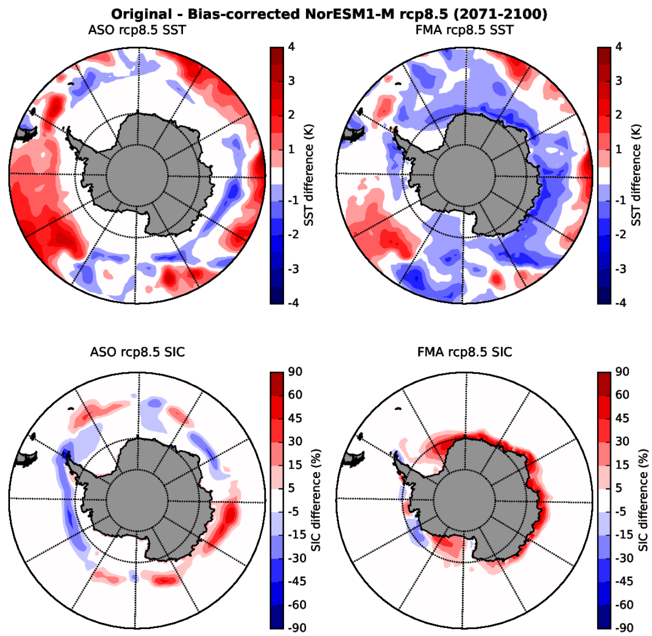



(a) NorESM1-M historical

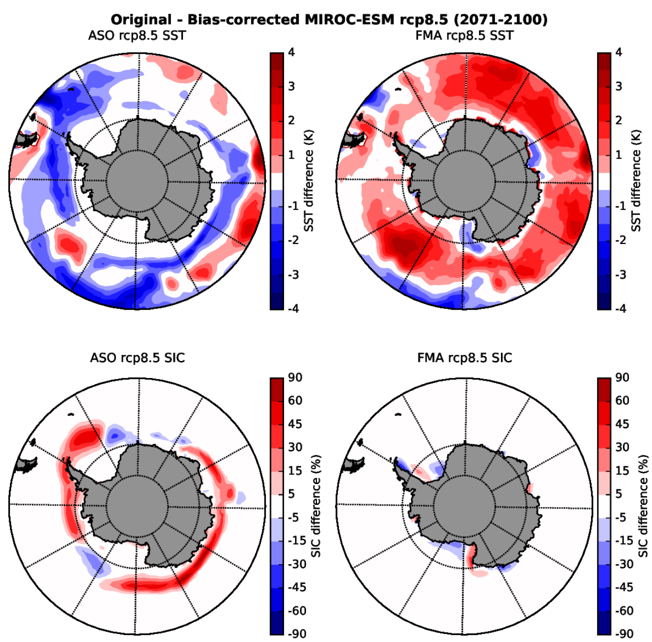



(b) MIROC-ESM historical

**Figure A1.** Bias in SST (*top*) and SIC (*bottom*) for late winter, August, September, October(*left*) and summer, February, March, April (*right*) historical simulations of (*a*) NorESM1-M and (*b*) MIROC-ESM.

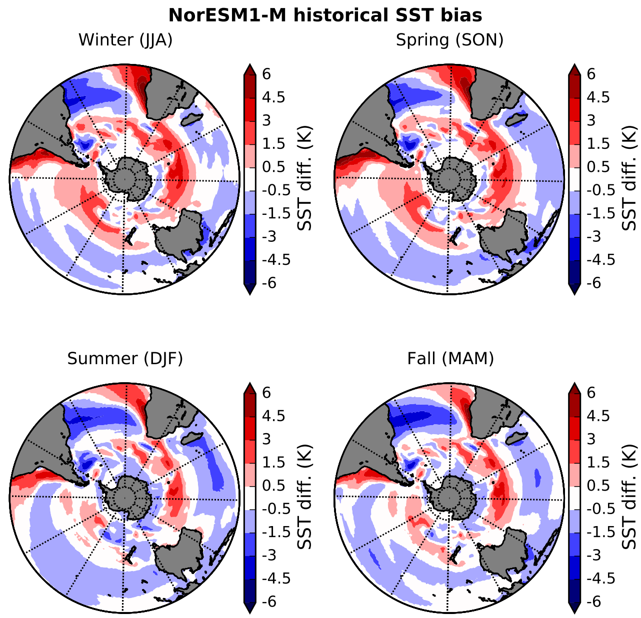



(a) NorESM1-M RCP8.5

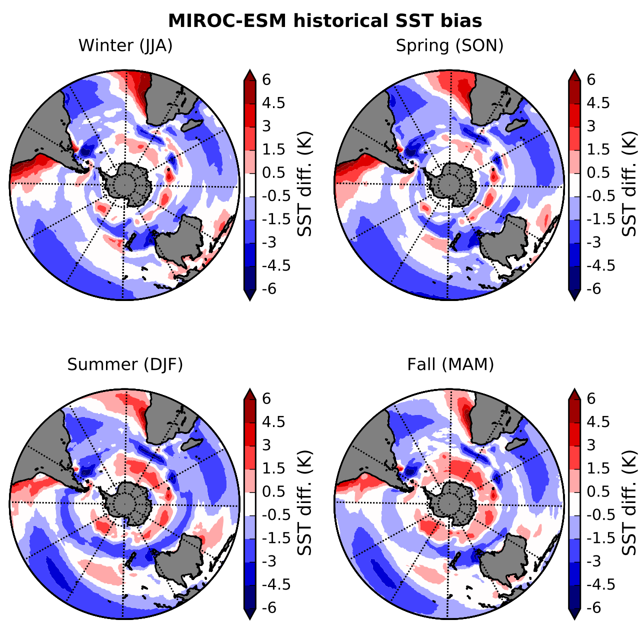



(b) MIROC-ESM RCP8.5

**Figure A2.** Same as Fig.**??** but for RCP8.5 scenario and corresponding bias corrected SSC




(a) NorESM1-M historical




(b) MIROC-ESM historical

**Figure A3.** Seasonal historical bias in SST in the Southern hemisphere from NorESM1-M (*top*) and MIROC-ESM (*bottom*).

**Table A1.** Annual and seasonal Southern Hemisphere mean historical Sea Ice Extent (SIE, $10^6$ km$^2$) in observations, NorESM1-M and MIROC-ESM.

| | Year | DJF | MAM | JJA | SON |
|---|---|---|---|---|---|
| Observations | 9.6 | 4.4 | 5.6 | 13.5 | 14.7 |
| NorESM1-M | 9.8 | 4.8 | 6.6 | 14.0 | 15.4 |
| MIROC-ESM | 8.9 | 3.1 | 4.0 | 13.3 | 15.3 |

**Table A2.** Annual and seasonal Southern Hemisphere mean projected Sea Ice Extent and absolute change with respect to historical climate ($10^6$ km$^2$) in NorESM-1M and MIROC-ESM ~~rcp8~~RCP8.5 ~~scenarios~~ projection and corresponding bias-corrected SSC.

| | Year | DJF | MAM | JJA | SON |
|---|---|---|---|---|---|
| NorESM1-M-rcp85 | 8.2 | 4.0 | 5.1 | 11.7 | 13.6 |
| *Change ($10^6$ km$^2$)* | *-1.6* | *-0.8* | *-1.5* | *-2.3* | *-1.8* |
| NorESM1-M-rcp85-bc | 7.9 | 3.5 | 4.2 | 11.1 | 12.7 |
| *Change ($10^6$ km$^2$)* | *-1.6* | *-0.8* | *-1.5* | *-2.3* | *-1.8* |
| MIROC-ESM-rcp85 | 4.2 | 0.9 | 1.2 | 6.8 | 8.2 |
| *Change ($10^6$ km$^2$)* | *-4.7* | *-2.2* | *-2.8* | *-6.5* | *-7.2* |
| MIROC-ESM-rcp85-bc | 4.2 | 1.0 | 1.5 | 6.8 | 7.6 |
| *Change ($10^6$ km$^2$)* | *-5.3* | *-3.4* | *-4.1* | *-6.7* | *-7.1* |

The effect of introducing biased SSC on the modelling of Antarctic $T_{2m}$ with ARPEGE AGCM is also presented in Fig. **??**. For ARP-NOR-20 (Fig. **??**), the introduction of biased SSC increase the warm bias on the East Antarctic Plateau (EAP) with respect to MAR and weather stations already present in ARP-AMIP (Fig. **??**). The same statement can be made for the winter cold bias over the Peninsula. In summer, there are relatively few differences in the skills of the latter two ~~simulation~~simulations, which is consistent with similar errors on large-scale atmospheric circulation (Fig. **??**).

For ARP-MIR-20 (Fig. **??**), the cold bias over the Peninsula is also larger than ARP-AMIP ~~in~~ for both seasons. The winter warm bias over the EAP is similar than in ARP-AMIP. In summer, the general tendency of ARP-MIR-20 to be cooler than ARP-AMIP over the continent leads to a decrease of the warm bias with respect to MAR over the margins of the EAIS and WAIS on one hand, but increase the cold bias on the EAP on the other hand, which can be seen in the differences with MAR and weather stations.

## B1 Ice Shelves

In this section, we further investigate the causes of the large discrepancies between ARPEGE and MAR over ice shelves and try to evaluate which part these discrepancies are actually due to the systematic biases of each model. Over the large ice shelves (Ronne-Filchner and Ross) the ARP-AMIP simulation is systematically 7 to 10 K (up to 12 K over the center of Ross) warmer than MAR in winter, while in summer, it is 5-7 K cooler (Fig. **??**). While no *in-situ* temperature records long enough to evaluate

**Table B1.** Error on READER weather station $T_{2m}$ (in K) in the ARP-AMIP simulation for the reference period 1981-2010. Errors significant at p=0.05 are presented in **bold**.

| Stations | DJF | MAM | JJA | SON |
|---|---|---|---|---|
| **EAP** | | | | |
| Amundsen Scott | 0.5 | **2.4** | 1.1 | 0.9 |
| Vostok | **-1.5** | **3.2** | **3.2** | **1.9** |
| *Mean error* | -0.5 | 2.8 | 2.1 | 1.4 |
| *RMSE* | 1.1 | 2.8 | 2.4 | 1.5 |
| **Coastal EA** | | | | |
| Casey | **-4.0** | **-5.7** | **-6.9** | **-5.4** |
| Davis | **-1.6** | **-4.2** | **-6.0** | **-3.3** |
| Dumont Durville | -0.5 | **-2.8** | **-4.1** | **-2.2** |
| Mawson | **-2.2** | **-4.3** | **-5.7** | **4.3** |
| McMurdo | **-7.1** | **-6.5** | **-8.1** | **-8.4** |
| Mirny | **-1.2** | **-2.2** | **-3.0** | **-2.0** |
| Novolazarevskaya | **2.5** | 0.6 | -1.0 | 0.6 |
| Scott Base | **-5.0** | **-3.1** | **-4.6** | **-5.0** |
| Syowa | -0.2 | -0.6 | **-1.5** | 0.0 |
| *Mean error* | -2.2 | -3.3 | -4.5 | -3.3 |
| *RMSE* | 3.5 | 3.9 | 5.1 | 4.3 |
| **Ice shelves** | | | | |
| Halley | **1.3** | **2.5** | 1.2 | 0.9 |
| Neumayer | **2.2** | **1.2** | 0.9 | **1.4** |
| *Mean error* | 1.7 | 1.8 | 1.1 | 1.2 |
| *RMSE* | 1.8 | 1.9 | 1.1 | 1.2 |
| **Peninsula** | | | | |
| Bellingshausen | **-1.0** | -0.4 | -0.2 | -0.1 |
| Esperanza | **-1.1** | 0.5 | -1.3 | -0.9 |
| Faraday | **-2.7** | **-4.7** | **-5.7** | **-3.7** |
| Marambio | **-1.9** | 1.0 | -1.3 | -1.6 |
| Marsh | **-0.8** | -0.4 | -0.3 | -0.0 |
| Orcadas | **-1.1** | -0.0 | 0.6 | -0.8 |
| Rothera | **-5.6** | **-7.9** | **-8.7** | **-6.1** |
| *Mean error* | -2.0 | -1.7 | -2.4 | -1.9 |
| *RMSE* | 2.6 | 3.5 | 4.0 | 2.8 |
| **Southern Ocean** | | | | |
| Gough | **-1.0** | -0.3 | 0.0 | **-0.8** |
| Macquarie | **-0.7** | -0.4 | 0.2 | **-0.5** |
| Marion | **-1.2** | **-0.4** | -0.1 | **-0.7** |
| *Mean error* | -1.0 | -0.4 | 0.0 | -0.6 |
| *RMSE* | 1.0 | 0.4 | 0.1 | 0.7 |

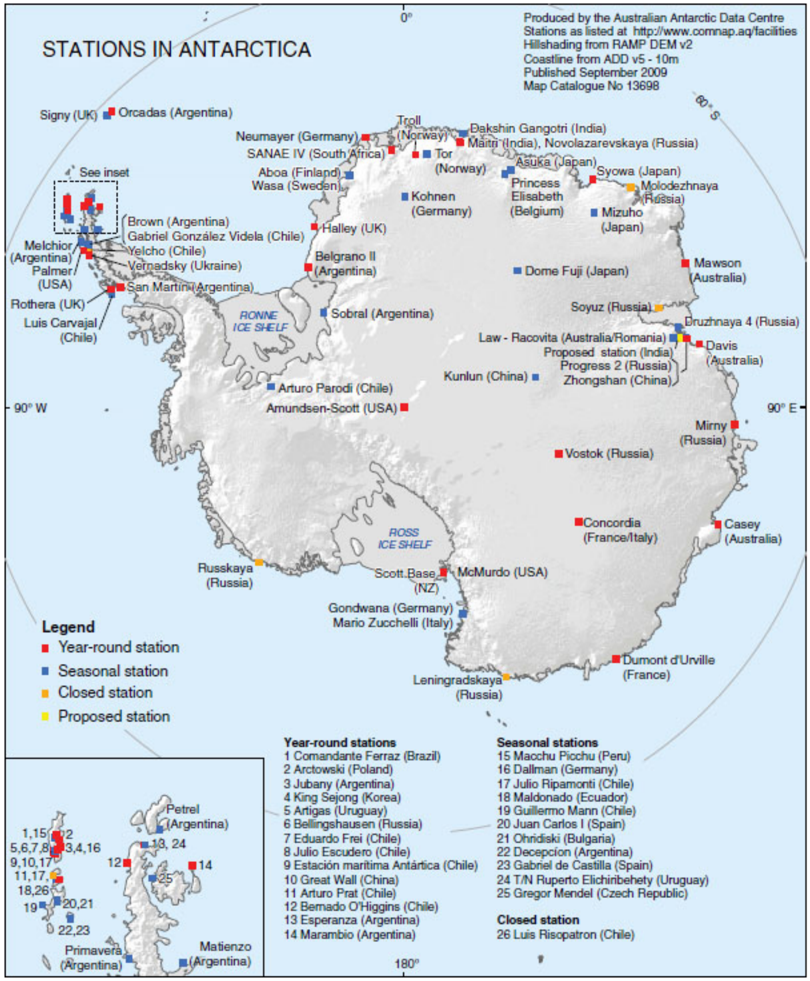
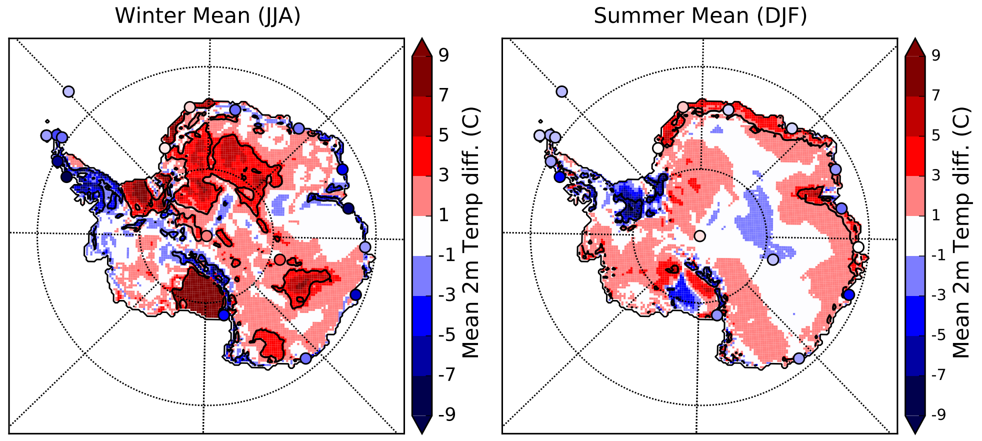
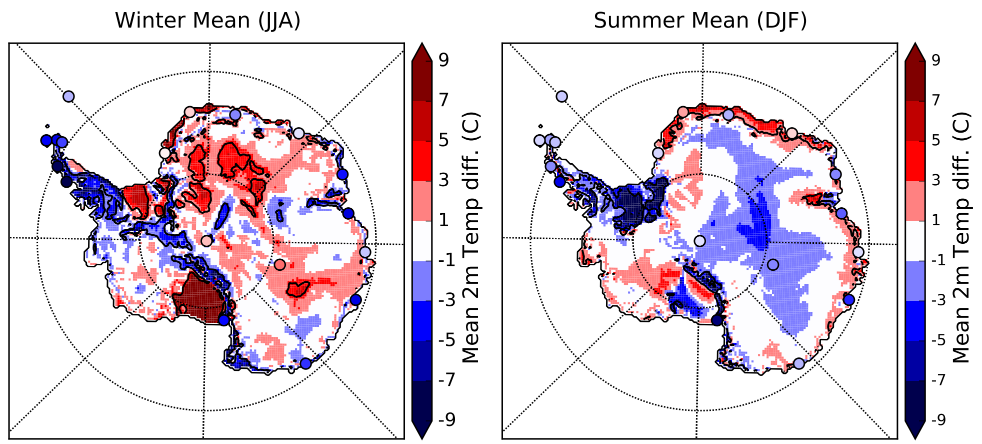



**Figure B1.** Map showing the location of Antarctic research stations including those from the MET READER data base. **Credit : Australian Antarctic Data Centre**

a freely evolving climate model such as ARPEGE is currently available for these areas, the MAR-ERA-I simulation has been evaluated against automatic weather station from the READER data base (**?**). Over the Ross Ice Shelf, MAR shows an average systematic bias of -2.8 K with biases larger than 5 K for the coolest stations (center of the ice shelf). This suggests that about 1/3 of the MAR-ARPEGE discrepancy over large ice shelves in winter seems to actually comes from a MAR cold bias over these areas. This can also be seen over smaller ice shelves of the Dronning Maud Land area where ARPEGE is 5-7 K warmer in winter when compared to MAR, while ARPEGE biases with respect to Halley and Neumayer weather station located over ice shelves of this area are respectively only + 1.2 and + 0.9 K (Table **??**). The evaluation in **?** shows that MAR also has a $\sim$ 3 K cold bias over ice shelves in summer, which suggests that ARPEGE cold bias might be even larger during this season. This analysis seems to be confirmed in the comparison between ARP-AMIP and RACMO2 (Fig. **??**) where ARPEGE "warm bias"




(a) ARP-NOR-20




(b) ARP-MIR-20

**Figure B2.** $T_{2m}$ differences between ARP-NOR-20 (*top*) and ARP-MIR-20 (*bottom*) and MAR-ERA-I simulations in winter (JJA, *left*) and summer (DJF, *right*) for the reference period 1981-2010. Circles are $T_{2m}$ differences between ARP-AMIP and weather stations from the READER data base. Black contour lines represent areas where $\mid ARPEGE - MAR \mid > 1.MAR\sigma$.

over ice shelves is reduced over most of the Ross Ice Shelf ($<$ 5 K) and almost completely disappears over Ronne-Filchner while ARPEGE "cold bias" over these areas in summer is more striking.

In the following, we examine differences between MAR-ERA-I and ARP-AMIP for different components of the surface energy balance (latent heat flux, sensible heat flux, downward long-wave radiation), albedo and near-surface temperature inversion. Unlike what has been done for near-surface temperature, wind speed, surface pressure and SMB, the MAR-ERA-I simulation has not been rigorously evaluated against observational data sets for these variables. As a consequence, here more than anywhere else, these comparisons are meant to help in understanding model-model differences rather than being an indirect evaluation of ARPEGE model.

In the version of ARPEGE used, ice shelves were not considered as land in the land surface model. To solve this issue, we forced the sea-ice concentration to be 100% and the sea-ice thickness to be 40 meters in order to simulate realistic heat fluxes at the surface. These modifications allowed to completely shut down latent heat fluxes from the surface (Fig. **??**) and to have negative sensible heat fluxes (heat transfert from the atmosphere to surface, Fig.**??**) in winter as expected, and in agreement with the fluxes modelled in MAR simulation. Thanks to the accumulation of snow on top of sea-ice accounted for in GELATO, the effective albedo (SWU/SWD, Fig. **??**) over ice shelves in ARPEGE compares reasonably well with MAR. This statement is also valid for most of the ice sheet. The structure of the near-surface inversion has been investigated as another possible explanation for discrepancies between MAR and ARPEGE. To do so, we represent the difference between surface temperature ($T_s$) and the temperatures at 20 metres ($T_{20m}$) in both model and the corresponding difference (Fig. **??**). Over large ice shelves, the seasonality of the differences (weaker near-surface inversion in ARPEGE in winter, and larger in summer) is consistent with the differences in near-surface temperatures between the two model along the seasons. This statement is also valid for the very top of the high Antarctic Plateau where ARPEGE tends to be too warm (with respect to MAR and observations) in winter and slightly too cold in summer. This suggests that ARPEGE underestimates the strength of near-surface temperature inversion due to the formation of very stable boundary layer in winter as many climate models do (**??**, e.g.,). Another part of the explanation for warmer ARPEGE temperatures over ice shelves in winter might also comes from higher latent and sensible fluxes over the sea-ice area (see Fig. **??** and **??**), which favours advection of warmer and moist air over ice shelves. The cloudiness (*not shown*) and the downward longwave radiation (Fig. **??**) over ice shelves being indeed higher in ARPEGE than in MAR.

Discrepancies between models for near-surface temperatures over large ice shelves and errors with respect to sparse *in-situ* observations even for polar-oriented RCMs widely used as reference (MAR and RACMO2) shows that there is still room for improvement and that these areas might be an even more challenging test cases for surface boundary layer scheme than the high Antarctic Plateau.

## Appendix C: ~~Precipitation~~Surface Mass Balance

### C1 Precipitation

In this section, the effects of driving ARPEGE with biased SSC (NorESM1-M an MIROC-ESM) on the modelling of Antarctic precipitation are presented trough comparisons with MAR-ERA-I total precipitation. Differences between ARP-AMIP, ARP-

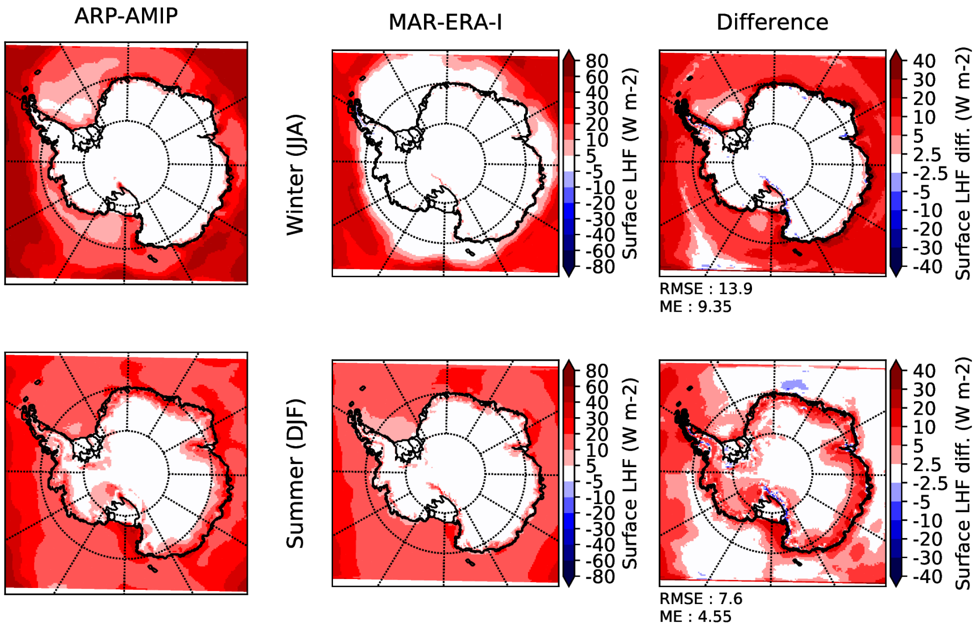



**Figure B3.** Mean surface latent heat flux (W $m^{-2}$) in ARP-AMIP (left), MAR-ERA-I (centre) and differences between the two models (right). The 1981-2010 mean flux over winter month (JJA) are shown on the upper part of the figure, while it is shown on the lower part for summer months (DJF).

NOR-20 and ARP-MIR-20 with MAR-ERA-I for total ~~precipitations~~ precipitation are show in Fig. **??**. Mean error and RMSE with respect to MAR are presented in the upper-left corner. The pattern of the errors is quite similar for each simulation. Unsurprisingly, the best agreement (smaller RMSE) with MAR is found the ARP-AMIP simulation. The wet biases with respect to MAR over Dronning Maud and Marie-Byrd Land ~~already present~~ also evidenced in ARP-AMIP tend to increase in both ARP-NOR-20 and ARP-MIR-20 simulations. The ARP-NOR-20 simulation has systematic wet bias (larger mean error) with respect to MAR at the continent scale consistent with the 10% increase in precipitation integrated over the whole ice sheet found in this simulation with respect to ARP-AMIP.

## Appendix D: Atmospheric general circulation

### D1 Present climate

In this section, we present and discuss the ability of ARPEGE atmospheric model to represent the broad features of the atmospheric general circulation around Antarctica. The winter (JJA) and summer (DJF) 500 hPa geopotentials and sea-level pressures (SLP) for ERA-I reanalyses and the ARP-AMIP simulation are presented in Fig. **??**. In winter, it can be seen than ARPEGE reproduces quite correctly the 3 climatological minimum in SLP and the localization of the maximum of the South

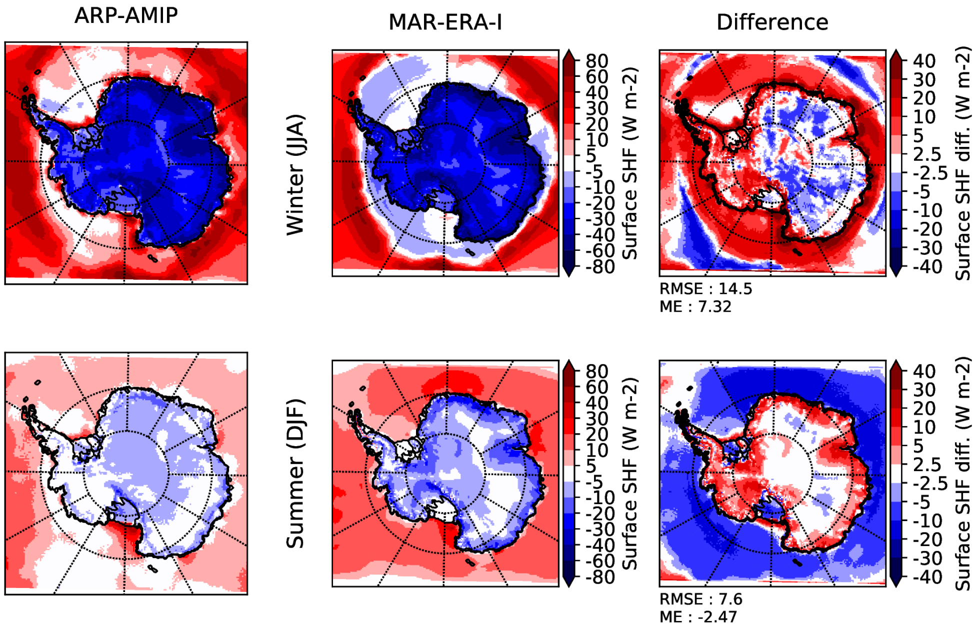



**Figure B4.** Mean surface sensible heat flux (W $m^{-2}$) in ARP-AMIP (left), MAR-ERA-I (centre) and differences between the two models (right). The 1981-2010 mean flux over winter month (JJA) are shown on the upper part of the figure, while it is shown on the lower part for summer months (DJF).

Polar vortex above the Ross Sea rather than on the South Pole. However, as already mentioned, the depth of the three SLP minimum and the meridional gradient around 50 to 60°S is underestimated. This remark is also valid in summer. It can also be noted that ARPEGE reproduces relatively correctly the displacement of the third SLP minima (Amundsen Sea Low) from eastern Ross Sea in winter to the Bellingshausen Sea ~~, west of the Peninsula~~ in summer.

### D2 Consistency of the atmospheric model response

In this section, we briefly discuss the consistency of the response of the atmospheric model ARPEGE when forced by similar SSC between present and future climate mentioned in the discussion. For the similarity of the SSC bias, see Fig. **??** and Fig. **??**. This consistency of the atmospheric model response is considered as being the key for having similar climate signals between climate projections realized with or without ~~bias corrected~~ bias-corrected SSC. In Fig. **??**, the difference in SLP between ARP-NOR-20 and ARP-AMIP for the four climatological seasons ~~in shown on the upper part,~~ and the corresponding difference for future climate (ARP-NOR-21-ARP-NOR-21-OC) ~~is shownon the lower part~~are shown. It can be seen that there are few changes in the differences pattern between present and future climate which is to be related with the minor differences in climate changes signal found for many variables in the experiment with bias-corrected and original NorESM1-M SSC. In Fig. **??**, the same differences for the experiment performed with MIROC-ESM SSC are displayed. Here again, the pattern of the

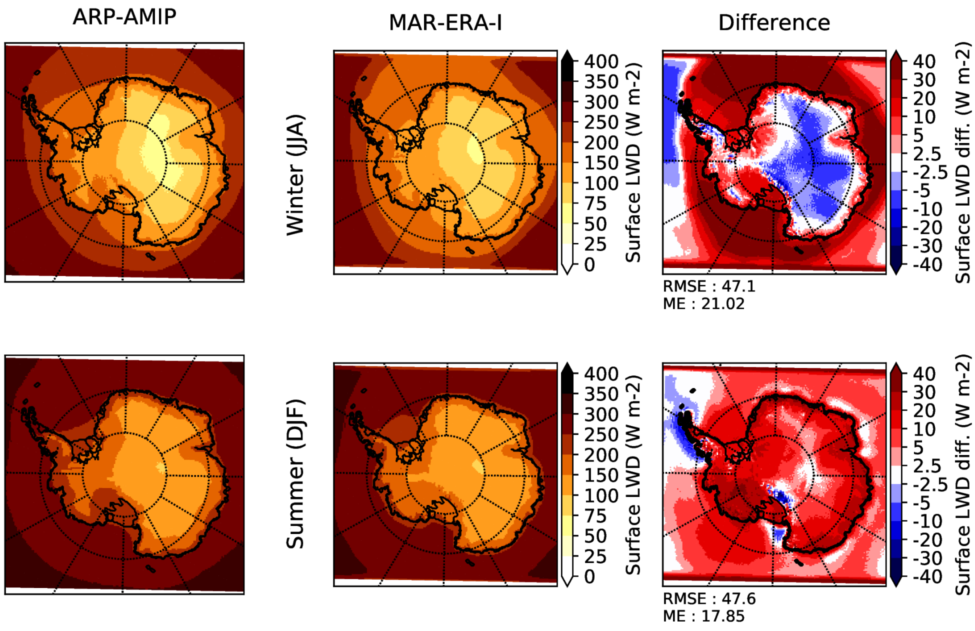



**Figure B5.** Mean surface longwave downward radiation (W m$^{-2}$) in ARP-AMIP (left), MAR-ERA-I (centre) and differences between the two models (right). The 1981-2010 mean flux over winter month (JJA) are shown on the upper part of the figure, while it is shown on the lower part for summer months (DJF).

differences are very similar. We note however a tripole in the difference for future climate (ARP-MIR-21 - ARP-MIR-21-OC) in autumn (MAM), which was absent in the difference for present climate. This tripole can certainly be related to the tripole observed for the differences in precipitation and sea-level pressure change signal observed in ~~Section~~ section **??**.

## D3 Surface melt

In this section, we present and briefly discuss additional results from the comparisons between ARPEGE and polar-oriented RCMs MAR and RACMO2. It can be seen in Table **??** that compared to reference RCMs MAR and RACMO2 driven by ERA-I reanalyses, ARPEGE represents reasonably the total integrated melt flux at the surface of the grounded AIS as the yearly mean in ARP-AMIP falls within the $\pm 1.\sigma$ of the estimation using RACMO2 (**??**) while the difference with MAR is +1.9 $\sigma$ of MAR standard deviation. In Fig. **??** and Fig. **??**, one can see that the spatial distribution of melt areas over the Antarctic Ice Sheet is reasonably represented in ARP-AMIP simulation if MAR and RACMO2 are taken as reference. In comparison with both RCMs, some limitation of ARPEGE model can however be mentioned : i) an underestimation of melt intensities over coastal areas and small ice shelves on the west and east side of the Antarctic Peninsula, consistent with ARPEGE errors on atmospheric general circulation and identified cold biases over these areas due underestimated warm and moist air advection from the north-west and possibly reduced Foëhn event frequencies on the east side of the Peninsula (Larsen Ice Shelf) ii)

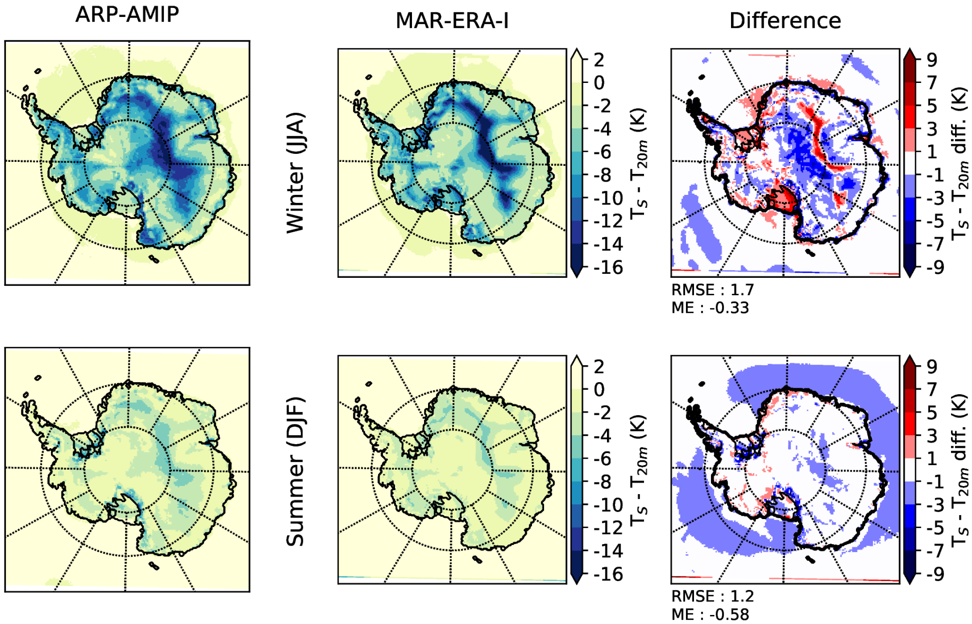



**Figure B6.** Mean near-surface temperature inversion ($T_S$ - $T_{20m}$, in K) in ARP-AMIP (left), MAR-ERA-I (centre) and differences between the two models (right). The 1981-2010 mean for winter month (JJA) are shown on the upper part of the figure, while it is shown on the lower part for summer months (DJF).

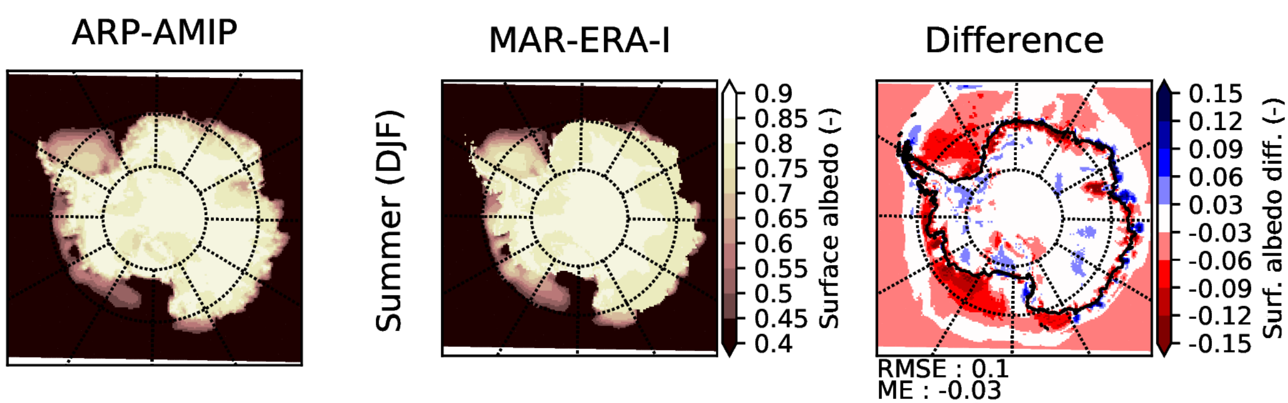



**Figure B7.** Mean surface summer (DJF) effective albedo (SWU/SWD) in ARP-AMIP (left), MAR-ERA-I (centre) and differences between the two models (right).

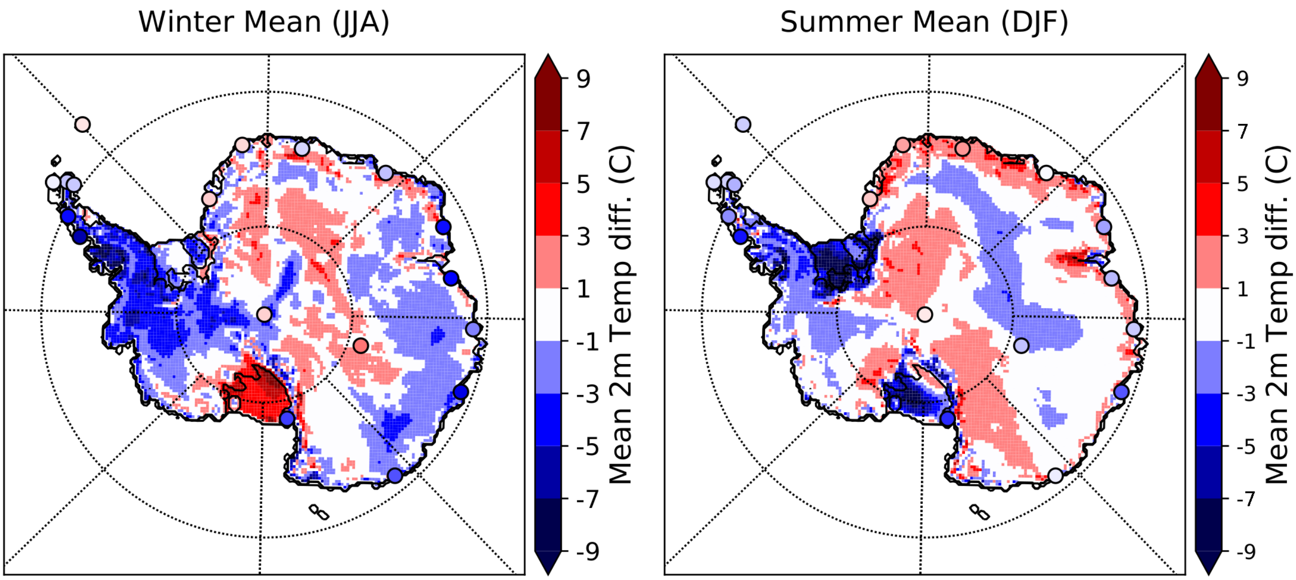



**Figure B8.** $T_{2m}$ differences between ARP-AMIP and ERA-I driven RACMO2 (**?**) in winter (JJA, *left*) and summer (DJF, *right*) for the reference period 1981-2010. Circles are $T_{2m}$ differences between ARP-AMIP and weather stations from the READER data base.

overestimated melt intensities over the ridge of the narrow northern part of the Peninsula likely due to poorer representation of the topography due to coarser ARPEGE horizontal resolution over this area ($\sim$ 45 kms vs 35 kms in MAR and 27 kms in RACMO2) iii) overestimation of melt intensities over large ice shelves (Ronne-Filchner and Ross) consistent with reduced ARPEGE skills for the representation of surface boundary layer processes over these areas. Despite these limitations, it can be assumed that ARPEGE represents reasonably surface melt fluxes over the grounded AIS. This statement is however no longer valid if we consider surface run-off, as about $1/3$ of surface liquid water inputs leaves the snowpack in ARPGE simulations (see Table **??**), while this fraction is only 1 to 2 $\%$ in MAR and RACMO2. This shows some limitations of ISBA-ES snow scheme for the representation of the retention capacity of the Antarctic snow pack. As a result, projected changes in surface run-off are not presented or discussed in section **??** due to limited ARPEGE skills for this variable in present climate and because of strong non-linearities often observed in changes in surface run-off in a warming climate.

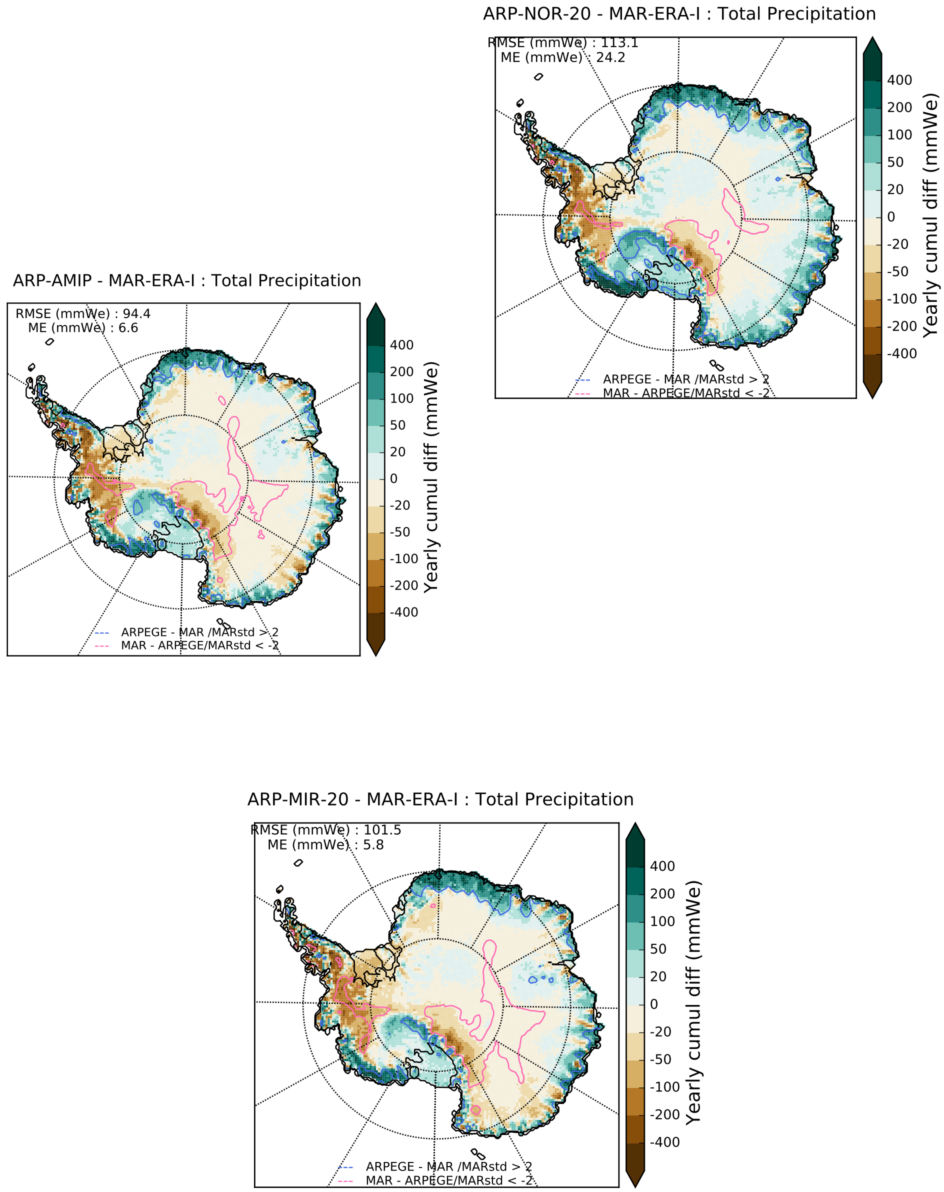
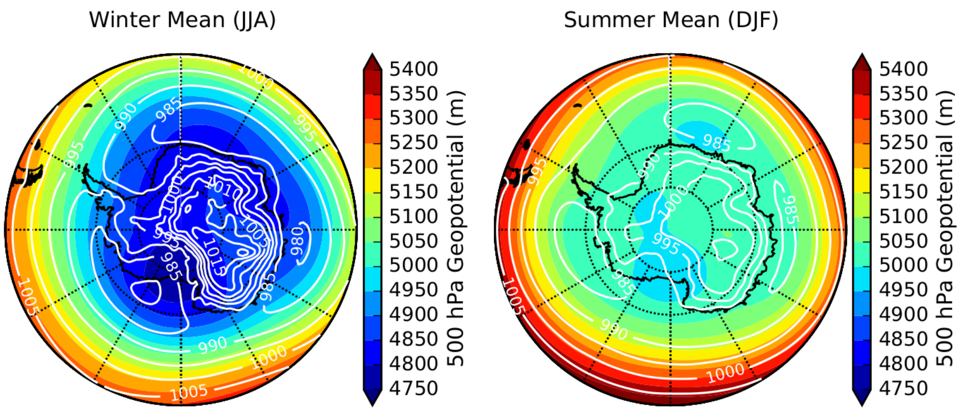
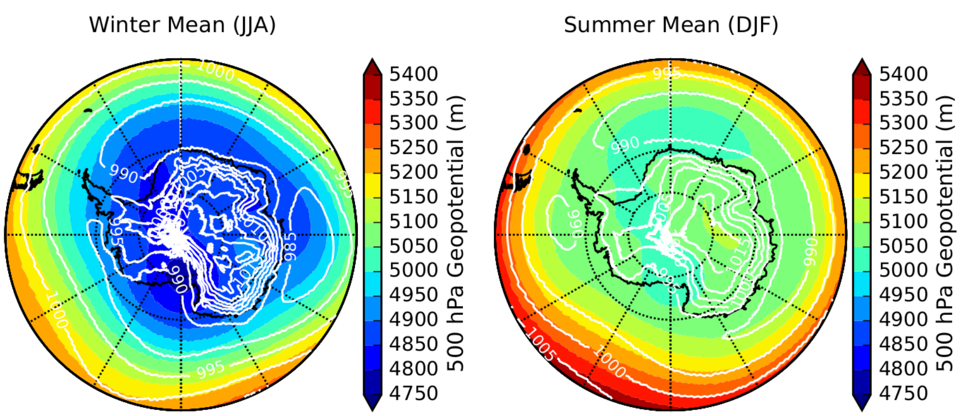



**Figure C1.** ARP-AMIP(*top*), ARP-NOR-20(*centre*) and ARP-MIR-20(*bottom*) minus MAR-ERA-I total precipitation. Pink and blue contour lines indicates where difference is larger than two MAR standard deviation (2-$\sigma$). RMSE and mean error with respect to MAR are indicated in the upper-left corner.

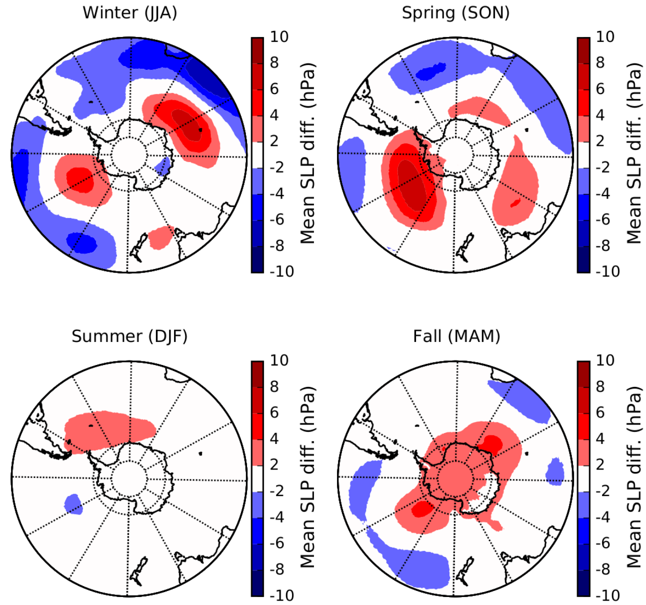



(a) ERA-Interim

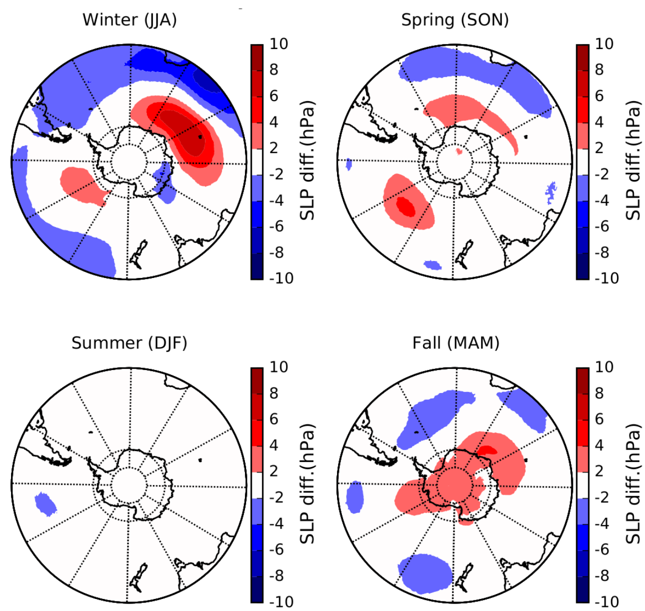



(b) ARP-AMIP

**Figure D1.** ERA-Interim (*top*) and ARP-AMIP(*right*) 500 hPa geopotentials (shadings) and sea-level pressures (white contour lines) in winter (*left*) and summer (*right*) for the reference period 1981-2010.

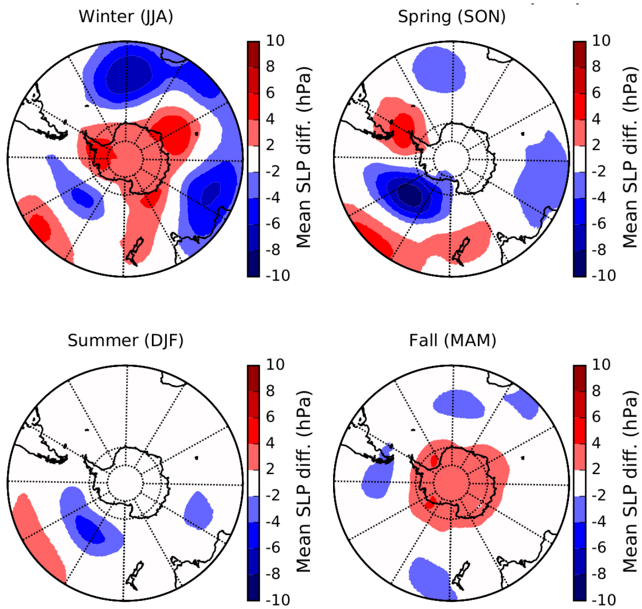



(a) ARP-NOR-20 - ARP-AMIP

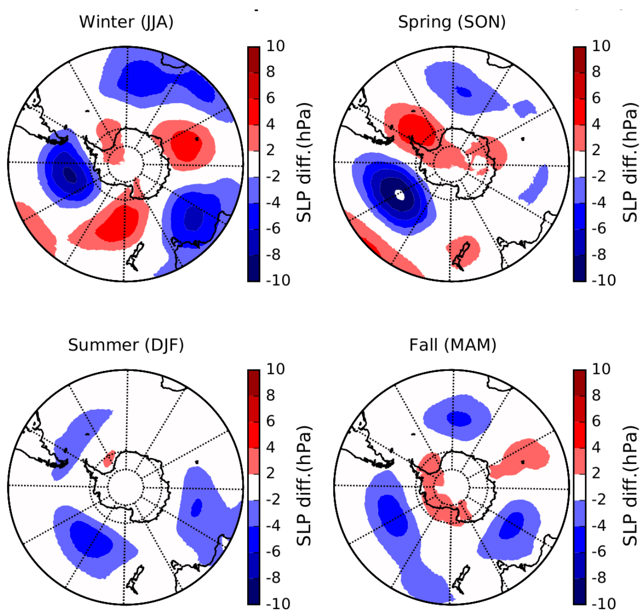



(b) ARP-NOR-21 - ARP-NOR-21-OC

**Figure D2.** Difference between ARP-NOR-20 and ARP-AMIP for seasonal sea-level pressure (*top*) and corresponding differences for late 21$^{st}$ century, ARP-NOR-21 minus ARP-NOR-21-OC




(a) ARP-MIR-20 - ARP-AMIP




(b) ARP-MIR-21 - ARP-MIR-21-OC

**Figure D3.** Difference between ARP-MIR-20 and ARP-AMIP for seasonal sea-level pressure (*top*) and corresponding differences for late $21^{st}$ century, ARP-MIR-21 minus ARP-MIR-21-OC

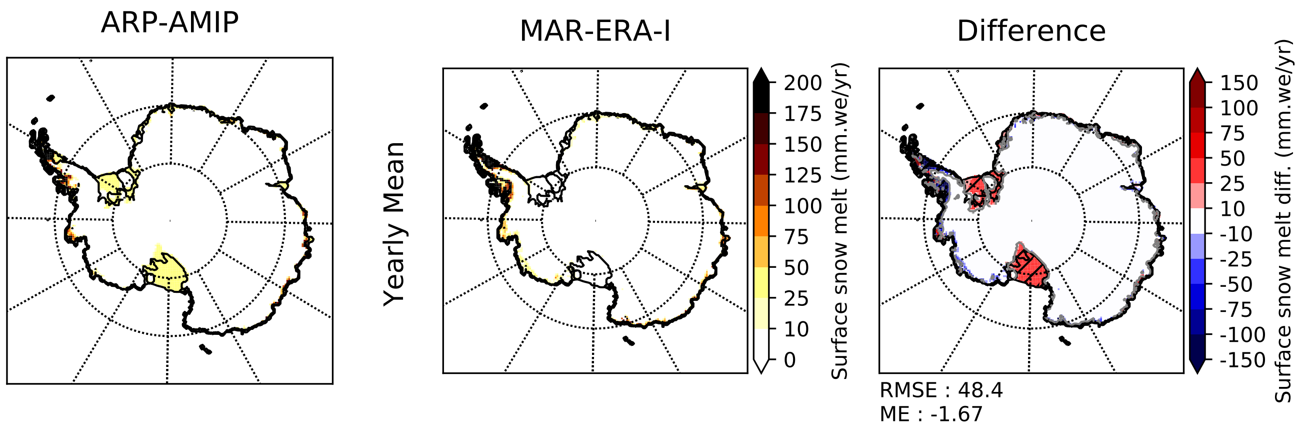



**Figure D4.** Yearly mean surface snowmelt (mm.we $yr^{-1}$ ) in ARP-AMIP (left), MAR-ERA-I (centre) and differences between the two models (right). Grey-contoured, hashed areas indicate where the difference is larger than 1 MAR standard deviation.

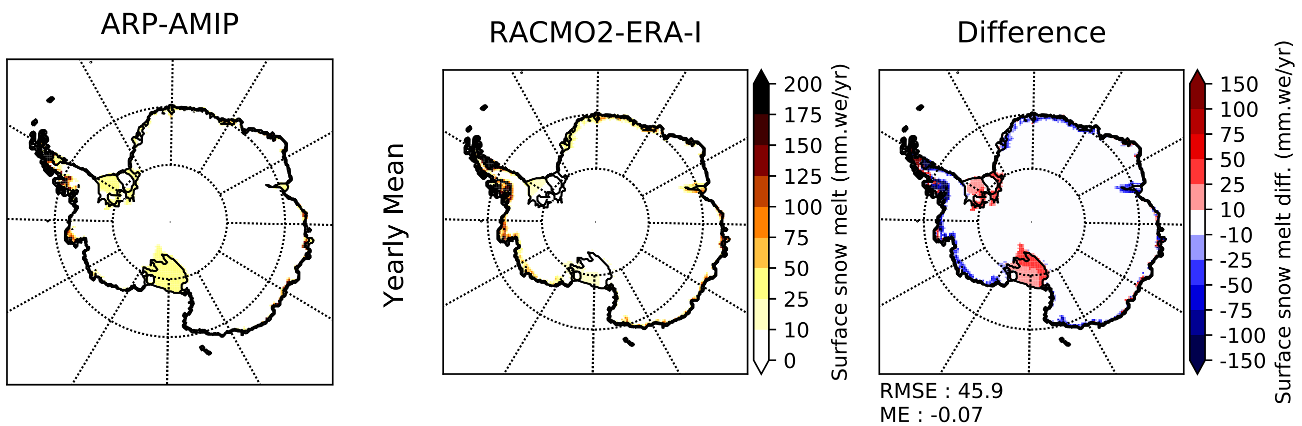



**Figure D5.** Yearly mean surface snowmelt (mm.we $yr^{-1}$ ) in ARP-AMIP (left), RACMO2-ERA-I (centre) and differences between the two models (right).