“**Significant additional Antarctic warming in atmospheric bias-corrected ARPEGE projections”** by J. Beaumet, M. Déqué, G. Krinner, C. Agosta, A. Alias & V. Favier

Interactive comment on “Significant additional Antarctic warming in atmospheric bias-corrected ARPEGE projections” by Julien Beaumet et al.

Anonymous Referee #2

With great interest I have read this manuscript which is generally well written. I do not see the need summarize the content of the manuscript. After reading the manuscript and collecting my comments, I’ve read the first review. I had also caught my attention that the discussion of tendency-corrected projection is less in depth as the discussion of the historical period. I know, verifying a projection is much more complicated as we do not know the future.

The approach proposed here assumes stationary of the model biases while the atmospheric mean state is changing due to anthropogenic forcings. It would be good if the authors provide more detail on the added/removed energy, moisture and momentum and how this relates to the total global energy, moisture and momentum budget. If the local/total tendency correction is significant compared to the local/total energy/moisture budget, this reduces the reliability of projections, as a different mean state would likely need a different mean tendency correction.

Author response : We thank the reviewer for their positive comments and constructive feedback on the manuscript. The first reviewer had similar concerns and we made a detailed answer, so we only briefly summarize our response to this question here in two points :

First, we will investigate the typical values of the added/removed energy, moisture and momentum associated with the typical values of the correction terms. Unfortunately, typical tendencies associated with the radiative scheme or the dynamics in our ARPEGE simulations were not saved in the output, but will take those typical values in inter-model studies from the literature (e.g., Cesana et al., 2019). Results of this comparaison will be shown in the final answer, and possibly added to the supplementary materials of the paper.

Second, we argue that the results from Krinner and Flaner (2019) and Krinner et al., (2020) are two strong arguments in favour of a reasonably preserved validity of the tendency correction terms built in present-day climate until at least the end of the current century even in the case of an abrupt 4xCO_2 scenario. The first study showed that the biases of each climate (assessed through its departure from the ensemble mean in future projection) is stationary through time, at least until the end of the current century. Each model can actually be easily identified automatically by its bias pattern (departure from the ensemble mean) in present-day and abrupt 4xC02 scenario.

The second study showed that a majority of the added-value of the tendency correction is preserved at the end of the 21st century using the perfect model test framework and three different

AGCM, their respective CGMCS and RCP8.5 projection as “pseudo-reality”. In their result, not only most of the improvement of the mean state is preserved throughout the 21st century, but so it is for interannual to synoptic time scale variability.

Other significant comments:

The title needs to be revised as it is not self-evident on with respect to what the additional warming has been observed.
Authors : Ok, we add “with respect to control projections” at the end of the title in order to make it more explicit.

I would propose to merge section 4.1 with 3.1 as 4.1 is an extended evaluation of discussion of the Present Climate, and hence the continuation of 3.1. It would connect
3.2 and 4.2 as well.

Authors : We agree with the reviewer, and we will reorganize and merge section 3.1 on the results of representation of present day climate and the discussion of these results (4.1) and do the same for section 3.2 and 4.2 (future climate). This will improve the readability of the paper and allow us to delete some repetition.

The discussion of SMB and precipitation (section 3.1.4) can be more clear, I propose to separate the discussion and figures concerning of precipitation and SMB. I would propose to dedicate section 3.1.4 on precipitation only, discussing the differences between ARP-AMIP-AC, ARP-AMIP, MAR and RACMO as is done now. Given the substantial differences between ARP-AMIP-AC and MAR (and RACMO), I would like to see figures of at least also the modelled precipitation (thus not a difference plot) of ARP-AMIP-AC and (MAR and/or RACMO). Possibly the new Figure 5 can combine these 2/3 precipitation plots with the old figures 5a, 6 and 7a,b. It would be good for the text, for example, as figures 5a and 7b are close/next to each other so that they can be compared easily. It might be worth considering reorganising P13L3 to P13L22 so that it becomes easier to read and grasp. Furthermore, anyone should be aware that MAR and RACMO2 are not the real truth of the precipitation, so in the discussion here the authors could take that into account. Hence, take the assessment of Agosta & van Wessem on the performance of their models against observations across the continent into account when MAR and RACMO2 disagree. In 3.1.5 (or at the end of 3.1.4 if 3.1.5 would become too short), the other SMB components and the SMB is discussed, e.g. Figure 5b,c.

Authors : Once again, we agree with the reviewer and we will separate the presentation of the result between precipitation and SMB, with a focus on precipitation as the improvement in the representation of precipitation distribution over coastal areas is the most interesting result. We will reorganize the figures and associated comments on precipitation, putting the plots for ARP-AMIP-AC, ARP-AMIP, MAR and RACMO and the associated differences in one figure, which will indeed facilitate the reading and comprehension of the paper. We acknowledge that MAR and RACMO2 are not the truth and will take into account the results of the comparison with observation in Agosta & van Wessem in our discussion. Besides, we compared precipitation from ARPEGE historical simulation with those from the CloudSAT climatology (Palerme et al., 2014). Even though this comparison has very limited validity (only 4 years available for CloudSAT), we can see an overall increased agreement in ARP-AMIP-AC with respect to ARP-AMIP in many coastal areas and an overall reduction in RMSE statistic (see Fig.R2 below). We will consider adding these figures to the supplementary materials of the paper.

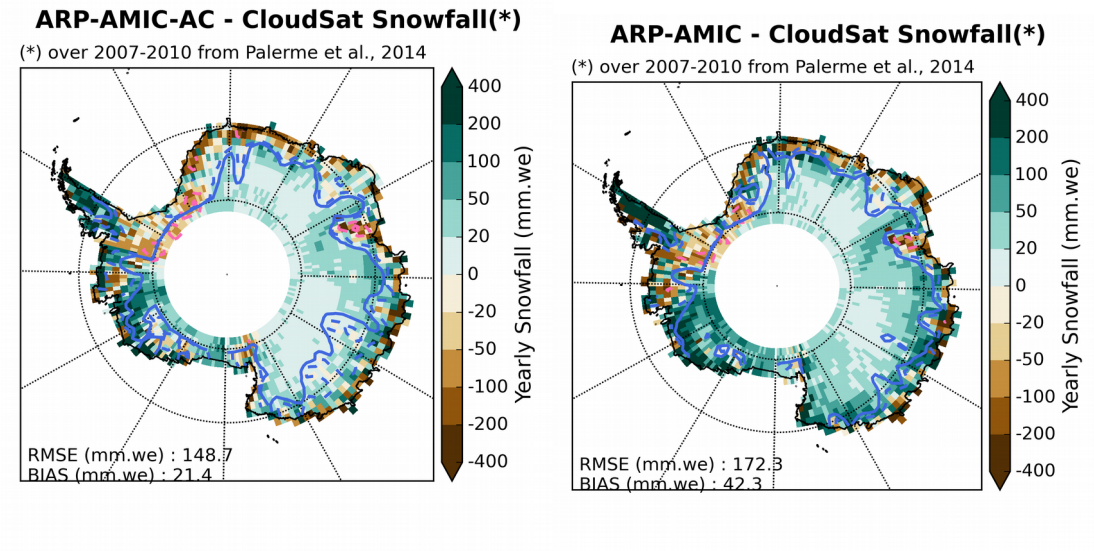

Fig. R2 : ARP-AMIP-AC (left) and ARP-AMIP (right) snowfall (mm.we) difference with CloudSAT over the 2007-2010 period. RMSE and bias statistics are shown in the bottom right of the subfigure.

It would be good to connect the dots: too high surface temperatures (-> too high LW emission?), too strong exchange in the ABL, too high sublimation. Of course, if these dots connect in your view. (If not, please argue why so in the reply to the review).

Authors : We agree with the reviewer and think indeed that ARPEGE warm biases near the surface, together with the inadequacy of its boundary layer parametrization for a correct modelling of very stable boundary layer, causes the model to overestimate exchanges and turbulent mixing in the ABL and therefore surface sublimation. We will connect these dots in the text.

Other textual comments:
P1L16: What's dramatically? It has an emotional load this sentence not necessarily needs. I'll prefer it to be changed into something like considerably.
Authors : Ok, we changed "dramatically" for "substantially".

P1L20: "Fails to compensate" I'll prefer a more neutral expression. Less drama, please.
Authors : Ok, we modified "fails to compensate" by "is now largely overtaken by the"

P2L2: Compared to the "dramatically" at P1L16, this "dramatically" is justified. . .

P2L2: As you are going to argue this SMB increase per K is higher, I would formulate this sentence slightly different as it now reads as a closed case. E.g. ". . ., existing studies align on an increase of the SMB of 5+1 % K-1 (. . ."

Authors : We rephrase this sentence in the following way : "..., existing studies agree on the fact that it is expected to increase at a rate of 5+-1 % K-1(..."

P2L5: As models seems to align, which uncertainties are missed? Please expand.
Similarly, please rephrase "In this regard" as it may seem to refer back to the SMB - Temp relation, but you do refer to the potential mass loss of the AIS.

Authors : We change 'In this regard' for 'therefore' : "Therefore, it is crucial to reduce the uncertainties on Antarctic regional warming and changes in SMB, in order to assess the SMB negative contribution…" and we add the following sentence thereafter : "Main source of uncertainties arise from poorly represented sea surface conditions and changes in atmospheric general circulation over southern high latitudes in most climate models (Turner et al., 2013, Bracegirdle et al., 2013}."

P3L27: I would like to see a figure of the grid. A reference "(see <paper>, Fig. <#>)" will do.

Authors : Two figures representing the grid spacing and the topography over Antarctica for the configuration used in this study are can be found in J. Beaumet Ph.D dissertation

(ttps://tel.archives-ouvertes.fr/tel-02145468). However, for convenience this figure is presented below and we will consider adding it to the supplementary material of the paper.

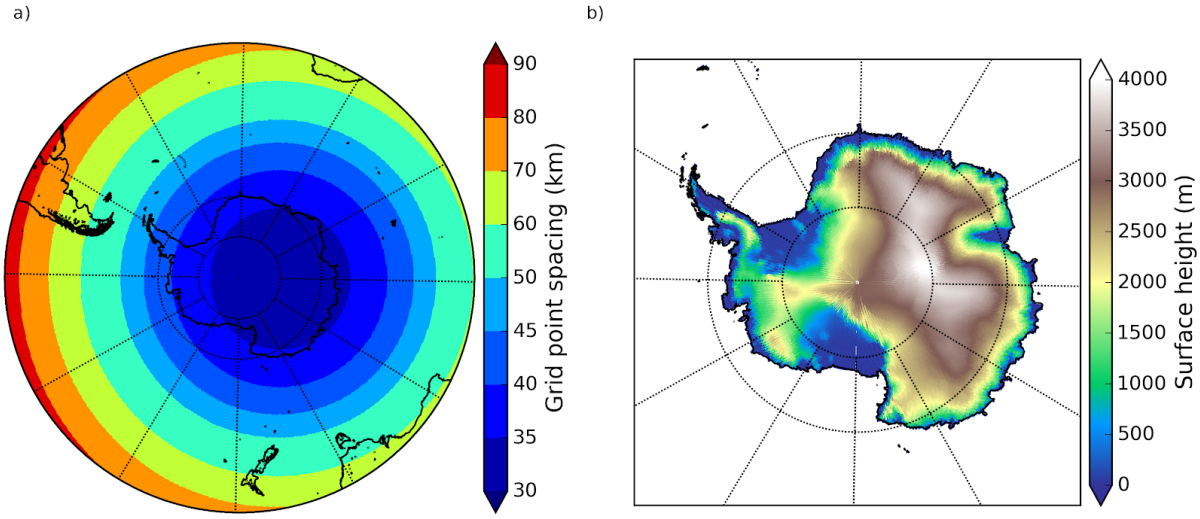

Fig R3 : Grid point spacing (a, in km) and surface height (b, in m) for the ARPEGE model grid configuration used in this study. The truncation is T255, the stretching factor is 2.5 and the stretching pole is placed at 80°S, 90°E.

P4L3: Please state clear that GELATO is only needed for a correct SEB over sea ice.
Authors : Ok, this is now clarified in the text.

P5L7: Brackets is not the most elegant option. “. . .conditions, e.g. greenhouse gas concentrations, and . . .”
Authors : Ok, modified in the text.

P5L32: I can imagine arguments to use ERA-Interim here even though it is now superseded by ERA5 for about a year. Nevertheless, provide these/this argument here; briefly of course.

Authors : This study was designed and realized more than two years ago at a time when ERA5 was not available. Considering that we use ERA-Interim mostly to evaluate mean state (and variability) of large-scale atmospheric circulation, we would not expect significantly different results using ERA5 instead of ERA-Interim. Using ERA5 instead of ERA-Interim to calibrate the correction

terms, we might expect a slight improvement of the representation of the humidity field (and therefore possibly surface climate and precipitation) and of some finer detail of the atmospheric circulation due to ERA5 finer resolution, but this would certainly not change significantly the correction of the large-scale atmospheric circulation and the resulting difference in projected climate change which is the main result of the paper.

P8, T2: Give a reference to Eq. (4) for \Delta_r E.
Authors : Ok, this was added in the text.

P9, F1: add in the caption that Mean SLP is shown.
Authors : It was at the end of the caption, but we moved it at the beginning of the caption to make it hopefully clearer.

P7L7: not the uncorrected ARP-AMIP run but the mean SLP of this run is low biased.
Authors : Ok modified in the text.

P7L20: Is there a specific process-based reason for the remaining warm bias in winter 200 hPa, near surface pressure bias over Antarctica and surface temperature errors (Sec 3.1.3)?. Is it related to radiative problems (too much LW TOA emission, and hence too strong meridional circulation) or too strong horizontal (stratosphere) and vertical (ABL) mixing? If studied before, a reference and short note will do.

Authors : For the bias on near surface pressure around the Antarctic seas in winter, we copy-paste for convenience our response to reviewer#1 who asked the same question :
“This positive bias in the seas surrounding Antarctica, even though substantially reduced, especially in the Amundsen Sea sector, remains mostly in winter and spring. During these seasons these areas witness the formation of rapidly developing and evolving meso-cyclons (polar lows). It is therefore likely that the model, even in the bias-corrected simulation, fails to fully capture the formation of these polar lows. Here are two possible explanation :

- The characteristic time of formation of these cyclones is much smaller than the characteristic time of other larger scale cyclones. Therefore, the relaxation time of 72h used in the first nudged simulation towards climate reanalyses that is used to derive correction terms might be too wide to retrieve the right values of correction terms that should be applied to correct for the model deficiencies in simulating these phenomena.
- Katabatic winds flowing from the ice-sheet towards the coast play a key role in the formation of these meso-cyclones. Besides, the formation of a very stable, cold boundary layer at the surface of the ice-sheet plays a key role in the formation of the katabatic winds.

In this study and in the previous one (Beaumet et al., 2019b), we have seen that the version of ARPEGE used in these studies has some deficiencies in capturing the formation of very stable boundary layer at the surface of the ice-sheet in winter (similarly to many climate models), which likely impacts the capacity of the model to reproduce correctly the katabatic winds regime around Antarctica and latter the formation of meso-cyclones over near-by seas. We remind that variables in the boundary layer (<100 m) are not corrected at all in the bias-corrected simulations.

We will briefly mention these hypotheses in our discussion of the remaining biases in the corrected historical simulation.

Regarding mid (500 hPa) and upper-tropospheric temperatures (200 hPa), we noted a significant cold bias in the uncorrected simulation ARP-AMIP in the mid-latitudes and in the Tropics, while there was no bias over the South Pole (only a slight warm bias in Spring). Consistently, the correction terms for temperature at these levels are strongly positive in the mid-latitudes and the tropics, while they are closer to zero near the South Pole (see Fig. R4). Possibly, the impact of the strong warming imposed at the mid and low latitudes results also in a warming at the polar latitudes through the re-adjustment of the geostrophic equilibrium which results in the apparition of this warm bias in the upper-troposphere over the Pole in winter and spring.

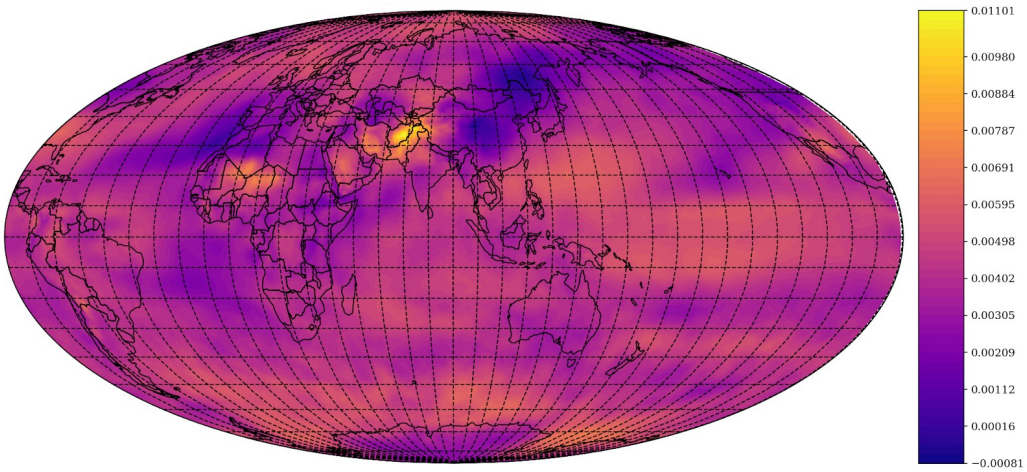

Fig R4 : Mean January empirical correction term (in °K/900s) on the temperature tendency at level 64 (~500 hPa) in ARPEGE bias-corrected experiment.

Concerning, the surface warm bias over the center of the Antarctic ice-sheet, we agree with some of the reviewer hypothesis: the temperatures in the uncorrected simulation were already warm-biased in these area as a result of too strong vertical mixing (ABL), which is also the cause of excessive surface sublimation. We suspect that the bias correction has caused the suppression of

other biases associated with the atmospheric general circulation that were slightly compensating for these ABL biases in the uncorrected simulation.

P8L11: If I read P6L6 correctly, these BMUs are derived using ARP-AMIP-AC data too.
Is there a reason that typical states of ARP-AMIP-AC are nonetheless missed?

Authors : The reviewer read correctly. However, the BMUs were derived using also two other ARPEGE historical simulations. Since the BMUs are limited to 20, we think that if some of the ARP-AMIP-AC typical states are non frequently represented in the other simulation and reanalyses, they will not appear in the 20 more representative units automatically selected by the algorithm.

P14 F5: 1) The numerous overlays make the graphs hard to assess 2) There is a typo in the caption ".W.e" 3) I don't see the necessity to clip precipitation (Fig. 5a) to the continent only. Please show ocean values as well (without changing the plotted region). That request involves also figures 6, 7 and 10.

Authors : We corrected the typo in the caption. This figure will be largely modified following your recommendations above. For precipitation, we will show ocean values as well.

P17 F8: it would be good if the legend would make clear too which lines belong to historical simulations and which to projections. Now it doesn't.

Authors : We will modify the legend and possibly the lines characteristics so that it appears clearly.

P17L7: a larger displacement than with? (NorESM1-M likely).

Authors : Indeed, modified in the text.

P17/18 S3.2.2: This section is rather descriptive. What is driving the regional warming?
Reduced LW TOA emission, better meridional exchange, or unmodified global warming. And why is much of the southern ocean not warming? I don't think it's wrong/err,but I'm missing explanations even brief.

Authors : Krinner et al., (2014) showed that changes in surface condition of the Southern Ocean are the main drivers of regional warming in Antarctica. Their impact on warming is clearly higher than the one of changes in greenhouse gases concentration projected for the late 21st century. Other papers by T. Bracegirdle showed the impact of the retreat of sea-ice on projected changes in atmospheric circulation and therefore Antarctic warming. The Southern Ocean is indeed warming but the colour scale used to fit locally extremely high warming rates in the ARP-MIR-xx simulations (high loss of sea-ice) hampers from appreciating the warming of the Southern Ocean in ARP-NOR simulations. The surface warming over the ocean surfaces is heavily constrained by the warming in the coupled GCMs from which surface ocean conditions are taken from. In these model projections, the summer warming of the Southern Ocean is respectively +1.8 K in MIROC-ESM and +0.4K in NorESM1-M (second lowest of the CMIP5 ensemble) at the end of the current century.

P19F9: The panels are really small, please blow them up by 50% at least. Grey lines needs to be searched with zoom. . .

Authors : Ok, we increased the panel size as much as possible.

P21F10: for ARP-MIR-21-AOC, changes are well over 75% for about half of Antarctica. Please adjust the scale so that is “colormap clipping” is largely removed.

Authors : Ok, the colour scale will be modified in order to better match with the values for ARP-MIR-21-AOC.

P21L4: Section. A is likely Appendix A.

Authors : Indeed, modified in the text.

P21L8: I personally don’t see the logic in trying strong tendency correction on boundary layer processes if you haven’t tried extending the current tendency correction on the boundary layer. Furthermore, it sounds logical to me that systematic errors in the boundary layer representation induce biases at 850 hPa even if this layer has tendency correction. Given that you now have an isolate region with biases (the ABL), retuning is now much more easy as indirectly induced global feedbacks of retuning can be removed by rerunning the tendency correction procedure on the retuned model.

Authors : We want to specify that the boundary layer processes (~lowest 100m) are not corrected at all, while the correction gradually increases from this level to a level corresponding to 850 hPa. We thank the reviewer for their suggestion on retuning, however this is first of all in conflict with the CNRM policy and this exercise would be quite complex and would involve a separate study and publication. Nevertheless, we will mention this possibility in the discussion (section 4.3) as this is a potentially interesting application of the bias-correction method.

P22L2: A reference to figure B1 (I presume) is missing. Make more clear in the text that you're comparing against MAR as I missed that on first sight. T2m temperature biases over land and ice sheets make only sense if the model topographies are (near) similar. An 100 m elevation difference gives a 0.5 to 0.8 K temperature difference, so the modelled biases over the smaller ice shelves and continent escarpment could potentially explain part of the biases. Of course, similar biases are observed over the larger ice shelves where topographic errors are unlikely. It would be good to add in the appendix a figure with local differences in the model orography along with Figure B1. If these orographic deviations are negligible, that should be stated clearly in the manuscript. Similarly, consider to add model and station elevations in Table B1.

Authors : We have clarified in the text that we compare against MAR and added a reference to figure B1. We have compared the differences in topography between ARPEGE and MAR for a case study on precipitation (as differences could be partially explained by differences in topography too) in Dronning Maud Land region and western East Antarctica in general (see figure below). The difference remains largely below 100 m even in coastal areas and rarely exceeds 200m, so it is unlikely to explain most of the temperature differences, especially over the ice-shelves or over the East Antarctic Plateau. Differences in topography might only be relevant for the Antarctic Peninsula. We will consider adding a similar figure to the supplementary material, while changing the region for whole Antarctica and contour lines for temperature instead of precipitation difference. We will consider adding model grid point and station elevation to Table B1, although we remind that we took into account this issue by correcting the model temperature using a 0.8K/100m gradient.

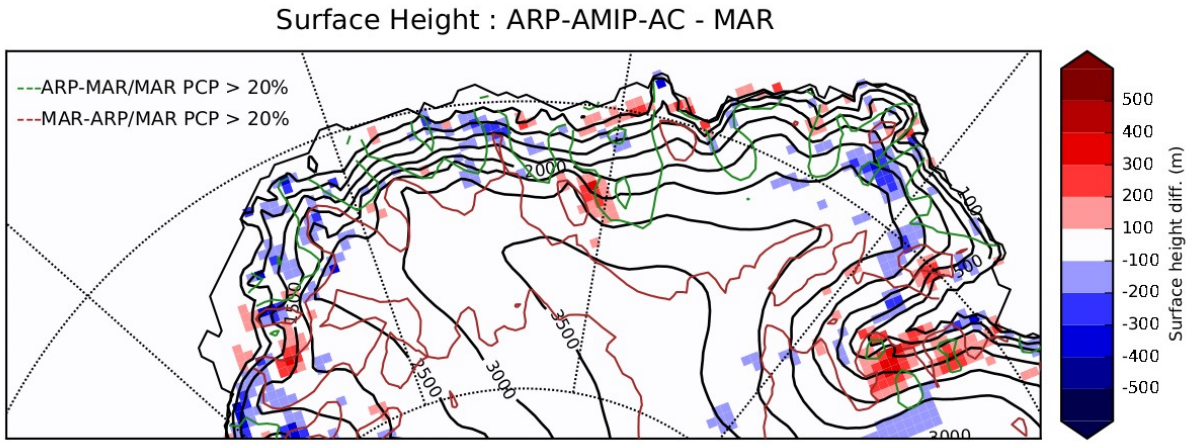

Fig. R5 : ARPEGE minus MAR model surface height (shading, in m) and ARP-AMIP-AC minus MAR-ERA-I relative precipitation difference (contour line, in %) for the Dronning Maud Land to Amery ice-shelf region.

P22L30: “Large discrepancies . . .” This is a very indirect way of saying that MAR and RACMO2 do not agree, right? Please formulate more direct to take away confusion. Furthermore, nice to hear that MAR and RACMO2 don’t agree, but what is the implica-
tion for this paper? Does ARP-AMIP align better with RACMO2?

Authors : Ok, we modified “discrepancies” for “disagreement”. The implication for this paper is that either MAR or RACMO2 (or maybe both) is likely a less robust reference for surface temperature in these areas than it is for the rest of Antarctica. We did not investigate for ARP-AMIP, but for ARP-AMIP-AC the warm bias in winter with respect to RACMO2 is much reduced over Ross Ice-shelf and almost nul over Ronne-Filchner ice-shelf. On the contrary, ARPEGE is much colder than RACMO2 over these ice-shelves in summer.

P23L27: The conclusions of this paper are slightly more nuanced than this. RACMO2 ignores horizontal transport of falling precipitation and subsequently misses evaporation of snow advected into dryer or warmer locations. If ARPEGE has also no prognostic precipitation, this error could be shared. However, the induced error by missing precipitation advection decreases for decreasing model resolution.

Authors : We modified this sentence in the following way “In this paper, it is argued that RACMO2 does not account for horizontal transport of falling precipitation and therefore misses some of the sublimation of snowfall..”. ARPEGE is at a better resolution than 40 kms over most of Antarctica, and better than 35 over most of East Antarctica, while MAR is at 35 kms and RACMO2 at 27 kms, if this error is shared between ARPEGE and RACMO2, we think it is likely to be in the same order of magnitude between both model.

P23L29: “. . . (15 min). Over the . . .” Add something like Furthermore/Finally to make clear that the following is not directly related to the “first Agosta 19 comments”.

Authors : Ok, modified in the text.

S4.2.1&4.2.2: It is good to add references to the figures that are discussed. Now the text is dry and requires the reader to have memorized all the graphs implicitly referenced. And, as discussed above, it is less thorough as the rest of the paper.

Authors : Ok, we will add references to the figures in these sections. As they will be modified and merged with section 3.2, they will be hopefully easier to go through.

Figure 1, 8, 9, A1, A2: The labels and legend text in these figures are too small.

Authors : Ok, we will modify the labels and legend in order to make the figures more comfortable to read.

Table B1 and B2: I do not see why you cannot merge these two tables into one table.
Authors : Indeed, we will merge these tables.