Dear Editor,

We would like to thank both reviewers for their relevant comments which have helped us to improve our manuscript.

Responses to each individual reviewer have been posted on TCD and can be also found hereafter.

The main changes compared to the original version are:

-the addition of Sébastien Doutreloup (ULiège) and Coraline Wyard (Uliège) as co-author to thank them for the constructive discussions and their help with the new figures presented in the revised version of our manuscript.
-the addition of a discussion about the biases of MAR at a 50 km resolution compared to MAR results at 35 km as well as new figures in supplementary material as requested by the reviewer #1 in order to assess the uncertainty related to the coarser resolution.
-a more detailed analysis of processes responsible of the increase in precipitation inland in the sensitivity experiments with a colder ocean as requested by the reviewer#2.

Best regards,
Christoph K. on behalf of the co-authors

We first would like to thank the reviewer #1 for his constructive comments which will help to improve our manuscript.

General comments

1. At several instances, the authors acknowledge that a horizontal resolution of 50 km is inadequate to accurately resolve orographic--forced and local precipitation at the AIS rough margins and over the Antarctic Peninsula (AP): e.g. P7 L17--18, P9 L2--4, P11 L10--13. Although the authors are fair on this point, and justify the use of a coarse spatial resolution as a tradeoff between manageable computational time and the number of simulation carried out, while still resolving the AIS SMB reasonably well (see Fig. 2), they fail at estimating the associated biases and uncertainties. This is an important concern as most SMB anomalies are found in marginal (steep) regions where the authors suggest potentially large resolution-- driven precipitation biases.

   To address this issue, the authors should present a 2D comparison between the 50 km reference run (this study) and the state--of--the--art 35 km run (Agosta et al., 2018), both forced by ERA--Interim (1979--2015). This would highlight the spatial distribution of precipitation/SMB biases and point out where large uncertainties, in both the reference run and sensitivity experiments, are likely to be found. This additional analysis would help the reader interpreting the significance of the SMB anomalies obtained in the sensitivity experiments; in other words, whether these SMB anomalies are larger/smaller than the local difference between the two MAR runs at 50 km and 35 km resolution.

2. As for comparison, the authors should also consider including a second scatterplot in Fig. 2 for the 35 km run, and list the associated statistics. Integrated values and uncertainty (standard deviation) derived from the 35 km run should also be listed in Table 1.

3. An additional Section 6 “Limitations” could discuss in more detail differences in SMB between the 50 km and 35 km simulations as well as related model limitations, i.e. unresolved or not well resolved foehn effect and orographic--enhancement affecting precipitation e.g. over the AP.

(Response to general comments 1 to 3)
As highlighted by the reviewer, the influence of the resolution is not discussed in our paper even if we use a coarser spatial resolution than the previous study using MAR (Agosta *et al.*, 2018). However, we think that discussing the sensitivity of the Antarctic simulated SMB to the (spatial) resolution used in the model is beyond the scope of this study. Furthermore, our methods for comparing the modeled and observed SMB will not enable a fair comparison between the statistics for 50km and 35km simulations as the number of pixels used for the comparison differs and becomes very small for the 35km resolution grid if our criterion of observations (P7L8) by pixel is kept (i.e, more than one observation by pixel).

Since the sensitivity of the Antarctic SMB to the horizontal resolution is an interesting matter of debate and still an unanswered question, we plan to tackle this specific topic in a brief communication that will be soon submitted to TCD (Kittel *et al.,* in preparation) rather than including this in a supplementary section of the current paper.

To address the reviewer’s comment about uncertainties of our results, we propose to present in supplementary materials the following 2D comparison between our 50 km reference simulations (MAR50 hereafter) and the Agosta *et al.* (2018)’s 35 km results (MAR35 hereafter) and a map illustrating the biases of MAR forced by ERA-Interim at 50 km compared to the SMB observations.

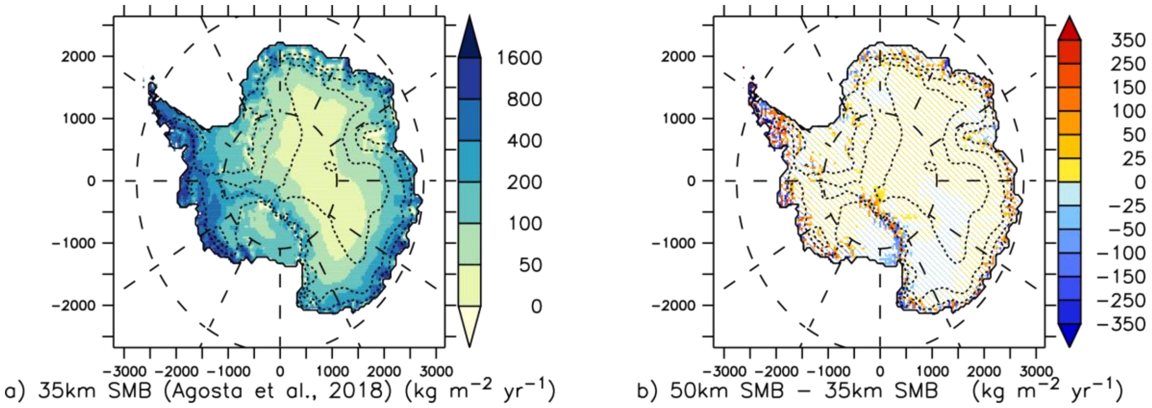

Figure 1. a: Mean SMB simulated by MAR over 1979 – 2015 from Agosta et al.(2018). b: Comparison between the MAR SMB at a 35 km resolution from Agosta et al. (2018) and the MAR SMB at a 50 km resolution (this study). Units are kg m^{-2} yr^{-1}. Non-significant anomalies (i.e., lower than the interannual variability) are hatched.

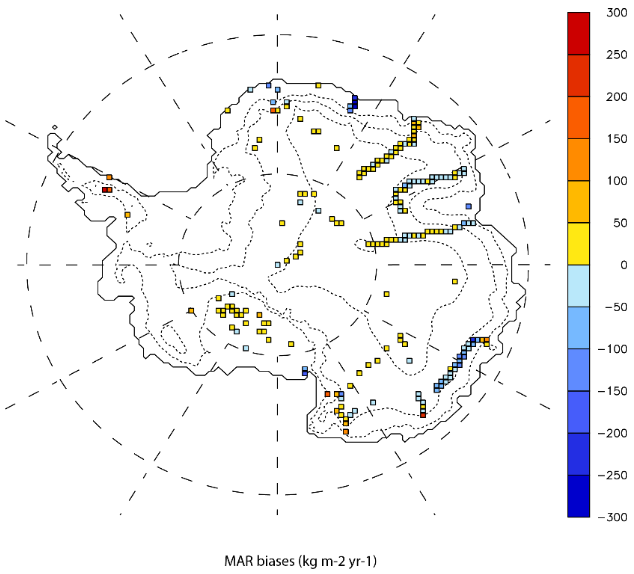

Figure 2. Comparison between MAR SMB and observed SMB from the GLACIOCLIM-SAMBA database (Favier et al., 2013) for 1950 – 2015. Units are kg m^{-2} yr^{-1}.

Figure 1 illustrates the SMB anomaly between MAR50 and MAR35. The largest anomalies are found over the Antarctic Peninsula and areas with a high orography spatial variability such as the Transantarctic Mountains. The significant anomalies are however smaller than the significant SMB anomalies due to changes in SSC from our study (except for the nearest pixels to the ocean where the MAR50 and MAR35 ice masks differ). Furthermore, they are mainly smaller than the SMB anomalies between MAR35 and RACMO2 presented in Agosta et al. (2018). Finally, it should also be noted that MAR50 biases compared to the observations are smaller than the SMB anomalies due to SSC changes (Fig. 2).

Besides adding Figure 1 and Figure 2 in supplementary materials, we also propose to modify the Section 3 "Evaluation against SMB observations" with a spatial analysis of MAR50 biases compared to the SMB observations as follows:

P7L11-18 *The high value of the correlation coefficient (r=0.93) between observed and modelled SMB values shows that MAR correctly represents the Antarctic SMB spatial variability at 50 km resolution over the 1979 – 2015 period (Fig. 2). Except over the Dronning Maud Land, the margins of the Amery ice shelf and a transect in the Wilkes Land, MAR overestimates the SMB (locally up to a factor of 5, Fig. S2).*

As also shown by Franco et al. (2012) over the Greenland ice sheet, these biases could partially arise from the coarse resolution used here (50 km) which induces a topography smoothed at the ice sheet margins. This leads to an *unsatisfactory representation of the topographic barrier effect allowing the precipitation systems modelled by MAR to penetrate too far inland.*

In order to estimate the biases and the uncertainty related to our resolution, the reference SMB of this study was briefly compared to the SMB at 35 km resolution from Agosta et al. (2018) (Fig. S3). This comparison also shows an SMB overestimation in the reference run compared to SMB results at a higher resolution, although this overestimation appears to be non-significant. The largest anomalies can be found over the Antarctic Peninsula and areas with a high orography spatial variability such as the Transantarctic Mountains. The coarse 50 km resolution used here leads to artificially overestimated precipitation on the windward sides of orographic barriers. This is notably the case over the Filchner-Ronne and Ross ice shelves where the Amundsen Sea Low generates a return flow. However it should be noted that the SMB anomalies of our 50 km reference run compared to both 35 km results (Agosta et al. 2018) and observations are smaller than the SMB anomalies due to SSC perturbations presented in Section 4.

4. I would strongly advise to replace Fig. 3 by Fig. S2 in the main manuscript, as it displays inefficient to move back and forth to the supplementary material to visualize and compare results from experiments not shown in the main manuscript.

Thank you for the advice, we will replace Fig. 3 by Fig. S2.

Substantive Comments

Section 2.3.4: P5 L1-2: Here, I understand that monthly SSC (1979--2005) derived from CMIP5 ensemble average and two extreme members, as well as from ERA--Interim are interpolated to the MAR grid (50x50 km) using an inverse distance weighting method based on the four CMIP5 models/ERA--Interim cells nearest to the current MAR one. If so, please reformulate accordingly.

L5: This is confusing, are the authors calculating monthly mean SIC--SST from CMIP5/ERA--Interim for 1979--2005 (12 values) or an annual mean (1 value). I understand that monthly SIC and SST anomalies are used, please clarify.

We calculated monthly mean SIC and SST anomalies between CMIP5 and ERA-Interim so as to take into account open water areas when computing the monthly SST anomalies and to not introduce additional temperature biases: monthly SST anomalies were computed only if SIC from both CMIP5 ensemble average and ERA-Interim are less than 50%. Monthly values of SIC and SST anomalies are then averaged to obtain an annual anomaly value, supposed to represent a constant bias.

We suggest to reformulate P5 L1-5:

For that purpose, we have determined a perturbation whose magnitude is representative of the CMIP5 ensemble bias. Monthly SSC over 1979–2005 from all the CMIP5 models (using the historical scenario), as well as from ERA-Interim were interpolated on the MAR grid (50 km x50 km) using an inverse-distance weighted method based on the four CMIP5 models/ERA-Interim grid cells nearest to the current MAR one. We then computed the CMIP5 ensemble average from the interpolated CMIP5 monthly SSC. Firstly, to not introduce additional temperature biases, monthly SST anomalies between CMIP5 and ERA-Interim were computed only if the SIC from both the CMIP5 ensemble average and ERA-Interim are less than 50%. Secondly, we average the monthly anomalies to obtain a mean anomaly, supposed to represent a constant bias over time.

L6--10: Are the new 6--hourly SST--SIC calculated as the sum of 6--hourly ERA-- Interim (i.e. for a specific day of a certain month) and the corresponding monthly anomaly in SST--SIC from CMIP5 models? If so, please reformulate.

Yes, it is. We propose to reformulate P5l6-10 as follows:

New 6-hourly forcing SST are calculated as the sum of the 6 hourly ERA-Interim (i.e., for a specific day of a certain month) and the corresponding monthly anomaly in SST from CMIP5 ensemble average (Fig. 1b), hereafter referred to as SST(CMIP5) experiment. In the same way, we define SIC(CMIP5) experiments in which SIC anomalies (Fig. 1e) from the CMIP5 ensemble average are added to the 6-hourly ERA-Interim SIC.

P7 L17--18: This is an important caveat that should be addressed in an additional section "Limitations". A 2D map comparison between 50 km and 35 km simulations could help the reader understanding where large uncertainties are likely to be found at 50 km, see also general comments #1 and #3.
See our answer to General comments 1-3.

Point Comments

P1 L10: The authors refer to "warm SSC" or "cold SSC" several times across the manuscript. While it may sound obvious that warm (resp. cold) SSC represents combined low SIC and high SST (resp. high SIC and low SST), this should be explicitly stated in the manuscript, e.g. in Section 2.3.3 or more generally in Section 2.3.

Warm and cold SSC are explicitly stated in the manuscript P14,L5 (Section Conclusion). We will define warm (i.e., high SST and low SIC) and cold (i.e., low SST and high SIC) SSC by modifying the abstract (P1,L10) and the first reference to "warm" or "cold " SSC (P6,L5) according to

P1,L10 *Results show increased (resp. decreased) precipitation due to perturbations inducing warmer, i.e. higher SST and lower SIC (resp. colder, i.e. lower SST and higher SIC) SSC than ERA-Interim significantly altering the SMB of coastal areas, as precipitation is mainly related to cyclones that do not penetrate far into the continent*

And

P6,L5 *Following the same method, we perform combined experiments for two selected CMIP5 models, namely NorESM1-ME (Bentsen et al., 2012) and GISS-E2-H (Schmidt et al., 2014), respectively representative of a colder (i.e., lower SST and higher SIC) and warmer (i.e, higher SST and lower SIC) SSC than ERA-Interim as shown in (Agosta et al., 2015).*

P2 L29--30: What do the authors mean by "neither feedbacks involving sea ice and ocean"?
We suggest to delete this part of the sentence as it was redundant with the beginning *"This means that we do not consider feedbacks on the general circulation associated to sea ice removal (e.g., Bromwich et al., 1998; Krinner et al., 2014)"*

P3 L18: Could the authors briefly elaborate on the reasons why the drifting snow module is switched off?
Similarly to Agosta et al. (2018), we decided to switch off the drifting snow as the new version of this module is still under evaluation against satellite and ground-based observations over the whole Antarctic ice sheet. We suggest to add this reason in our manuscript P3L1*8*:

Although MAR includes a drifting snow module (Gallée et al., 2001), this module has been switched off similarly to Agosta et al. (2018) as the new version of this module is still under evaluation against satellite and ground-based observations.

L25: Could the authors define OSTIA?
The Operational SST and Sea Ice Analysis (OSTIA) is a daily global SST analysis produced at a 0.05° resolution (Stark *et al.,* 2007; Donlon *et al*., 2012). We suggest to change the text P3L25 as follows:

It is worth noting that ERA-Interim uses the SST and SIC values from ERA-40, which are based on monthly and weekly ocean forcing fields (Fiorino, 2004), until January 2002. Afterwards, a switch was made with the daily operational NCEP product and since 2009 with the Operational SST and Sea Ice Analysis (OSTIA). The latter is a daily global SST analysis product at a 0.05° resolution (Stark et al., 2007; Donlon et al., 2012)

L31: I guess the authors mean "[…] from a previous reference simulation", or is the initialization based on multiple simulations, please clarify.
Indeed, we use a snowpack from a previous reference simulation. Thank you for the correction.

P4 L2: Could the authors mention the original resolution of their DEM?
The original resolution of the DEM is 1km. We add it P4L2:
The Antarctic topography is based on the 1-km resolution DEM Bedmap2 from Fretwell et al. (2013).

P5 L7: I guess the authors mean (Fig. 1b). **L8:** (Fig. 1e).

Yes, thank you. (See our answer to the first point comment where we already corrected it).

P6 L3: Could the authors estimate by how many ºC on average these two extreme CMIP5 members are "colder" or "warmer" than ERA--Interim.
The mean temperature anomaly as well as the mean SIC anomaly is listed in Table 1. We will specify it in our manuscript P6L3:

Table 1 compares SSC perturbations to the reference SSC for June-July-August (JJA) and December-January-February (DJF) SST and sea ice area (SIA). The mean SST and SIC anomalies of CMIP5 ensemble average, NorESM1-ME, and GISS-E2-H are also listed in Table 1.

L4--5: I guess the authors mean: (Fig. 1a,d) and (Fig. 1c,f.)
Yes, Thanks. We modify P6L4-5 accordingly:
These experiments are hereafter called SST/SIC(NorESM1-ME) (Fig. 1a,d) and 5 SST/SIC(GISS-E2-H) (Fig. 1c,f).

P7 L4: Could the authors mention how many measurements were discarded from the evaluation?
The original SMB data base from Favier *et al.* (2013) contains 3236 observations among which, as indicated p7,L3, 206 observations do not fit our selection criterions (i.e, covering more than 8 years if the observations interval is not included in the period 1979-2015).
P9 L2-7: Modeling limitations in the AP could be discussed in an additional "Limitations" section, see general comment #3.
As we have dedicated a full paper to the influence of the resolutions and strengthened the discussion on the biases related to resolution (see answer to General comments 1-3), we think that an additional "Limitations" section for discussing only the limitations over the AP is not necessary anymore.

P10 L11--12: Do the authors mean that the SMB from SIC(CMIP5) does not significantly differ from the reference, both spatially and integrated over the whole AIS? If so, please reformulate.
Yes, it is. We reformulate P10-L11-12:
Finally, the mean SMB from SIC(CMIP5) does not significantly differ from the reference SMB, both spatially (Fig. 3j) and integrated over the whole AIS (Table 2.)

L16: "SST+2/SIC--3", same at **L27**.
Thanks.
L19--20: I do not see snowfall decreasing over the AP in the supplementary figures, this rather seems to occur in the surrounding ocean. Please clarify.
The significant decrease in snowfall that we described "over the AP" only occurs over the Larsen C and George VI ice shelves. We will clarify it by changing P10 L19-20:

Moreover, snowfall significantly decreases over Larsen C and George VI ice shelves (both located in the AP) but is largely compensated by rainfall refreezing into the snowpak.

L32: The authors certainly mean (Fig. 1f).
Yes, corrected thank you.

L32--33: "SST/SIC(CMIP5) suggests", what do the authors mean by "as SIC and SST anomalies [...] around the mean"? Please, clarify.
We mean that the CMIP5 average anomalies for both SIC and SST are weak in our experiment as CMIP5 models are more or less equally distributed (warm or cold SSC anomalies) around the ERA-Interim SSC, even if the mean CMIP5 SSC are slightly warmer (lower SIC and higher SST) than ERA-Interim (see Table 1). We suggest to modify P10 L32-33 by:

SST/SIC(CMIP5) suggests a non-significant positive anomaly for both integrated and spatial SMB (Fig. 3k) as the mean SIC and SST anomalies in CMIP5 models do not significantly differ to the ERA-Interim SSC (Table 1, Fig. 1b,e). CMIP5 models anomalies are more or less equally distributed (warm or cold SSC anomalies) around the ERA-Interim

SSC, even if the mean CMIP5 SSC are slightly warmer than ERA-Interim explaining the non-significant positive SMB anomaly.

P11 L7--9: I am not sure to understand the links between unchanged inland temperature, coastal precipitation enhancement and downward (katabatic?) winds. Could the authors reformulate this sentence?

We suggest to reformulate P11 L7-15 as follows

These results suggest that precipitation can be formed further inland depending on the properties of air masses. In agreement with Gallée (1996), our hypothesis is that colder and drier air masses in cold ocean experiments are not sufficiently loaded with moisture to enable saturation and then snowfall over the margins. The decrease in moisture is likely to be larger than the decrease in the maximal moisture content in the atmosphere associated to lower temperatures. This leads to a larger amount of remaining humidity that can be advected further inland (Fig. 4b,d and S10b,d) where saturation occurs because of the lower temperatures. On the opposite, the additional humidity in warm ocean experiments results in air masses that reach saturation faster (the increase in humidity overcompensates the increase in the maximal moisture content) and thus generating precipitation over the ice sheet slopes. MAR also simulates significantly higher upper air temperature over the central part of the ice sheet (Fig. S11c,e and Fig S12c,e) that, combined with the lower remaining humidity, (Fig. 4C,e and S10c,e) limit snowfall. (see also our response to R#2)

L10-13: This discussion should be moved to a new section "Limitations".

We suggest to move this discussion in the section "Results" (see our answer to general comments 1-3)

L29--31: Please reformulate this sentence "present--climate [...] 21st century", it reads better at **L18--19 of P14**.

We will reformulate P11 L29-31 by:

[...]Our sensitivity tests with warmer (CMIP5-based) oceans reveal SMB anomalies over the current climate in the lower range of the SMB increase projected for the end of the 21st century

Stylistic suggestions

Thank you for all the stylistic suggestions. We will take them into account in the revised version of our manuscript.

P1 L2: [...] boundary forcing fields prescribed by reanalyses [...]. **L7:** Altering is rather negative, and suggests that data have been deteriorated. I would suggest: "by modifying the ERA--Interim SSC". **L10:** Replace "altering" by "affecting". **L17:** "exchange of gas". **L18:** Remove "behaviour"; "impacts" or "affects" instead of "alters". **L19:** "[...] water vapour loading of air masses, potentially [...]". **L20:** Remove "as the Antarctic" and insert "that" after "(SMB)". **L23:** The authors could consider reformulating as follows: "[...] have experienced a significant increase since the 1970s (e.g. Massonnet et al., 2013), highly contrasting with the dramatic decline reported in the Arctic Ocean [...]".

P2 L9: Maybe "[...] and increased precipitation [...]". **L13:** I suggest: "[...] (e.g. Weatherly, 2014), with simplified physics resulting [...]". **L14:** I suggest: "[...] (RCMs) forced by former and less reliable reanalyses (e.g. ERA--15 in Bromwich et al., 2007) over short periods [...]". **L24:** "[...] with the 'Modèle Atmosphérique Régional' (MAR) for the period 1979--2015. This allows partitioning [...]". **L27--31:** I suggest: "[...], this study only discusses the direct [...]. This means that no feedback on the [...] removal is considered [...] Krinner et al. 2014). Only direct impacts on [...] components are accounted for. Note that the general [...]". **L34:** Replace "altered" by "perturbed".

P3 L7: Maybe "The effect of sea spray on [...]". **L10:** I suggest: "[...] sub--modules, that simulate energy and [...]". **L15:** Remove "Consequently,". **L16:** I suggest: "[...] and open--ocean fractions". **L21:** "forced by". **L27:** "[...] evolve as a function of accumulated snowfall and surface [...]". **L29:** "we start". **L33:** "[...] moisture source for precipitation over the AIS [...]".

P4 L1: Maybe "selected" instead of "chosen". **L2:** "extending 6 km above". **L5:** "[...] SMB to SSC perturbations is limited to the [...] SIC anomalies within the MAR [...]". **L9--10:** "perturbed" instead of "modified". **L13--16:** "for ice--free pixels", "converted into full ice--covered pixels if the SST drops [...] (-- 2ºC). For an SST [...] SIC value is set to [...]". **L18:** Maybe "at the interface between [...]". **L22:** "[...] and maintain SST of sea ice--covered pixels [...]". **L25:** "in sea ice extent associated". **L29:** Replace "present climate" by "present--day" or "contemporary".

P5 L9: "[...] anomalies into the original [...] enables to account for constant [...]".

P6 L9: "perturbed" instead of "altered". **L10:** I suggest: "SST and/or SIA anomalies for JJA and DJF periods are 1.5 times as large as CMIP5 mean [...]". **L14:** "brief" instead of "short". **L14:** This is rather negative, I would suggest: "to highlight the impact of using a coarser horizontal resolution on SMB representation". **L15:** Remove "the one described".

P7 **L1:** Replace "by" by "using". **L2:** "observations collected prior to our study period". **L3:** "for the same period.". **L6:** Add "the" before "observation locations". **L7:** I suggest: "(Agosta et al., 2012), unresolved at 50 km […]". **L8:** Replace "consequently" by "i.e." or by "or". **L13:** "noted" instead of "noticed". **L16:** "significantly smoothed topography".

P9 **L1:** "enhanced" instead of "stronger". **L7:** "This allows locating". **L12:** For consistency, "interannual variability". **L14:** "The warmer ocean leads to […] of similar magnitude as […] converting snowfall into rainfall." **L16:** "[…] higher temperature also causes […] SST+4 relative to the reference simulation (Fig. S7a--l)." **L18--20:** "[…] sublimation are larger in SST+4 (Fig. S6a) because […] temperature, increased precipitation dominates and the SMB anomaly is significantly positive (Fig. 3a and Table 2)." **L22:** "ocean surface and reduce the water vapour". **L26:** "Over the plateau, larger deposition combined with snowfall […] than for the reference run.". **L28--29:** "[…] colder ocean as lower SST also decrease the near--surface air temperature […]". **L31:** "revealing similar patterns as in SST+2 (Fig. S2m) although non--significant […]".

P10 **L1:** "smaller" instead of "lower". **L5--7:** "[…] decrease in precipitation is observed over the new ice--covered ocean […] act as an insulator […] 2--m air temperature by 10ºC". **L9:** Maybe "pronounced" instead of "strong"; "[…] SIC--6/SIC+6). This is likely due to the smaller magnitude […] SIC--3 compared to the magnitude of SIC extension […]". **L23:** "show similar anomalies as". **L24:** "larger anomalies […] Besides, the sensitivity of AIS SMB to SSC is non--linear".

P11 **L2:** Maybe "marginal" instead of "external". **L14--15:** I suggest: "opposite pattern: drier air masses have to rise up higher […] so that precipitation is generated further inland.". **L22:** "affect" instead of "modify". **L23:** "three times as large". **L29:** "perturbed SSC".

P13 **L1:** "are by far smaller". **L2:** Maybe "showing" instead of "with potential"; the authors could consider "[…] SMB anomalies do not significantly differ from observed SMB". **L4:** Replace "assess" by "evaluate". **L7:** Replace "driven" by "forced".

P14 **L2:** Replace "altering" by "perturbing" and move "unchanged" to the end of the sentence. **L3:** "The first set consists of […]". **L8:** "(resp. decreased) precipitation due to warmer (resp. colder) […]". **L12:** Maybe "leads to earlier/faster saturation as they rise […]". **L15:** I suggest: "However, comparing modelled SMB from sensitivity experiments with observations shows no significant difference, suggesting […]". **L18:** "with warmer (CMIP5--based) SSC reveal that SMB […] climate stand in the lower". **L20:** Remove "as demonstrated in this study". **L21:** "using potentially biased SSC as forcing". **L22:** Replace "produce new" by "carry out future".

Figures and Tables

Table 1: For the reference run, insert "0.00" or "--" to fill the blanks in the anomaly columns.

Ok, we will fill the blanks with "-" in our revised manuscript.

Table 2: Caption **L2**: "floating ice" instead of "not grounded ice".

We will modify accordingly the caption of Table2.

For comparison with the coarser resolution simulation, the authors should consider adding integrated numbers from the 35 km run discussed in Agosta et al. (2018). See also general comment #2.

See our response to general comment 1-3

Fig. 2: For comparison, the authors should consider including a second scatterplot showing outputs of the 35 km run.

See our response to general comment 1-3

Fig. 3: This figure could be replaced by Fig. S2. See also general comment #4.

Thank you for the suggestion, Fig 3 will be replaced by Fig S2

Fig. S6: Caption **L1**: "minus" instead of "mines".

Thank you for the correction

We would like to thank the reviewer #2 for his constructive comments which will help to improve our manuscript.

1. You perturb both the SST and the SIC, but not necessarily in a consistent way. In my opinion, more material should be given to illustrate a consist perturbation, for example by comparing how the SST bias in the GCM compares to the SIC bias? Another way would be to assume – for example – that meridional SST gradient remains unchanged as the SST increases, which imposes the retreat of the sea-ice edge.

We recognize that our method does not necessarily lead to consistent SIC perturbations associated to the SST perturbations since SIC perturbations depend on the number of neighbouring pixels taken into account. However, the experiments has been designed in order to study the effect of perturbations similar to SST and SIC biases in the GCMs (see Table 1 and p6, L9-11). Our SIC and SST perturbations can also be compared to previous works such as Van Lipzig et al. (2002). They reduced the mean sea ice cover by 50% for a 2°C temperature rise (values also suggested by Thompson and Pollard (1995) in a 2°C warmer climate), which is close to our SIC perturbations (-53% in winter).

Furthermore, the methods used in this study lead to smoothed SST field preventing abrupt SST changes near the sea ice edge, and also enable to modify polynya extents as SIC can vary from 0 to 100% in MAR. This would not have been possible with a method using a retreat of sea-ice edge only based on an unchanged meridional SST gradient. We would also encounter difficulties for determining the sea-ice edge as the MAR ice mask is not a binary mask. Assuming that the meridional SST gradient remained unchanged is also a strong hypothesis that still have to be demonstrated as the meridional SST gradient strongly depends on the presence/absence of the sea ice. In the context of the polar amplification (even less strong in the southern hemisphere), the gradient can be expected to decrease but if some sea ice remains in a warmer climate, it would constrain the SST at the freezing point over the highest latitudes while increasing at lower latitudes. They are thus two opposite effects, probably leading to high uncertainties about the meridional SST gradient (François Massonnet, UCL, personal communication, 2018). Although it is an interesting debate and research, we think that the future of the meridional SST gradient is beyond the scope of this study and we have thus preferred not to rely on the hypothesis of an unchanged meridional gradient.

The aim of using CMIP5 anomalies was also to apply to the ERA-Interim SSC a SIC perturbation related to the SST bias. However, it appears that SIC biases in CMIP5 models are not only related to SST but also to process parameterization such as lateral melting (e.g., Roach et al., 2018) so that SST biases and SIC biases could not be consistently derived from one to another.

For all those advantages compared to disadvantages of each method, we have preferred to follow the methods defined by Noel et al. (2014) for constructing our SSC perturbations. We suggest to clearly report that our sensitivity experiments does not necessarily lead to consistent SIC perturbations associated to SST changes by adding this discussion to P6L6.

P6, L6: *Table 1 compares SSC perturbations to the reference SSC for June-July-August (JJA) and December-January-February (DJF) SST and sea ice area (SIA). The SIA is defined as the sum of the products of the SIC and area of all grid cells with a SIC value of at least 15%. SIA is preferred to sea ice extent because it better accounts for SIC variations (Roach et al., 2018). Sensitivity experiments with altered SST by ±2 °C and SIC with the ±3 neighbour pixels are in the range of CMIP5 anomalies. Other perturbations (SST±4 and SIC±6) represent a 1.5 times larger anomaly in SIA and/or SST for both JJA and DJF mean values than CMIP5 mean anomalies over the current climate. However, it should be remembered that our sensitivity experiments are not based on climatological consistent SIC (resp. SST) perturbations related to SST (resp. SIC) perturbations. For instance, the SIC prescribed in our experiments associated to 2°C warmer SST could be significantly different from the real SIC in a 2°C warmer climate since we do not use SIC projections from a GCM.*

2. I do not really following the reasoning throughout the paper why there is more precipitation inland when SST is lower or SIC is higher. You argue that this is because the dryer air has to rise up higher to reach saturation. Although, this is of course true, it does not imply that precipitation can be brought higher up – it just means the saturation point is at a higher elevation. For saturated air, the amount of moisture transported in the interior is only dependent on temperature and circulation. So additional analyses are needed to shed light on this issue. The best way would be to do a moisture budget over the interior and see whether small circulation changes might be responsible for this.

Although you do spectral nudging, circulation close to the surface might deviate which can be relevant for moisture advection. Although this comment is valid for the entire results/discussion section, p11, line 14/15 is particularly misleading.

We do not mean that precipitation can be brought higher up, but only that the saturation is likely to occur at a higher elevation. In cases of marine air (i.e., with a high humidity content) intrusion towards the central part of the ice sheet, precipitation is then formed further inland (p11, L13-15).

The indiscriminate nudging applied to the upper atmosphere of the model is designed to prevent any wind deviation from the forcing. Figure 1 presents the mean near-surface (2 m) wind speed in the reference simulation and wind anomalies for both wind speed and direction in SST-4/SIC/6 and SST+4/SIC-6 experiments. It highlights the absence of a wind deviation but shows a strengthening (resp. weakening) of the flow in a warmer (resp. colder) ocean over both the ice sheet and the ocean. However, these changes are mainly significant over areas where sea ice is removed or added similarly to Gallée (1996) and Van Lipzig *et al.*(2002). These changes are due on one hand to the surface roughness strongly modified over the ocean. On the other hand, the higher (resp. lower) temperature contrast between the ocean and the atmosphere reinforces (resp. weakens) the ice-breeze effect as described by Gallé. (1996). Although we show here the mean surface flow and direction over 1979-2015, it is also true for any specific day.

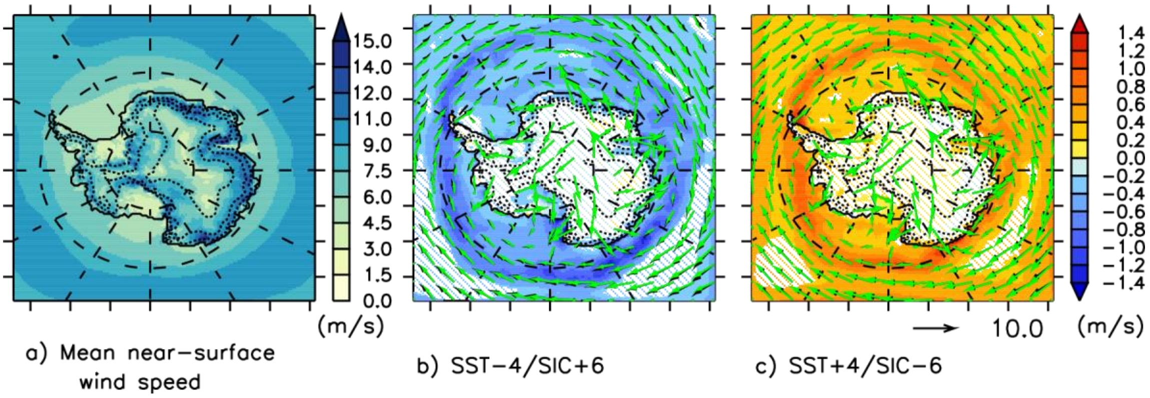

Figure 1. a: Mean near-surface (2m) wind speed modelled by MAR over 1979 – 2015. Difference in mean surface wind speed (m/s) between the reference simulation and (b) SST-4/sSIC+6, (c) SST+4/SIC-6 experiments. Wind speed differences lower than the interannual variability are considered as non-significant and are dashed. The wind direction is also indicated with black (resp. green) vectors for the reference simulation (resp. sensitivity experiments).

The large amount of MAR simulations did not enable us to store the atmospheric variables at each vertical level of the model preventing us to compute a moisture budget over the ice sheet. As an alternative, we propose to analyze the specific humidity (Figs 2 and 3) and temperature (Figs 4 and 5) at 600 hPa (Figs 2a,b,c,d,e and 4a,b,c,d,e) and at 700 hPa (Figs 3a,b,c,d,e and 5a,b,c,d,e). We found a negative anomaly at the ice sheet margins but a higher specific humidity over the central part of the ice sheet in SST-4/SIC+6 (Fig 3b and Fig 4b). On the opposite, the specific humidity is significantly increased in the SST+4/SIC-6 over the margins and decreased over the central region (Fig 3c and Fig 4c). We also compared the snowflakes content between the sensitivity experiments (SST-4/SIC/6; SST+4/SIC-6) and our reference simulation (not shown). These anomalies are very similar to the snowfall anomalies pattern presented in our supplementary materials (Figure 4, p5) with for instance, higher snowflake concentration (up to 30%) over the central ice sheet in the SST-4/SIC+6 experiment and lower snowflake concentration over the same area in SST+4/SIC-6 (up to -30%).

These results suggest that precipitation can be formed further inland depending on the properties of air masses. In agreement with Gallée (1996), our hypothesis is that colder and drier air masses in cold ocean experiments are not sufficiently loaded with moisture to enable saturation and then snowfall over the margins. The lack in moisture is likely to overcompensate the lower temperature. This leads to a larger amount of remaining humidity that can be advected further inland (Figure 2b and 3b) before saturation occurs due to lower temperatures. On the opposite, the additional humidity in warm ocean experiments results in air masses that reach saturation faster (humidity still overcompensates the higher temperature) and thus generating precipitation over the ice sheet slopes. MAR also simulates significantly higher air temperatures over the central part of the ice sheet (Figure 4c and 5c) that, combined with the lower remaining humidity, (Figure 2c and 3c) limit snowfall.

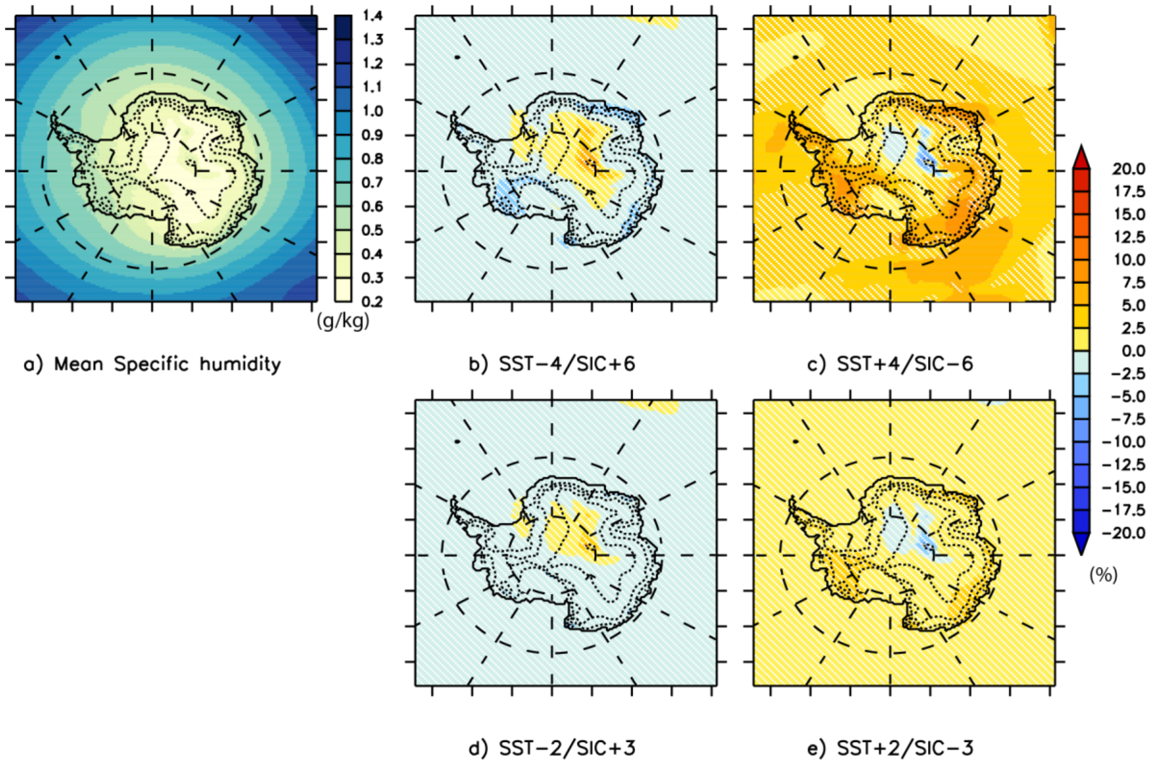

Figure 2. a: Mean specific humidity modelled by MAR over 1979–2015 at 600 hPa (Units: g/kg). Difference in mean specific humidity (%) between the reference simulation and (b) SST-4/SIC+6, (c) SST+4/SIC-6, (d) SST-2/SIC+3, (e) SST+2/SIC-3 experiments. Differences lower than the interannual variability are considered as non-significant and are dashed.

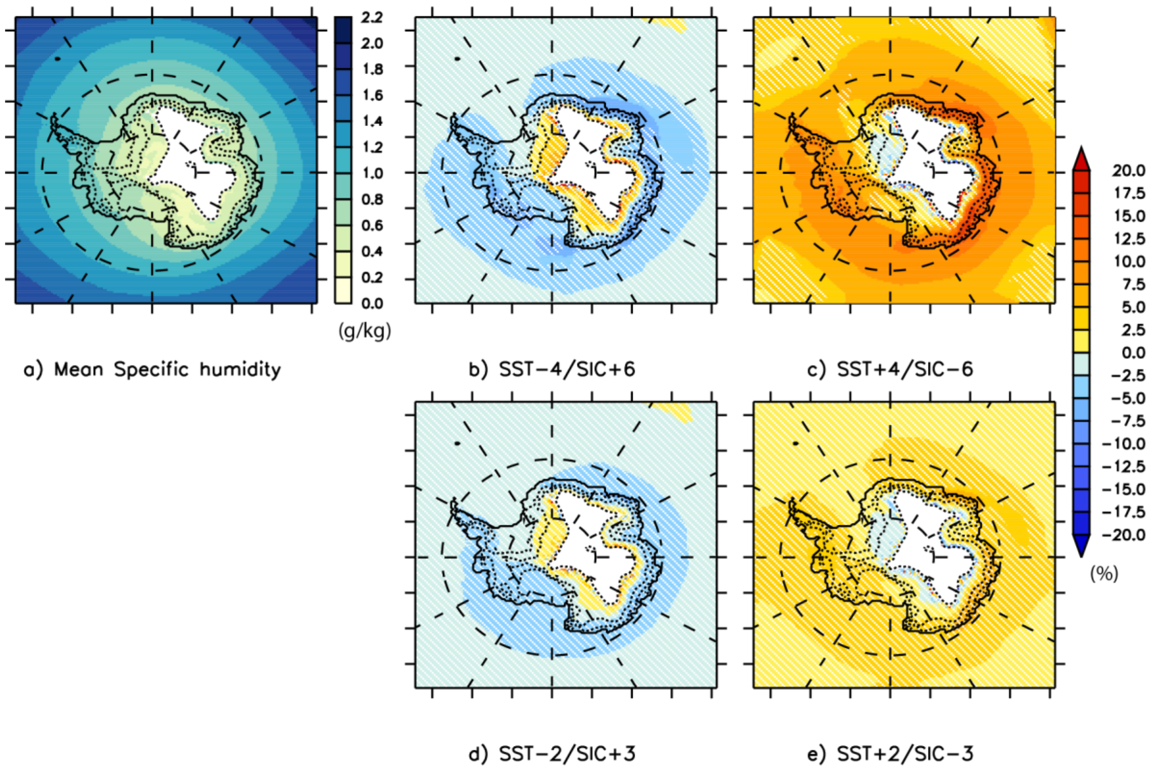

Figure 3. Idem as Figure 2 but at 700 hPa.

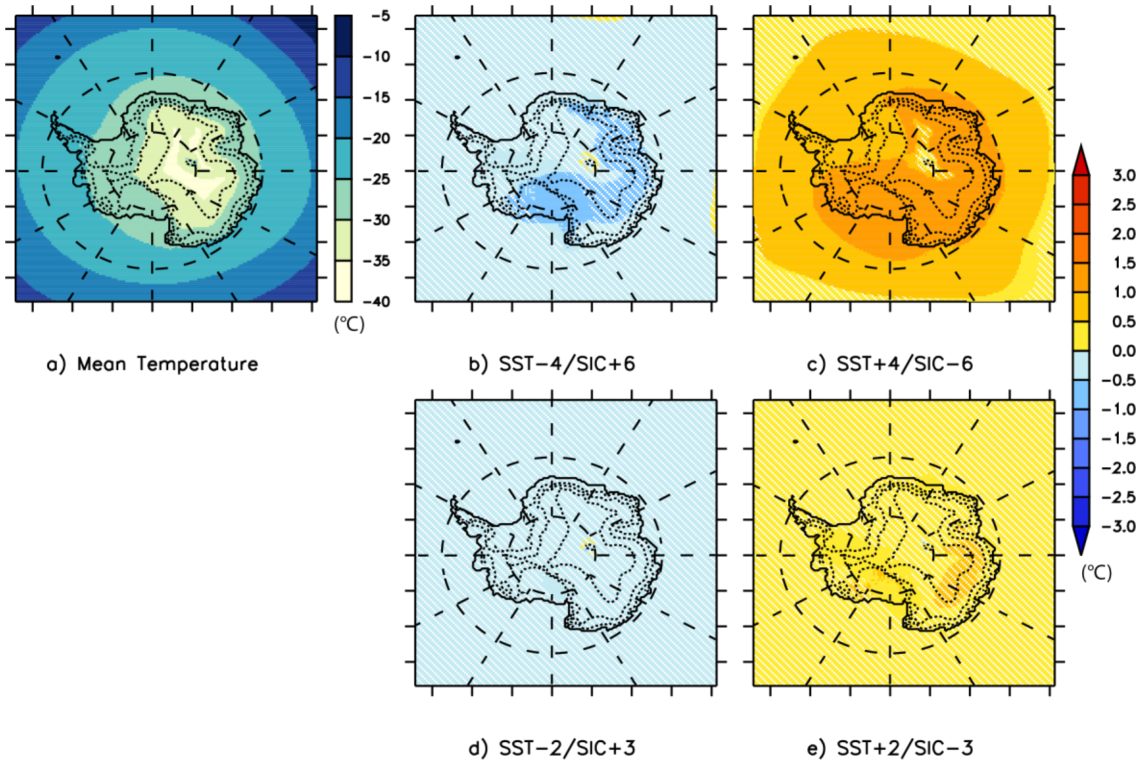

Figure 4. Idem as Figure 2 but for the mean temperature (°C) at 600 hPa.

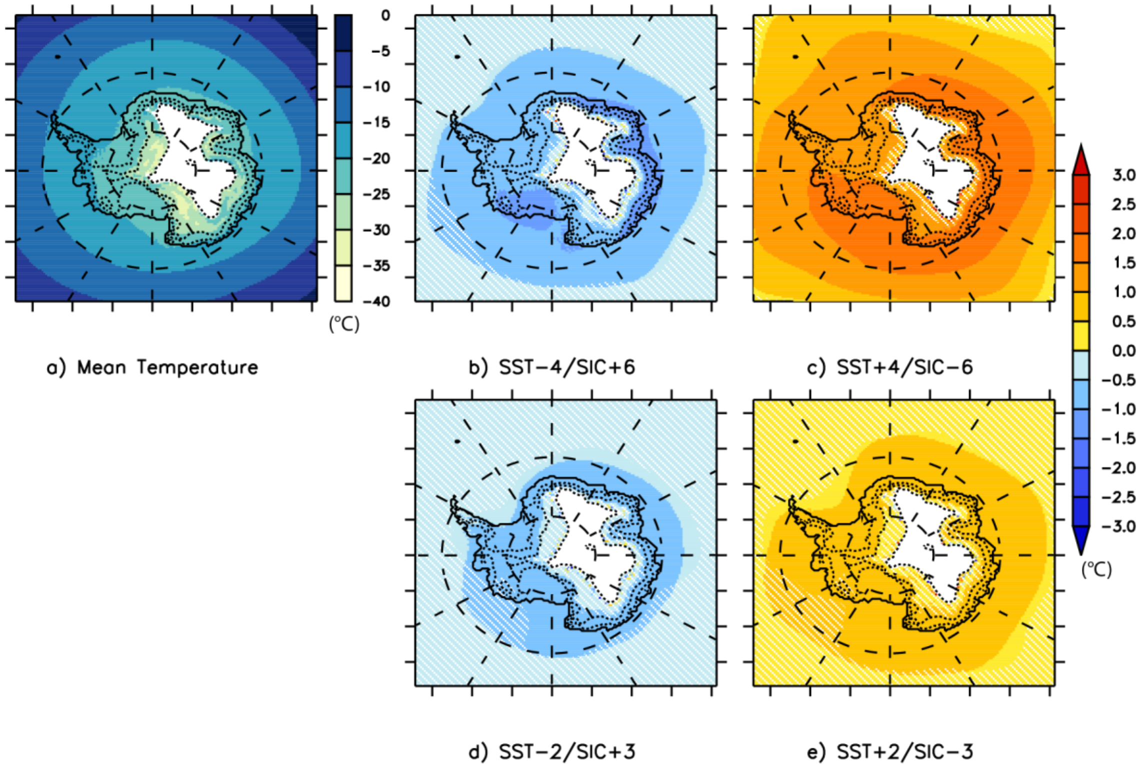

Figure 5. Idem as Figure 2 but for the mean temperature (°C) at 700 hPa.

We suggest to clarify our explanation and add the Figure 2 in our manuscript, Figures (3-5) in supplementary materials and modify P11 L7-15 by

These results suggest that precipitation can be formed further inland depending on the properties of air masses. In agreement with Gallée (1996), our hypothesis is that colder and drier air masses in cold ocean experiments are not sufficiently loaded with moisture to enable saturation and then snowfall over the margins. The decrease in moisture is likely to be larger than the decrease in the maximal moisture content in the atmosphere associated to lower temperatures. This leads to a larger amount of remaining humidity that can be advected further inland (Fig. 4b,d *and S10b,d) where saturation occurs because of the lower temperatures. On the opposite, the additional humidity in warm ocean experiments results in air masses that reach saturation faster (the increase in humidity overcompensates the increase in the maximal moisture content) and thus generating precipitation over the ice sheet slopes. MAR also simulates significantly higher upper air temperature over the central part of the ice sheet (Fig. S11c,e and Fig S12c,e) that, combined with the lower remaining humidity, (Fig. 4C,e and S10c,e) limit snowfall.*

3.On p 11 line 19 you state that 'Katabatic winds prevent significant impacts of SSC on the Antarctic SMB'. Although this might be true, I do not see proof for this in the manuscript. Even if there would be no katabatics, the fact that air has to rise over the topographic barrier and additional moisture is constrained to the boundary layer, might be enough to prevent significant effect.

Similarly to Gallée (1996) and Noel et al. (2014), we found a strengthening of the near-surface katabatic flow associated to lower SIC and higher SST (Figure 6c). Increased katabatic winds bring more cold air masses from the central ice sheet and cool the ice sheet margins. Furthermore, they also export humidity away from the continent (Van Lipzig *et al.*, 2002). However, this effect is limited to the katabatic layer.

Our deepest analysis about the humidity and temperature suggests that a significant part of the additional moisture is not constrained to the boundary layer and reaches upper atmospheric layers (600 hPa or ~4km height) for the experiments with the strongest SSC perturbations (Fig 2b,c and 3b,c). This contrasts with the results presented in Van Lipzig *et al.* (2002) where the surface anomalies were restricted below the lowest 1-2km. The blocking effect due to the topographic barrier is likely to be reduced as these large anomalies reach higher atmospheric levels, contrary to experiments with slightly perturbed SSC (SST+-2/SIC-+3) where anomalies remain confined in the low levels.

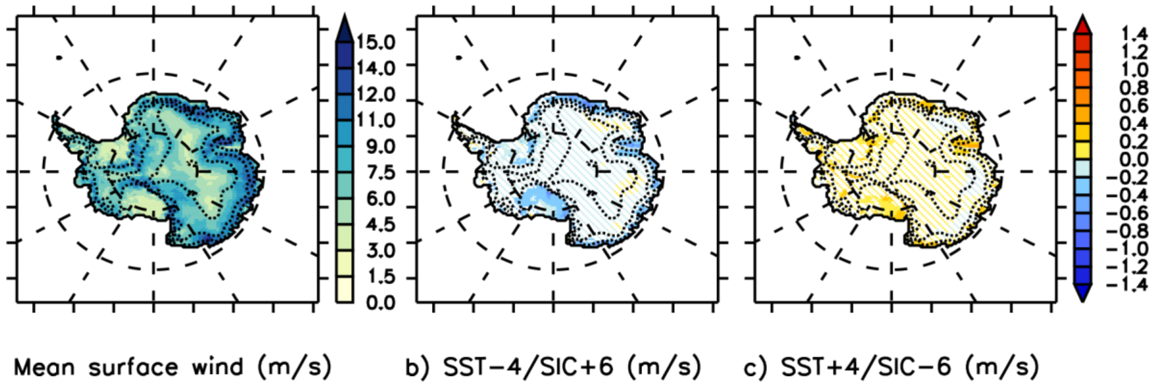

Figure 6. Idem as Figure 1 but without wind vectors and only on the ice sheet.

We thus propose to clarify of our statement P11 L19-21 about the effect of katabatic winds as well as our refutation about the topographic barrier and the additional moisture. We also suggest to add Figure 6 in supplementary material

Similarly to Van Lipzig et al.(2002), moisture and temperature anomalies remain confined below 700 hPa in the experiments with slightly perturbed SSC (SST+-2/SIC-+3) (Fig S10d,e and Fig S12d,e). *On the* opposite, in the experiments with the largest SSC perturbations (SST+-4/SIC-+6), a significant part of the additional moisture is not constrained to the boundary layer and reaches upper atmospheric layers (600 hPa*) (Fig 4b,c). The blocking effect due to the topographic barrier is likely to be reduced suggesting that these large anomalies can have a deeper influence inland.*

Furthermore, katabatic winds are enhanced when the SIC is decreased and the SST increased (Fig S13c) as already shown in Gallée, 1996; Van Lipzig et al., 2002. Due to their offshore direction, they prevent the influence of warm ocean anomalies by precluding their propagation at the surface of the ice sheet and by advecting cold air from inland regions towards the margins.

Minor comments:

1. Abstract: last sentence: a number for a sensitivity in % is meaningless when the magnitude of the perturbation is not specified. Please clarify in the abstract

We think that giving a magnitude of the perturbation is meaningless as the SSC in these experiments are computed with the CMIP5 biases that significantly differ spatially. We therefore propose to specify that the SSC perturbations are based on the CMIP5 biases in the sentence of *P1 L13*

Sensitivity experiments with warmer SSC based on the CMIP5 biases reveal integrated SMB anomalies (+5% – +13%) over the present climate (1979 – 2015) in the lower range of the SMB increase projected for the end of the 21st century

2. P1, line 22: I am not sure if I follow the definition of the Sea Ice Extent given there. Can you give a reference for this definition or clarify?

This definition can be notably found in Parkinson and Cavalieri (2012), Cavalieri and Parkinson (2012), Roach *et al. (*2018) (all cited in our manuscript) as well as in Vaughan *et al.* (2013).

We propose to slightly modify the definition to use the exact same definition:

P1l22: generally defined as the area of all grid cells of satellite or model products with a SIC of at least 15%

3. P 2, l11: reference is van Lipzig et al., (2002) not van Lipzig and van Meijgaard (see below). Van Lipzig, N.P.M., E. van Meijgaard and J. Oerlemans, 2002. Temperature sensitivity of the Antarctic surface mass balance in a regional atmospheric climate model. J. Clim., 15(19), 2758-2774. doi:10.1175/1520-0442(2002)0152.0.CO;2.

Thank you for the correction of the reference. We have also identified a second reference mistake P2,L2. Turner *et al.* (2013) was right but the interesting paper for our study is:

Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., & Scott Hosking, J. An initial assessment of Antarctic sea ice extent in the CMIP5 models. *Journal of Climate*, 26(5), 1473–1484. https://doi.org/10.1175/JCLI-D-12-00068.1, 2013

Both references will be corrected in the revised version of our manuscript.

4. P9: l12: Air does not have 'a capacity' to hold water vapour. The water vapour is one of the components of air. Please reformulate.

Ok, we suggest to modify *P9 L12* by:

The higher evaporation and inherent increase in air moisture content [..]

References

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Noël, B., Fettweis, X., van de Berg, W. J., van den Broeke, M. R., and Erpicum, M.: Sensitivity of Greenland Ice Sheet surface mass balance to perturbations in sea surface temperature and sea ice cover: a study with the regional climate model MAR, The Cryosphere, 8, 1871–1883, doi:10.5194/tc-8-1871-2014, 2014.

Parkinson, C. L. and Cavalieri, D. J.: Antarctic sea ice variability and trends, 1979-2010, The Cryosphere, 6, 871–880, doi:10.5194/tc-6-871- 2012, 2012.

Roach, L. A., Dean, S. M., and Renwick, J. A.: Consistent biases in Antarctic sea ice concentration simulated by climate models, The Cryosphere, 12, 365–383, doi:10.5194/tc-12-365-2018, 2018.

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Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen and T. Zhang: Observations: Cryosphere. In: Climate Change 2013: The Physical Sci- ence Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 2013

Sensitivity of the current Antarctic surface mass balance to sea surface conditions using MAR

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Abstract. Estimates for the recent period and projections of the Antarctic surface mass balance (SMB) often rely on high-resolution polar-oriented regional climate models (RCMs). However, RCMs require large-scale boundary forcing fields ~~provided~~ prescribed by reanalyses or general circulation models (GCMs). Since the recent variability of sea surface conditions (SSC, namely sea ice concentration (SIC) and sea surface temperature (SST)) over the Southern Ocean are not reproduced by most GCMs from the 5th phase of the Coupled Model Intercomparison Project (CMIP5)~~for the last decades~~, RCMs are then subject to potential biases. We investigate here the direct sensitivity of the Antarctic SMB to SSC perturbations around the Antarctic. With the RCM MAR, different sensitivity experiments are performed over 1979 – 2015 by ~~altering~~ modifying the ERA-Interim SSC with (i) homogeneous perturbations and (ii) mean anomalies estimated from all CMIP5 models and two extreme ones, while atmospheric lateral boundary conditions remained unchanged. Results show increased (resp. decreased) precipitation due to perturbations inducing warmer, i.e. higher SST and lower SIC (resp. colder, i.e. lower SST and higher SIC) SSC than ERA-Interim significantly ~~altering~~ affecting the SMB of coastal areas, as precipitation is mainly related to cyclones that do not penetrate far into the continent. At the continental scale, significant SMB anomalies (i.e, greater than the interannual variability) are found for the largest combined SST/SIC perturbations. This is notably due to moisture anomalies above the ocean reaching sufficiently high atmospheric levels to influence accumulation rates further inland. Sensitivity experiments with warmer SSC based on the CMIP5 biases reveal integrated SMB anomalies (+5% – +13%) over the present climate (1979 – 2015) in the lower range of the SMB increase projected for the end of the 21st century.

1 Introduction

Sea ice concentration (SIC) and sea surface temperature (SST), hereafter referred as sea surface conditions (SSC), influence the ~~exchanges of gases~~exchange of gas, momentum and heat at the air-sea interface in high latitudes. Due to its high albedo and thermal insulation~~behaviour~~, sea ice notably ~~alters~~ affects the thermodynamic and radiative properties of the ocean surface. Sea ice also prevents evaporation and inherent water vapour loading of air masses~~in water vapour~~, potentially affecting precipitation at high latitudes. This is of particular importance for the Antarctic ice sheet (AIS) as ~~the Antarctic~~ its surface mass balance (SMB) is mainly controlled by precipitation (van Wessem et al., 2018; Agosta et al., 2018).

Southern Ocean SSC and especially sea ice extent (generally defined as the area of all grid cells of satellite or model products with a SIC of at least 15%in satellite and model products) have experienced a large change since the late significant increase since the 1970s (e.g., Massonnet et al., 2013). A significant increase in sea ice extent has been observed in the Southern Ocean(e.g., Parkinson and Cavalieri, 2012; Massonnet et al., 2013), highly contrasting with the dramatic decline reported in the Arctic Ocean (Cavalieri and Parkinson, 2012; Parkinson and Cavalieri, 2012)(Cavalieri and Parkinson, 2012). Nonetheless, this general trend conceals major regional differences. For instance, the Amundsen–Bellingshausen Seas showed a strong decrease in sea ice extent, unlike other surrounding Antarctic seas (Turner et al., 2016). Despite the observed changes in the Antarctic SSC and their large potential impacts on the climate system, the Antarctic SMB did not exhibit any significant trend at the continental scale over the last decades (Bromwich et al., 2011; Lenaerts et al., 2012; Frezzotti et al., 2013; Favier et al., 2017; Agosta et al., 2018).

Several modelling studies have illustrated the influence of open ocean open-ocean areas on the AIS climate, for instance through a strong atmospheric heating (Simmonds and Budd, 1991; Gallée, 1995), an enhancement of cyclone activity (Simmonds and Wu, 1993; Gallée, 1996; Krinner et al., 2014), and higher intensified precipitation related to intensified evaporation (Wu et al., 1996; Bromwich et al., 1998; Weatherly, 2004). Conversely, the atmosphere has been shown to be less sensitive to SIC anomalies than SIC to atmosphere anomalies (Simmonds and Jacka, 1995; Bailey and Lynch, 2000) as anomalies induced by the ocean surface are often restricted to the lower atmospheric layers above the Southern Ocean (?)(Van Lipzig et al., 2002). However, these previous studies were based on coarse-resolution models (e.g., Weatherly, 2004), with missing physical processes simplied physics resulting notably in biased surface sublimation (e.g., Noone and Simmonds, 2004), or on regional climate models (RCMs) forced by the former ERA-15 reanalysis (known as less reliable than more recent renalyses; see (Bromwich et al., 2007)) and run former and less reliable reanalyses and over short periods (?)(e.g., Van Lipzig et al., 2002).

High-resolution polar-oriented RCMs provide more reliable estimates of the Antarctic SMB components, but they depend on their forcing boundary conditions, including SSC. Using adequate SSC in climate models could be as crucial as using a suitable downscaling model (Krinner et al., 2008; Beaumet et al., 2017). This is of particular importance since most general circulation models (GCMs) from the 5th phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) fail to reproduce the SSC temporal and spatial variability in the Southern Ocean area over the last decades (Mahlstein et al., 2013; ?; Shu et al., 2015; Agosta et al., 2015; Roach et al., 2018)(Mahlstein et al., 2013; Turner et al., 2013; Shu et al., 2 As the projected Antarctic SMB could highly depend on the representation of the present sea-ice extent (Agosta et al., 2015), we investigate here the sensitivity of the Antarctic SMB to SSC and more specifically to CMIP5 SSC anomalies with the RCM MAR («Modèle Atmosphérique Régional»(MAR) for the recent period 1979 – 2015. This will help partitioning the uncertainty in Antarctic SMB projections resulting from biased SSC in GCMs from the uncertainty resulting from biased large-scale circulation patterns. Even tough MAR is a well adapted tool to study the climate sensitivity to SSC (Gallée, 1995, 1996; Messager et al., 2004; Noël et al., 2014), our study only focuses on discussing this study only discusses the direct and local impact of SSC on the Antarctic SMB. This means that we do not consider no feedbacks on the general circulation associated to sea ice removal (e.g., Bromwich et al., 1998; Krinner et al., 2014), neither feedbacks involving sea ice and ocean, but only is considered (e.g., Bromwich et al., 1998; Krinner et al., 2014). Only directs impacts on air temperature, moisture, and SMB components ~~knowing~~ are accounted for. Note that the general atmospheric circulation remains unchanged in our sensitivity experiments.

A description of MAR, model set-up, and sensitivity experiments is given in Section 2. Section 3 presents model evaluation, as well as the observations and methods used for comparison. The influence of SSC on the Antarctic SMB is analysed in Section 4, while we discuss the direct impacts of ~~altered~~ perturbed SSC in Section 5. Our main conclusions are summarized in Section 6.

2 Methods and data

2.1 The MAR model

The ability of the regional climate model MAR to reproduce the climate specificities of polar regions has been extensively evaluated (e.g., Lang et al., 2015; Gallée et al., 2015; Amory et al., 2015; Fettweis et al., 2017; Agosta et al., 2018). MAR is a hydrostatic, primitive equation atmospheric model (Gallée and Schayes, 1994) which includes a cloud microphysics module solving conservation equations for specific humidity, cloud droplets, rain drops, cloud ice crystals, and snow particles (Gallée, 1995). ~~Sea spray effects~~ The effect of sea spray on heat fluxes or on water vapour concentration ~~are~~ is parameterized following Andreas (2004). The atmospheric model is coupled to the 1-D SISVAT (Soil Ice Snow Vegetation Atmosphere Transfer; De Ridder and Gallée, 1998) module, which consists of soil and vegetation (De Ridder and Schayes, 1997), snow (Gallée and Duynkerke, 1997; Gallée et al., 2001) and ice (Lefebre et al., 2003) sub-modules~~. They simulates~~ , that simulate energy and mass fluxes between the surface and the atmosphere. The snow-ice module includes sub-modules for surface albedo, melt-water refreezing and snow metamorphism based on the CROCUS model (Brun et al., 1992). Regarding interactions between the atmosphere and ocean, SISVAT considers distinct sea ice and open-water sub-pixels. Open-ocean roughness length for momentum and heat follows Wang (2001), while the momentum roughness length over snow surfaces (sea ice and ice sheet pixels) is computed as a function of air temperature as proposed in Amory et al. (2017). ~~Consequently, fluxes~~ Fluxes and roughness lengths are separately calculated over sea ice and water and are afterward weighted according to sea ice and open-ocean ~~proportions~~ fractions (Gallée, 1996). In this study, we use MAR version 3.6.4, recently adapted to Antarctica (Agosta et al., 2018). Although MAR includes a drifting snow module (Gallée et al., 2001), this module has been switched off ~~as in Agosta et al. (2018)~~ similarly to Agosta et al. (2018) as the new version of this module is still under evaluation against satellite and ground-based observations.

2.2 Set-up

As the ERA-Interim reanalysis (Dee et al., 2011) is considered as one of the most reliable reanalyses for the Antarctic region (e.g., Bromwich et al., 2011; Bracegirdle and Marshall, 2012; Agosta et al., 2015), MAR is forced ~~with~~ by ERA-Interim every 6 hours over 1979 – 2015 at its atmospheric lateral ~~and upper~~ boundaries (pressure, wind, specific humidity and temperature~~at each vertical level~~) and over the ocean surface (SIC and SST). It is worth noting that ERA-Interim uses the SST and SIC values from ERA-40, which are based on monthly and weekly ocean forcing fields (Fiorino, 2004), until January 2002 and from the OSTIA real daily products afterwards 2002. Afterwards, a switch was made with the daily operational NCEP product and since 2009 with the Operational SST and Sea Ice Analysis (OSTIA). The latter is a daily global SST analysis product at a 0.05° resolution (Stark et al., 2007; Donlon et al., 2012). For each grid cell with a ERA-Interim SIC value greater than 0%, MAR sea ice thickness is initially fixed at 55 cm and sea ice can be covered by snow. The sea ice thickness can then evolve in as a function of accumulated snowfall or surface snow/ice melt, with a minimum thickness of 10 cm as long as the ERA-Interim SIC is positive. The sub-pixel SST beneath sea ice is fixed at -2 °C in the MAR snow model while the sea ice surface temperature is free to evolve according to its surface energy balance. Finally, as for spin-up time, we starts start our simulations in March 1976 using ERA-40 reanalysis (Uppala et al., 2005) until 1979 with initial snowpack conditions interpolated from previous reference simulations a previous reference simulation (Agosta et al., 2018).

Compared to Agosta et al. (2018), our integration domain (Fig. 1a) has been extended to include the maximum seasonal sea ice extent as well as major moisture source areas for precipitation particles for precipitation over the AIS (Sodemann and Stohl, 2009). A resolution of 50 km has been chosen selected to preserve a reasonable computational time. The Antarctic topography is based on the digital elevation model 1-km resolution DEM Bedmap2 from Fretwell et al. (2013). An upper-air relaxation until extending from the top of the atmosphre to 6 km above the surface is used in order to constrain the MAR general atmospheric circulation (van de Berg and Medley, 2016; Agosta et al., 2018). This upper relaxation prevents potential feedbacks between the ocean state and the general atmospheric circulation. Similarly to Noël et al. (2014), the sensitivity of the Antarctic SMB in our study SMB sensitivity to SSC perturbations will thus be restrained limited to the direct and local impacts of SST and SIC anomalies into the within MAR integration domain.

2.3 Simulations

In this study, we consider MAR forced by ERA-Interim over 1979 – 2015 as the reference simulation. We perform two sets of sensitivity experiments in which SSC from ERA-Interim are modified perturbed as described below. The first set follows the methods described in Noël et al. (2014), that are simplified and idealized scenarios, while in the second set, SSC are modified according to SSC anomalies from CMIP5 models. In both cases, we analyse the direct impact of SSC anomalies on the Antarctic SMB.

2.3.1 SST sensitivity experiments

In these experiments, the 6-hourly ERA-Interim SST are decreased (resp. increased) by 2 °C (SST±2) and 4 °C (SST±4) in for ice-free pixels. In cases of an SST reduction, ice-free oceanic pixels are converted into a full ice-covered pixels if the SST drop below the assumed seawater freezing point (-2 °C)while for . For an SST increase, the SST of any grid cell with a positive SIC value is limited set to the melting point (0 °C) to avoid positive SST and to prevent any SIC change.

2.3.2 SIC sensitivity experiments

To prevent too strong changes at the ~~edge~~ interface between ice-covered and ice-free pixels, ERA-Interim SIC are reduced (resp. increased) by the minimum (resp. maximum) SIC value of the three and six ocean neighbours of each MAR pixel. These experiments are called SIC$\pm$3 and SIC$\pm$6. Knowing that the resolution is 50 km, this means that the SIC is gradually decreased (resp. increased) by a distance of 150 and 300 km. Following Noël et al. (2014), a SST correction is applied in order to prevent open-water temperature from dropping below -2 °C and maintain the SST of sea ice-covered pixels ~~higher than~~ below the melting point (0 °C).

2.3.3 Combined SST/SIC sensitivity experiments

Combined SST-SIC forcing fields are computed according to the two previous subsections. The added value of these experiments is the simultaneous representation of the increase (resp. decrease) in sea ice ~~extension~~ extent associated to the decrease (resp. increase) in SST. They are named SST$\pm$2/SIC$\mp$3, SST$\pm$4/SIC$\mp$6.

2.3.4 CMIP5-based sensitivity experiments

In addition to the spatially homogeneous perturbations described above, we evaluate how SSC anomalies from CMIP5 models over the current climate can influence the ~~present-climate~~ present-day Antarctic SMB modelled by RCMs. For that purpose, we ~~interpolate mean ocean monthly outputs~~ have determined a perturbation whose magnitude is representative of the CMIP5 ensemble bias. Monthly SSC over 1979 – 2005 from all the CMIP5 models (using the historical scenario~~(1979 – 2005)and~~), as well as from ERA-Interim ~~by a four-nearest inverse distance-weighted method on our~~ were interpolated on the MAR grid (50 km x 50 km~~MAR grid . The interpolated~~) using an inverse-distance weighted method based on the four CMIP5 ~~SIC outputs are compared to the interpolated ERA-Interim SIC fields, considered here as the reference, in order to obtain monthly SIC anomalies. Then, monthly SST anomalies are computed only for grid cells where the SIC value for both interpolated ERA-Interim~~ models/ERA-Interim grid cells nearest to the current MAR one. We then computed the CMIP5 ensemble average from the interpolated CMIP5 monthly SSC. Monthly SST anomalies between CMIP5 and ERA-Interim were computed only if the SIC from both the CMIP5 ~~model outputs is~~ ensemble average and ERA-Interim are less than 50% ~~. Finally, SIC and SST anomalies are averaged over 1979 – 2005.~~ to not introduce additional temperature biases. Secondly, we average the monthly anomalies to obtain a mean anomaly, supposed to represent a constant bias over time.

New 6-hourly forcing SST are ~~computed~~ calculated as the sum of the 6-hourly ERA-Interim ~~forcing fields and the average of all CMIP5 SST anomalies~~(i.e., for a specific day of a certain month) and the corresponding monthly anomaly in SST from CMIP5 ensemble average (Fig. 1b), hereafter referred to as SST(CMIP5) experiment~~(Fig. 1c).~~ . In the same way, we define SIC(CMIP5) experiments in which SIC anomalies ~~from all~~ (Fig. 1e) from the CMIP5 ~~models are averaged and applied~~ ensemble average are added to the 6-hourly ERA-Interim SIC~~(Fig. 1g).~~ . Introducing CMIP5 anomalies ~~to~~ into the original ERA-Interim SSC enables to ~~take into account~~ account for constant CMIP5 anomalies with the seasonal and ~~inter-annual~~ interannual SSC variability represented in the ERA-Interim reanalysis. The combined SST-SIC anomaly experiment is per-

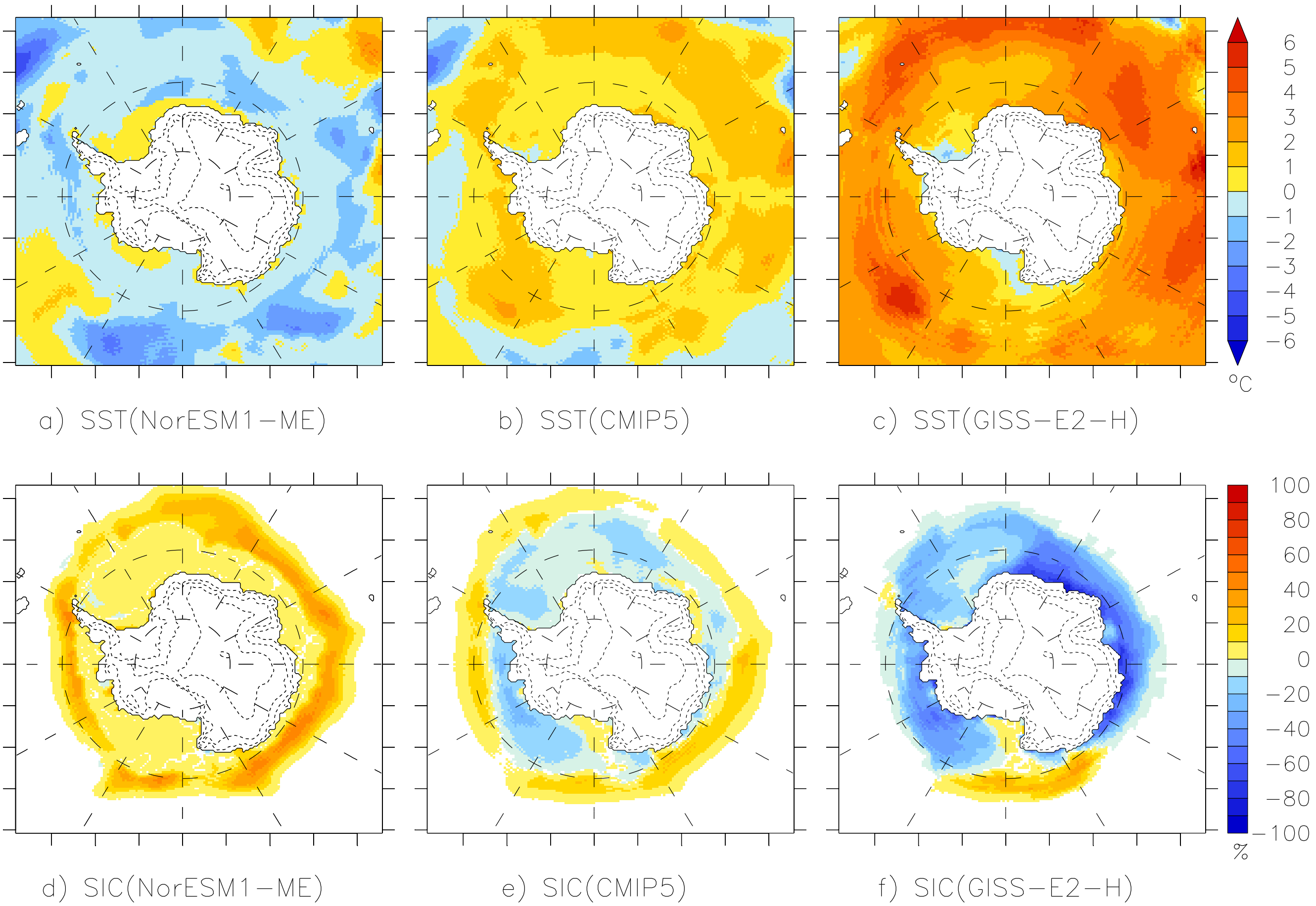

Figure 1. Top: SST anomalies (°C) of (a) NorESM1-ME, (b) CMIP5 average and (c) GISS-E2 compared to ERA-Interim SST over 1979 – 2005. Bottom: SIC anomalies (%) for (d) NorESM1-ME, (e) CMIP5 average and (f) GISS-E2 compared to ERA-Interim SIC over 1979 – 2005. These anomalies were introduced in the 6-hourly ERA-Interim SSC.

formed by adding CMIP5 averaged SST and SIC anomalies to ERA-Interim and is hereafter referred to as SST/SIC(CMIP5). Following the same method, we perform combined experiments for two selected CMIP5 models, namely NorESM1-ME (Bentsen et al., 2012) and GISS-E2-H (Schmidt et al., 2014), respectively representative of a colder and warmer ocean (i.e., lower SST and higher SIC) and warmer (i.e, higher SST and lower SIC) SSC than ERA-Interim (Agosta et al., 2015)as shown in Agosta et al. (2015). These experiments are hereafter called SST/SIC(NorESM1-ME) (Fig. 1b,fa,d) and SST/SIC(GISS-E2-H) (Fig. 1d,hc,fi).

Table 1 compares SSC perturbations to the reference SSC for June-July-August (JJA) and December-January-February (DJF) SST and sea ice area (SIA). The mean SST and SIC anomalies of CMIP5 ensemble average, NorESM1-ME, and GISS-E2-H are also listed. The SIA is defined as the sum of the products of the SIC and area of all grid cells with a SIC value of at least 15%. SIA is preferred to sea ice extent because it better accounts for SIC variations (Roach et al., 2018). Sensitivity

Table 1. JJA and DJF sea ice area (SIA) (10^6 km^2) within the MAR domain over the period 1979-2015. SIA is defined as the sum of the products of the SIC and area of all grid cells with a SIC value of at least 15%. The DJF (resp. JJA) seasonal mean SST are computed for the ocean free of ice in all experiments in DJF (resp. JJA). We only considered grid cells remaining free of ice (SIC $<$ 15 %) in all experiments in order to remove the influence of sea ice on surface temperature and numerical artefacts due to differences in open ocean areas.

Experiment	JJA SIA (10^6km^2)		DJF SIA (10^6km^2)		JJA SST (°C)		DJF SST (°C)	
	Mean	Anomaly	Mean	Anomaly	Mean	Anomaly	Mean	Anomaly
Reference	13.31	–	4.49	–	5.55	–	6.36	–
SST-4/SIC+6	20.63	+7.32	10.83	+6.34	1.55	-4.00	2.36	-4.00
SST-2/SIC+3	17.04	+3.73	7.70	+3.21	3.55	-2.00	4.36	-2.00
SST+2/SIC-3	9.70	-3.61	2.08	-2.41	7.55	+2.00	8.36	+2.00
SST+4/SIC-6	6.77	-6.54	0.96	-3.53	9.55	+4.00	10.36	+4.00
SST/SIC(NorESM1-ME)	16.06	+2.75	8.63	+4.14	5.02	-0.33	5.78	-0.58
SST/SIC(CMIP5)	12.71	-0.60	4.05	-0.44	5.86	+0.31	6.77	+0.41
SST/SIC(GISS-E2-H)	9.66	-3.65	2.34	-2.15	8.30	+2.75	9.22	+2.86

experiments with ~~altered~~ perturbed SST by ±2 °C and SIC with the ±3 neighbour pixels are ~~in the range of CMIP5 anomalies. Other perturbations (SST±4 and SIC±6) represent an~~ 1.5 ~~times larger anomaly in SIA and/or SST for both JJA and DJF mean values than~~ times as large as CMIP5 ~~mean anomalies over the current climate~~ mean anomalies over the current climate. However, it should be remembered that our sensitivity experiments are not based on climatologicaly consistent SIC (resp. SST) perturbations related to SST (resp. SIC) perturbations. For instance, the SIC prescribed in our experiments associated to 2°C warmer SST could be significantly different from the real SIC in a 2°C warmer climate since we do not use SIC projections from a GCM.

3 Evaluation against SMB observations

Since the MAR SMB has already been evaluated against the GLACIOCLIM-SAMBA dataset (Favier et al., 2013) over the AIS at 35 km resolution by Agosta et al. (2018), only a ~~short~~ brief evaluation is proposed here to highlight ~~a possible deterioration in the representation of the SMB arising from the use of a coarser resolution~~the influence of using a coarser horizontal resolution on the SMB representation. We follow the same method as ~~the one described~~ in Agosta et al. (2018).

Modelled values are interpolated to ~~observation locations by~~ the observation locations using a four-nearest inverse distance-weighted method. Only SMB observations after 1950 are considered. Concerning observations ~~beginning~~ collected before our study period (1979 – 2015), the mean 1979 – 2015 modelled SMB values are compared to observations covering more than eight years. For SMB observations beginning after 1979, modelled SMB are compared to SMB observations on the same period. This procedure removed 206 observations from the GLACIOCLIM-SAMBA dataset. Then, all remaining observations located into a same MAR grid cell are averaged, and so are the modelled SMB values previously interpolated to the observation locations. Finally, as snow accumulation exhibits a very high variability at the kilometre-scale (Agosta et al., 2012)that cannot be resolved , unresolved at 50 km resolution, we restrain our comparison to grid cells containing more than one observation, consequently i.e. 205 averaged comparison pairs. The comparison without the minimum observation number criterion per grid cell (462 points) is available in supplementary material (Fig. S1).

The high value of the correlation coefficient (r=0.93) between observed and modelled SMB values shows that MAR correctly represents the Antarctic SMB spatial variability at 50 km resolution over the 1979 – 2015 period , in spite of an overall underestimation of the SMB by 5% on average (Fig. 2). However, it should be noticed that, in the reference run, MAR generally tends to slightly underestimate the SMB values between 200 and 600 kg m^{-2} yr^{-1}. These values are typical of accumulation rates at the ice sheet margins (Agosta et al., 2018). Except over the Dronning Maud Land, the margins of the Amery ice shelf and a transect in the Wilkes Land, MAR overestimates the SMB (locally up to a factor of 5, Fig. S2).

As also shown by Franco et al. (2012) over the Greenland ice sheet, these biases could partially arise from the coarse resolution used here (50 km) that results in a topography significantly smoothed which induces a significantly smoothed topography at the ice sheet margins. This leads to an unsatisfactory representation of the topographic barrier effect allowing the precipitation systems modelled by MAR to penetrate too far inland.

In order to estimate the biases and the uncertainty related to our resolution, the reference SMB of this study was briefly compared to the SMB at 35 km resolution from Agosta et al. (2018) (Fig. S3). This comparison also shows an SMB overestimation in the reference run compared to SMB results at a higher resolution, although this overestimation appears to be non-significant relatively to the modelled interannual variability. The largest anomalies can be found over the Antarctic Peninsula and areas with a high spatial variability in orography such as the Transantarctic Mountains. The coarse 50 km resolution used here leads to artificially overestimated precipitation on the windward sides of orographic barriers. This is notably the case over the Filchner-Ronne and Ross ice shelves where the Amundsen Sea Low generates a return flow. However it should be noted that the SMB anomalies of our 50 km reference run compared to both 35 km results (Agosta et al., 2018) and observations are smaller than the SMB anomalies due to SSC perturbations presented in Section 4.

4 Results

In this section, we analyse the local and direct impact of SSC anomalies on the Antarctic SMB and its components modelled by MAR forced by ERA-Interim over 1979 – 2015 (maps of SMB components for all experiments can be found in supplementary material Figs. S2-7). Since liquid precipitation accounts for negligible mass gains compared to snowfall (Table S1), we do no distinctly analyse snowfall and rainfall over the AIS. As the large majority of surface meltwater and rainfall percolates and refreezes into the snowpack, runoff is a negligible component of the Antarctic SMB in both the reference and sensitivity experiments. However, some runoff events can occur on the Antarctic Peninsula (AP) and are stronger enhanced in sensitivity experiments with warmer SSC (+2 Gt yr^{-1} in SST/SIC(GISS-E2-H) and +6 Gt yr^{-1} in SST+4/SIC-6). The AP is characterized by a sharp elevation gradient inadequately resolved at 50 km resolution leading to a poor representation of specific climatic

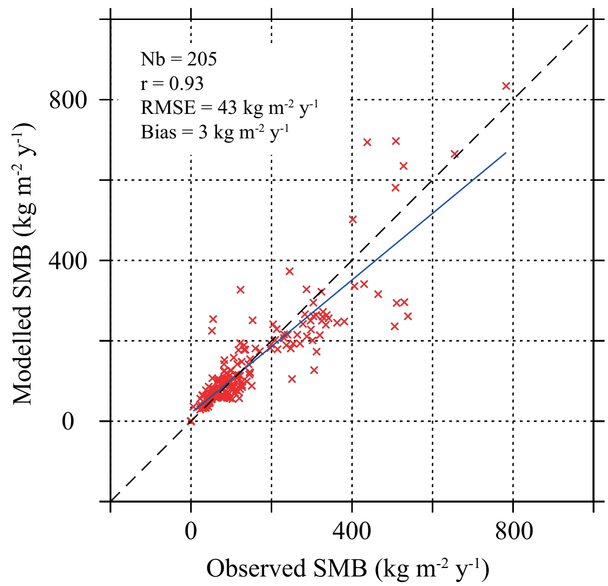

Figure 2. Comparison between MAR SMB and observed SMB from the GLACIOCLIM-SAMBA database (Favier et al., 2013) for 1950 – 2015. Bias and RMSE units are kg m^{-2} yr^{-1}. The averaged observation mean is 65 kg m^{-2} yr^{-1}.

processes encountered in complex topography such as the Foehn effect. Elsewhere coastal runoff amounts stand for very low values. Due to the coarse model resolution limiting the representation of the atmosphere dynamics over the AP and the marginal contribution of runoff to surface mass loss compared to sublimation, surface meltwater production is discussed hereafter instead of runoff amounts. This ~~will help to locate~~ allows locating possible areas where the occurrence of surface melting could possibly affect the surface climate through an increase in snowpack cohesion inhibiting wind erosion (Li and Pomeroy, 1997), or the ice sheet dynamics through meltwater percolation and subsequent ice shelf destabilization (Bevan et al., 2017).

4.1 Sensitivity to SST perturbations

The higher evaporation and ~~air capacity to hold water vapour~~ inherent increase in air moisture content in SST+2 and SST+4 experiments induce significantly stronger precipitation rates (i.e., greater than the ~~inter-annual~~ interannual variability) in coastal areas. Figure 3a points out an opposite pattern between AIS coastal and central areas with a decrease in precipitation over the plateau and large ice shelves (Filchner-Ronne, Ross and Amery). The warmer ocean ~~lead~~ leads to an increase in near-surface air temperature of the same magnitude ~~than~~ as the increase in SST converting snowfall ~~in favour to~~ into rainfall over the ocean (Fig. ~~S4a~~S5a,m and Fig. ~~S5a~~S6a,m). Higher air temperature also ~~cause~~ causes a significant increase in surface melt, twice as large as for SST+4 ~~than in~~ relatively to the reference simulation ~~.~~ (Fig. S8a). However, melt and rainfall water can percolate into the snowpack which remains unsaturated except in scarce places. As a consequence, the surface albedo remains high and does not strengthen melting. Even if mass losses due to surface sublimation are ~~stronger~~ larger in SST+4 (Fig. S7a and

Table 2. Top: Annual mean integrated (Gt yr^{-1}) and standard deviation (Gt yr^{-1}) SMB, precipitation, water fluxes (sublimation and deposition processes) and surface meltwater production over the whole AIS (including grounded and not grounded floating ice) for the reference run (1979–2015). Positive water fluxes represent a mass loss through sublimation and evaporation while negative water fluxes are representative of deposition processes. Bottom: Difference of annual mean integrated SMB (Gt yr^{-1} and %), its components and meltwater (Gt yr^{-1}) between each sensitivity test and the reference simulation (1979 – 2015). Anomalies larger than the inter-annual interannual variability are considered as significant and are displayed in bold.

Mean (Gt y^{-1})	SMB		Precipitation	Water fluxes	Meltwater
Reference	2569 ± 115		2678 ± 110	109 ± 10	97± 29
Anomaly (Gt y^{-1})	**SMB**	**SMB%**	**Precipitation**	**Water fluxes**	**Meltwater**
SST-4	-50	-1.9	-64	**-14**	-21
SST-2	-82	-3.2	-89	-7	-21
SST+2	+41	+1.6	+50	+9	**+39**
SST+4	**+143**	**+5.6**	**+162**	**+17**	**+117**
SIC+6	**-169**	**-6.6**	**-170**	0	-1
SIC+3	-108	-4.2	-107	+1	-1
SIC-3	+24	+0.9	+25	+2	-5
SIC-6	+90	+3.5	+91	+1	-5
SST-4/SIC+6	**-121**	-4.7	**-136**	**-15**	+1
SST-2/SIC+3	**-126**	-4.9	**-129**	-7	-11
SST+2/SIC-3	**+122**	+4.7	**+133**	+9	**+53**
SST+4/SIC-6	**+326**	**+12.7**	**+344**	**+13**	**+218**
SST/SIC(NorESM1-ME)	-104	-4.0	-105	0	+3
SIC(CMIP5)	+36	+1.4	+36	0	+7
SST(CMIP5)	+78	+3.0	+80	+1	+12
SST/SIC(CMIP5)	+103	+4.0	+105	+1	+18
SST/SIC(GISS-E2-H)	**+355**	**+13.8**	**+368**	**+11**	**+95**

Table 2) because of higher air temperature, increased precipitation dominates and the SMB anomaly is significantly positive as precipitation changes dominate (Table 2 and Fig. 3a).

Conversely, a reduction of the SST leads to non-significant negative integrated SMB anomalies (Table 2). Lower SST weaken evaporation at the ocean surface and the water vapour holding capacity of the air reduce the saturation water vapour pressure resulting in smaller annual mean integrated precipitation over the whole AIS. This decrease in precipitation mainly explains local negative SMB anomalies in coastal areas (e.g., Victoria Land, Wilkes Land, Drauning Maud Land, Ellsworth Land and Marie Byrd Land, Fig. 3eand Fig. S2p,p; Fig. S8 S9 locates these coastal areas). However, precipitation over large ice shelves are slightly enhanced and are locally significantly larger. Over the plateau, stronger deposition processes ~~in addition to a snowfall increase~~ combined with an increase in snowfall induce a higher SMB than the reference ~~simulation~~run. These features are discussed in more details in Section 4.3. The total accumulation by deposition is the highest in SST-4 (Table 2). Moreover, a significant part of rainfall is converted into snowfall over the colder ocean as the near-surface air is also cooled by the decreased SST (Fig. ~~S4e~~S5e,p and Fig. ~~S5e~~S6e,p).

In the SST(CMIP5) experiment (Fig. 3i)), SST are slightly higher (+0.3 °C in winter and +0.4 °C in summer) revealing ~~a similar pattern than~~ similar patterns as in SST+2 ~~and SST+4 even tough~~ (Fig. 3m) although non-significant for both integrated and local mean SMB values.

4.2 Sensitivity to SIC perturbations

A sea ice retreat induces a precipitation increase over the ice sheet although most of the changes are ~~lower~~ smaller than the interannual variability (Fig. 3b~~and Fig. S2n~~,n) because it favours the advection of moister air masses towards the AIS as already suggested by Gallée (1996). On the opposite, a sea ice increase produces a negative SMB anomaly driven by the reduction of precipitation over the whole AIS (Fig. 3f,~~Fig. S2q,~~ q and Table 2). Similarly, a significant decrease in ~~the precipitation amounts~~ precipitation is observed over the new ~~frozen~~ ice-covered ocean in SIC+6 (Fig. ~~S3~~S4.f) because sea ice mainly acts as an isolator preventing evaporation at the ocean surface. Despite the decrease of the mean summer 2-m air temperature ~~of~~ by 10 °C over new sea ice-covered areas in SIC+3 and SIC+6, surface melting does not exhibit a significant decrease over the ice sheet. The sensitivity of the Antarctic SMB to a decrease in SIC seems to be less ~~strong~~ pronounced than the sensitivity to an increase in SIC (resp. +3.5% in SIC-6 vs. -6.6% ~~for SIC-6/~~in SIC+6)~~, likely linked to the~~. This is likely due to the smaller magnitude of the ~~SIC~~ sea ice retreat in SIC-6 and SIC-3 ~~smaller than~~ compared to the magnitude of the sea ice extension in SIC+3 and SIC+6 (Table 1). Finally, the ~~application of CMIP5 SICpertubations to ERA-Interim fields~~ mean SMB from SIC(CMIP5) does not significantly ~~alter both spatial~~ differ from the reference SMB, both spatially (Fig. 3j) and integrated ~~SMB and its components~~ over the whole AIS (Table 2).

4.3 Sensitivity to combined SST/SIC perturbations

Higher SST associated to lower SIC reinforce anomalies found for individual perturbations. Evaporation at the ocean surface is stronger while warmer air masses have a greater moisture content. Anomalies for integrated precipitation are significantly positive and account for +4.7% and +12.7% in the integrated Antarctic SMB for respectively SST+2/SCI-3 and SST+4/SIC-6 (Table 2). Similarly to SST+4 and SST+2, SST+4/SIC-6 and SST+2/SIC-3 show a large conversion of snowfall to rainfall over the ocean and enhanced precipitation rates over near-coastal regions, while the interior of the AIS exhibits lower accumulation rates (Fig. 3c~~and Fig. S2o~~,o). Moreover, snowfall ~~decreases over the AP~~ significantly decreases over Larsen C and George VI ice shelves (both located in the AP) but is largely compensated by rainfall refreezing into the snowpack. Finally, due to higher air temperatures, surface melting and sublimation are also significantly larger. On the opposite, colder SSC (SST-4/SIC+6 and SST-2/SIC+3) prevent evaporation and result in lower precipitation over the AIS (Table 2), more particularly at the ice sheet margins (Fig. 3g~~and Fig. S2r~~,r). While SSC combined sensitivity experiments over the Greenland ice sheet ~~showed similar~~

~~anomalies than~~ show similar anomalies as the SST sensitivity experiments (Noël et al., 2014), coupled perturbations act here together to induce ~~stronger~~ larger anomalies over the AIS than the SST sensitivity experiments. Besides, the ~~AIS sensitivity to SSC seems to be~~ sensitivity of the Antarctic SMB to SSC is non-linear~~for SST, SIC and combined SST-SIC forcing changes,~~, illustrating the complexity of the ~~sea ice/ocean –~~ interactions between the (sea ice-covered) ocean surface and the near-surface atmosphere~~interactions~~.

As SSC anomalies in SST/SIC(GISS-E2-H) are close in magnitude to anomalies in SST+2/SCI-3 and SST+4/SIC-6, integrated values (Table 2) and spatial anomaly patterns (Fig. 3d) also illustrate the ~~positive~~ effect of warmer SSC on the Antarctic SMB by a significant increase in precipitation, sublimation, and melt. However, the spatial pattern of precipitation is slightly different in comparison to SST+4/SIC-6. The precipitation anomaly in SST/SIC(GISS-E2-H) is reduced at Adélie Land and George V Land margins in comparison to SST+4/SIC-6 due to the positive SIC anomalies in GISS-E2-H over the Ross and D'Urville Seas (Fig. 1f). SST/SIC(CMIP5) displays a non-significant positive anomaly for both integrated and spatial SMB (Fig. 3k) ~~as~~) as the mean SIC and SST anomalies in CMIP5 models ~~are mainly equally distributed around the mean~~do not significantly differ to the ERA-Interim SSC (1, 3b,e). CMIP5 models anomalies are more or less equally distributed (warm or cold SSC anomalies) around the ERA-Interim SSC, even if the mean CMIP5 SSC are slightly warmer than ERA-Interim explaining the non-significant positive SMB anomaly. Finally, for SST/SIC(NorESM1-ME), SSC are representative of a colder ocean (lower SST and essentially higher SIC) resulting in a non-significant negative SMB anomaly with a precipitation decrease at the ice edge and over ~~the external~~ marginal areas of the plateau (Fig. 3h).

Since snowfall is the largest component of the Antarctic SMB, precipitation changes mainly explain the spatial anomaly patterns observed in our experiments. A warmer ocean with a smaller sea ice cover tends to strongly enhance precipitation at the ice sheet margins while decreased accumulation rates are modelled over the ice shelves and the central part of the ice sheet. ~~Since the temperature of the air massesfrom the central AIS are not impacted by SSC, a higher humidity content at the ice margins results in a quicker saturation of air masses during lift-up processes and the meeting with downward cold air masses from the central AIS as described by Gallée (1996). More precipitation falls then over the steep marginsfurther reducing precipitation inland and over areas downwind of the AP~~ These results suggest that precipitation can be formed further inland depending on the properties of air masses. In agreement with Gallée (1996), our hypothesis is that colder and drier air masses in cold ocean experiments are not sufficiently loaded with moisture to enable saturation and then snowfall over the margins. The decrease in moisture is likely to be larger than the decrease in saturation water vapour pressure associated to lower temperatures. This leads to a larger amount of remaining humidity that can be advected further inland (Fig. ~~S3c)~~ 4b,d and Fig. S10b,d) where saturation occurs because of lower temperatures. On the opposite, the additional humidity in warm ocean experiments results in air masses that reach saturation faster (the increase in humidity overcompensates the increase in saturation water vapour pressure) and thus generating precipitation over the ice sheet slopes. MAR also simulates significantly higher upper-air temperature over the central part of the ice sheet (Fig. S11c,e and S12c,e) that, combined with the lower remaining humidity (Fig. 4c,e and S10c,e), limit snowfall. ~~However, it should be noted that the coarse 50 km resolution used here does not adequately resolve the orography leading to artificially overestimated precipitation on the windward sides of orographic barriers. This is notably the case over the Filchner-Ronne and Ross ice shelves where the Amundsen Sea Low~~

generates a return flow. On the contrary,sensitivity experiments based on a coupled increase in SIC and a SST cooling exhibit the opposite pattern. Knowing that air masses are drier,they have to rise up higher to reach saturation so that precipitation systems can form further inland.

5 Discussion

Even if our sensitivity experiments rely on larger SSC perturbations than the interannual variability, mean integrated SMB anomalies are not systematically significant in comparison to our reference simulation. As already shown for the Greenland ice sheet (Noël et al., 2014), katabatic winds prevent significant impacts of SSC on the Antarctic SMB. Anomalies in Similarly to Van Lipzig et al. (2002), moisture and temperature caused by SSC changes are confined under an inversion layer (Deser et al., 2010) and blocked by katabatic winds,limiting the transport of moisture and energy towards the central part of the AIS. However, SSC perturbations in the range of CMIP5 anomalies modify the Antarctic SMB with integrated anomalies close to the interannual variability, and even three times larger for some models (e. g., GISS-E2-H) . anomalies remain confined below 700 hPa in the experiments with slightly perturbed SSC (SST±2/SIC∓3) (Fig. S10d,e and Fig. S12d,e). On the opposite, in the experiments with the largest SSC perturbations (SST±4/SIC∓6), moisture anomalies are not constrained to the boundary layer and reach upper atmospheric layers (600 hPa) (Fig. 4b,c). The blocking effect due to the topographic barrier is likely to be reduced so that these large anomalies influence accumulation rates further inland (Fig. **??**c,d,g). Furthermore, katabatic winds are enhanced when the SIC is decreased and the SST increased (Fig. S13c) as already shown in Gallée (1996) and Van Lipzig et al. (2002). Due to their offshore direction, they prevent the influence of warm ocean anomalies by precluding their propagation at the surface of the ice sheet and by advecting cold air from inland regions towards the margins.

In the context of Global Warmingglobal warming, it is important to note that the Antarctic SMB increases by 2 – 6% for a SST increase alone and by 5 – 13% for a SST increase coupled to a SIC drop (Table 2). Similar increases are found in sensitivity experiments based on CMIP5 SSC anomalies compared to ERA-Interim over the current climate (+4% and +13% respectively for SST/SIC(CMIP5) and SST/SIC(GISS-E2-H)). Knowing that the regional model RACMO2 projects an increase in SMB by 6–16% in 2100 (Ligtenberg et al., 2013) and the global model LMDZ4 suggests a SMB increase of 17% for the same horizon (Krinner et al., 2008), present-climate simulations with altered SSC in the range of present-climate biases from CMIP5 models lead to our sensitivity tests with warmer (CMIP5-based) oceans reveal SMB anomalies over the current climate in the (lower) lower range of the projected SMB increase SMB increase projected for the end of the 21st century.

Sensitivity experiments are compared to SMB observations from the GLACIOCLIM-SAMBA dataset with the same methods used for the reference simulation (Sect. 3). Correlation and RMSE do not vary significantly between the sensitivity experiments and the reference run (Table 3). Only mean biases vary but the variations are by far smaller than the observed variability. Consequently, sensitivity experiments with potential showing large local or integrated SMB anomalies seems to not significantly affect the comparison with observationsdo not significantly differ from the observed SMB. This is explained by the low amount of available observations and highlights the importance of continuing to carry out field campaign measurements, as well as extending their spatial coverage to better assess evaluate model results.

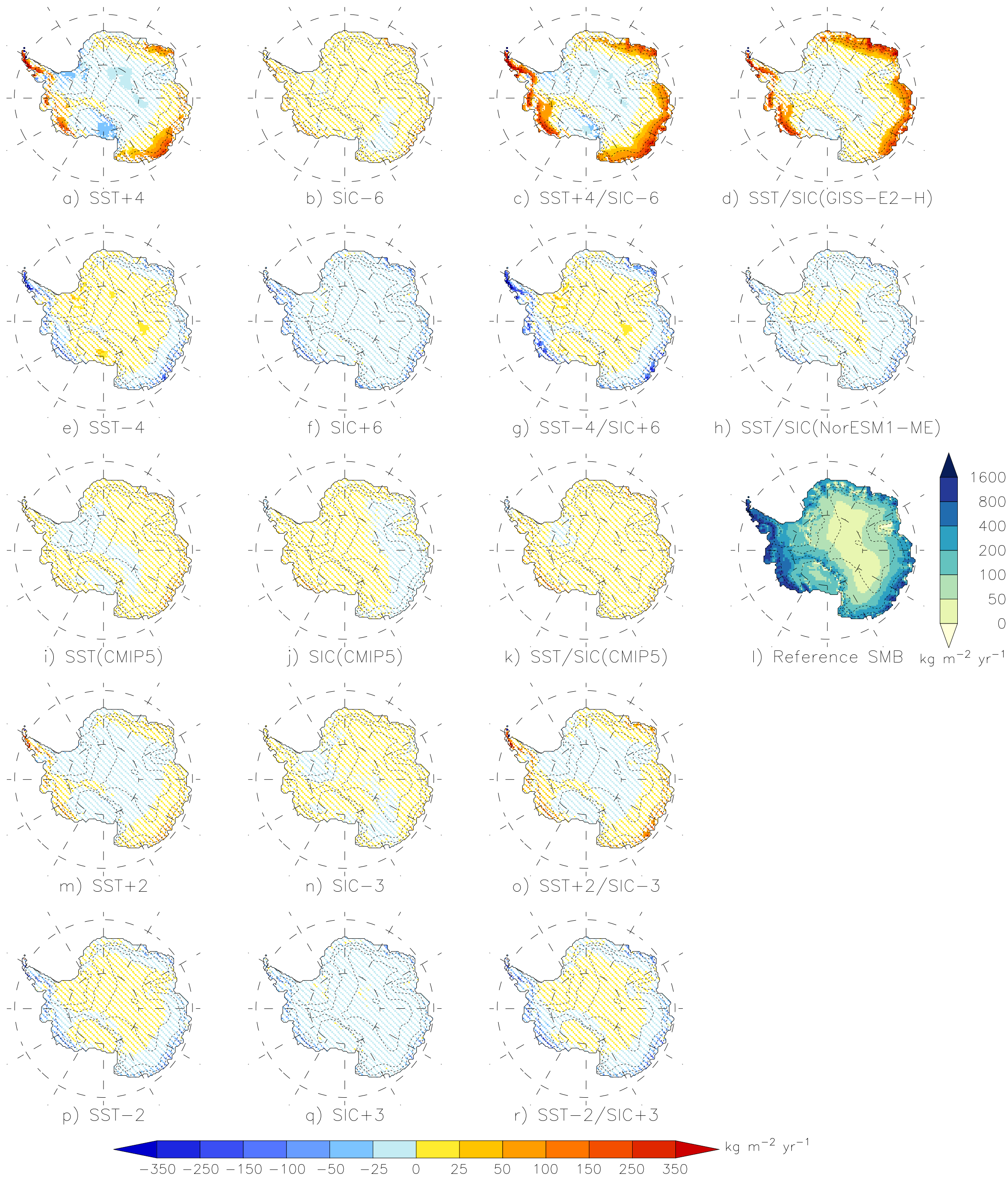

Figure 3. Difference in mean annual SMB (kg m^{-2} y^{-1}) between the reference simulation and (a) SST+4, (b) SIC-6, (c) SST+4/SIC-6, (d) SST/SIC(GISS-E2-H), (e) SST-4, (f) SIC+6, (g) SST-4/SIC+6, (h) SST/SIC(NorESM1-ME), (i) SST(CMIP5), (~~i~~j) SIC(CMIP5), (k) SST/SIC(CMIP5), (m) SST+2, (n) SIC-3, (o) SST+2/SIC-3, (p) SST-2, (q) SIC+3, (r) SST-2/SIC+2 experiments. Difference less than the interannual variability are considered as non-significant and are dashed. l) Mean annual SMB (kg m^{-2} y^{-1}) simulated by MAR forced by ERA-Interim over 1979 – 2015.

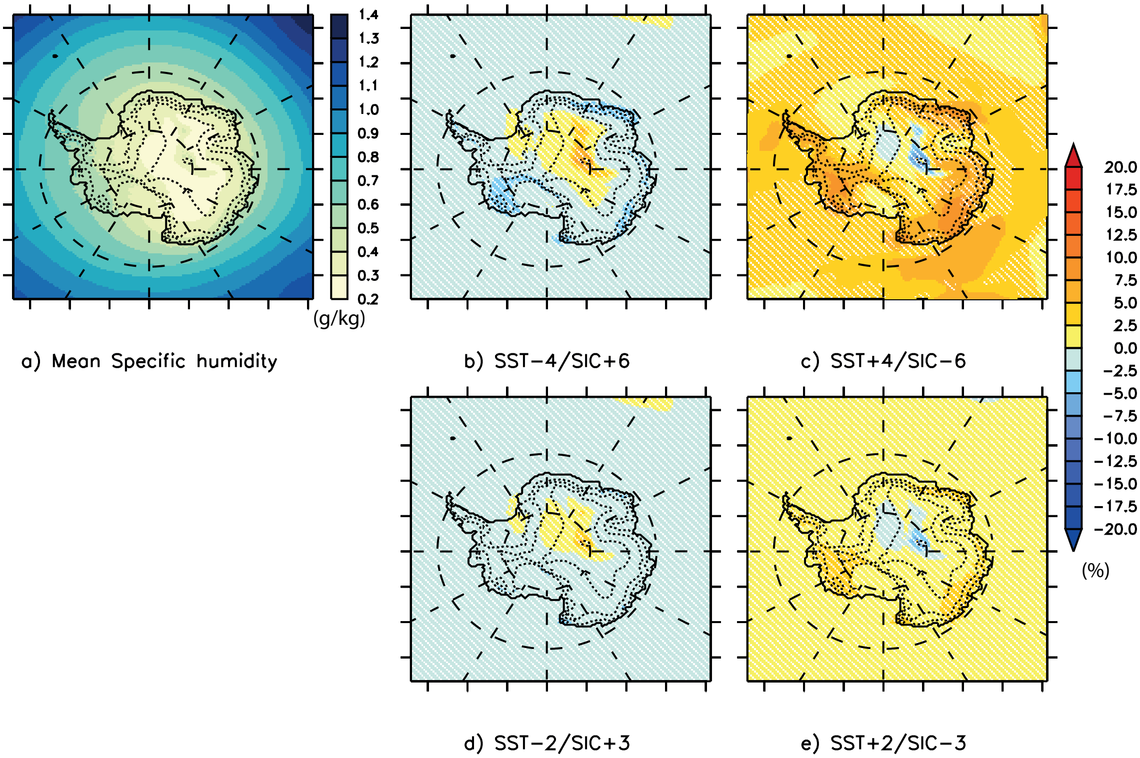

Figure 4. a: Mean specific humidity modelled by MAR over 1979–2015 at 600 hPa (Units: g/kg). Difference in mean specific humidity (%) between the reference simulation and (b) SST-4/SIC+6, (c) SST+4/SIC-6, (d) SST-2/SIC+3, (e) SST+2/SIC-3 experiments. Differences lower than the interannual variability are considered as non-significant and are dashed.

6 Conclusion

Polar-oriented RCMs are suitable numerical tools to study the SMB of the AIS due to their high spatial resolution and adapted physics. Nonetheless, they are ~~driven~~ forced at their atmospheric and oceanic boundaries by reanalyses or GCM products and are then influenced by potential biases in these ones. These biases can be notably significant for SSC (e.g., Agosta et al., 2015). With the RCM MAR, two sets of sensitivity experiments were carried out to assess the direct response of the Antarctic SMB to oceanic perturbations around Antarctica by ~~altering~~ perturbing the ERA-Interim SSC over 1979 – 2015 while keeping ~~unchanged~~ the atmospheric conditions at the MAR lateral and upper boundaries unchanged. The first set ~~consisted in~~ consists of spatially homogeneous SSC perturbations. The second set of experiments involved ERA-Interim SSC perturbations estimated from CMIP5 models anomalies over the ~~present~~ current climate. We introduced mean anomalies from the historical run of CMIP5 models and two extreme models of CMIP5, namely NorESM1-ME and GISS-E2-H respectively representative of warmer ~~(i.e., higher SST and lower SIC) and colder (i.e., lower SST and higher SIC)~~ and colder SSC than ERA-Interim.

Results mainly show increased (resp. decreased) precipitation due ~~to anomalies related to warmer (~~warmer (resp. colder) SSC affecting the SMB of the AIS. As precipitation is mainly caused by low-pressure systems that intrude into the continent

Table 3. Comparison between modelled and observed SMB from the GLACIOCLIM-SAMBA database (Favier et al., 2013) over 1950–2015. Bias et RMSE units are kg m^{-2} yr^{-1}. The observation mean is 65 kg m^{-2} yr^{-1} while the observation standard deviation is 119 kg m^{-2} yr^{-1}.

Simulation acronym	SMB (kg m^{-2} yr^{-1})		
	R	BIAS	RMSE
Reference	0.93	-3	43
SST-4	0.93	-5	43
SST-2	0.93	-5	43
SST+2	0.93	-2	43
SST+4	0.93	+1	48
SIC+6	0.93	-8	42
SIC+3	0.94	-6	43
SIC-3	0.93	-3	43
SIC-6	0.93	0	43
SST-4/SIC+6	0.93	-6	44
SST-2/SIC+3	0.93	-7	44
SST+2/SIC-3	0.93	0	45
SST+4/SIC-6	0.92	+6	55
SST/SIC-NorESM1-ME	0.93	-7	44
SIC-CMIP5	0.93	-3	44
SST-CMIP5	0.93	+3	47
SST/SIC-CMIP5	0.93	0	43
SST/SIC-GISS-E2-H	0.93	+8	52

and do not penetrate far inland, coastal areas are more sensitive to SSC perturbations with more significant anomalies compared to inland regions. Warmer SSC significantly enhance precipitation at the ice sheet margins since a greater moisture ~~loading~~ content of air masses leads to ~~saturation more rapidly~~ earlier saturation as they rise and adiabatically cool over the topography. On the contrary, colder SSC reduce precipitation at the ice sheet margins and slightly increase it further inland as air masses have to rise up to higher elevations to reach saturation. Finally, the largest combined SST/SIC perturbations lead to significant (i.e., greater than the interannual variability) SMB anomalies integrated over the whole AIS due to moisture anomalies above the ocean reaching sufficiently high atmospheric levels to influence accumulation rates further inland. However, comparing ~~the results of the various modelling experiments with SMB observations shows that statistics remained mostly identical~~modelled SMB from sensitivity experiments with observations shows no significant difference, suggesting that large integrated anomalies can remain unperceived if compared to scarce field observations.

Our sensitivity tests with warmer (CMIP5-based) ~~altered oceans reveal~~ SSC reveal that SMB anomalies over the current climate stand in the lower range of the SMB increase projected for the end of the 21st century. Given the influence of SSC perturbations on the Antarctic SMB over the current climate~~as demonstrated in this study~~, a special attention should be paid to future SMB projections using potentially biased SSC as forcing. This highlights the necessity of improving the representation of the ~~present-climate~~ current-climate SSC in the context of downscaling the forthcoming CMIP6 model outputs to ~~produce new~~ carry out future Antarctic SMB projections.

Competing interests. The authors declare that they have no conflict of interest.

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Senstivity of the Antarctic surface mass balance to sea surface conditions using MAR

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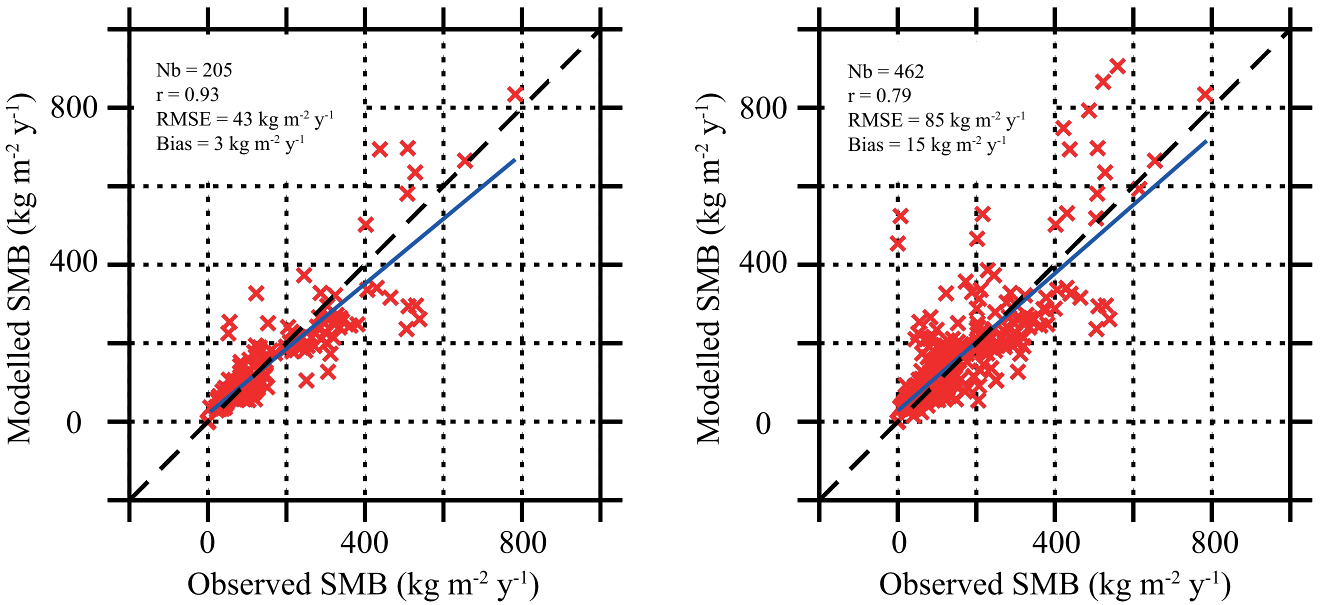


Figure S1. Comparison with SMB from the GLACIOCLIM-SAMBA database over 1950–2015. a) Only grid cells containing more than one observation are conserved for the comparison. b) All grid cells containing at least one observation are used. Bias et RMSE units are kg m^{-2} yr^{-1}.

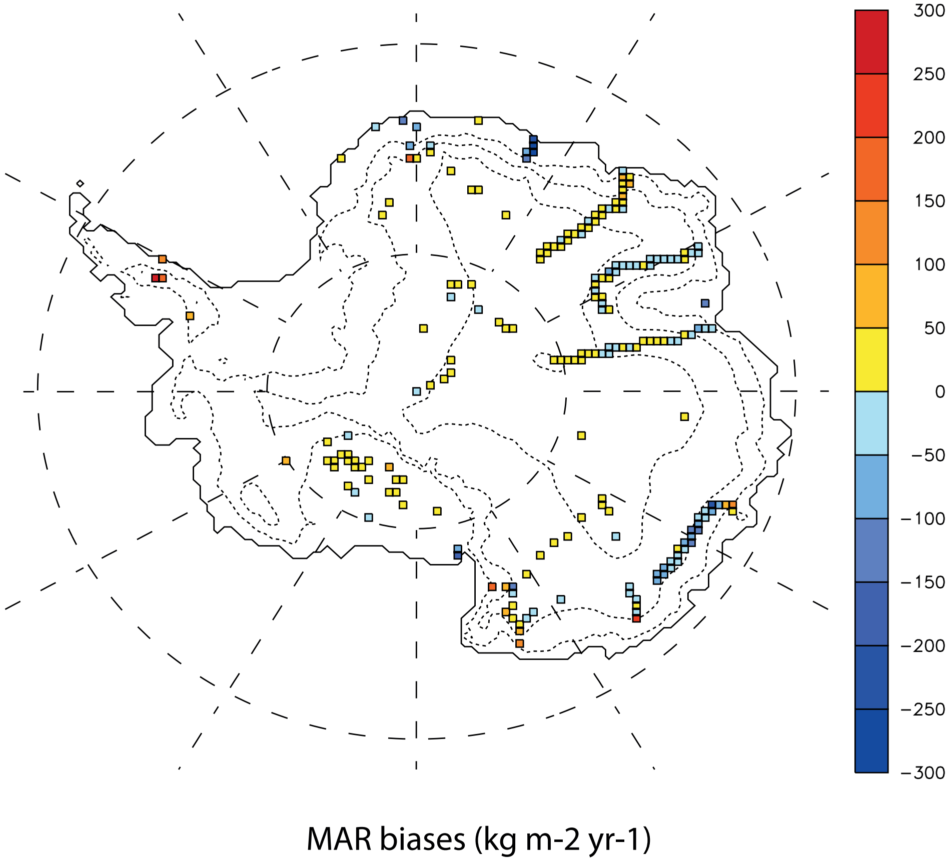


Figure S2. ~~Difference in mean annual~~ Comparison between MAR SMB and observed SMB from the GLACIOCLIM-SAMBA database (Favier et al., 2013) for 1950 – 2015. Units are kg m^{-2} ~~y~~yr^{-1}.

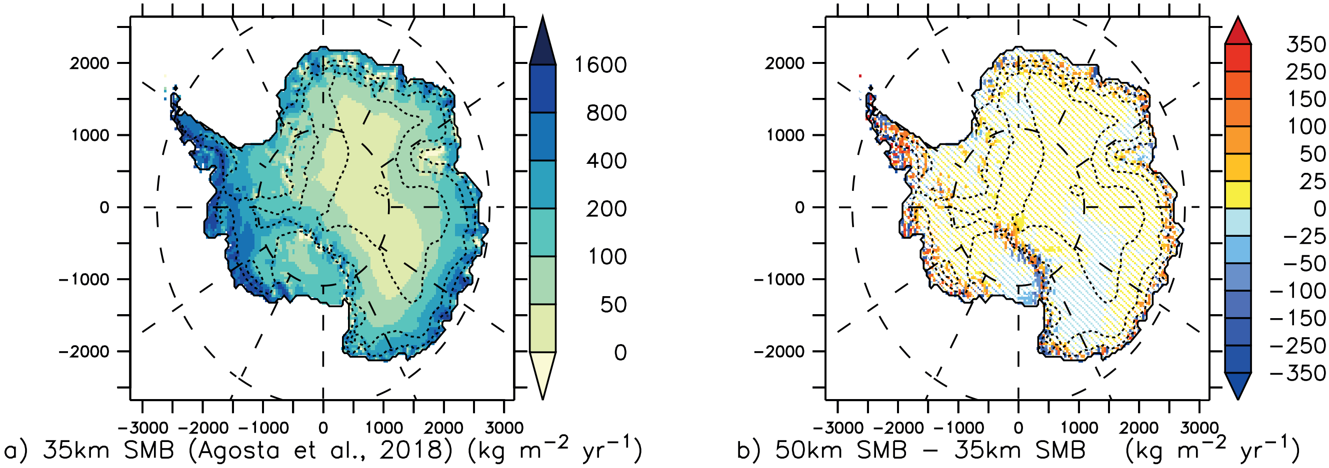
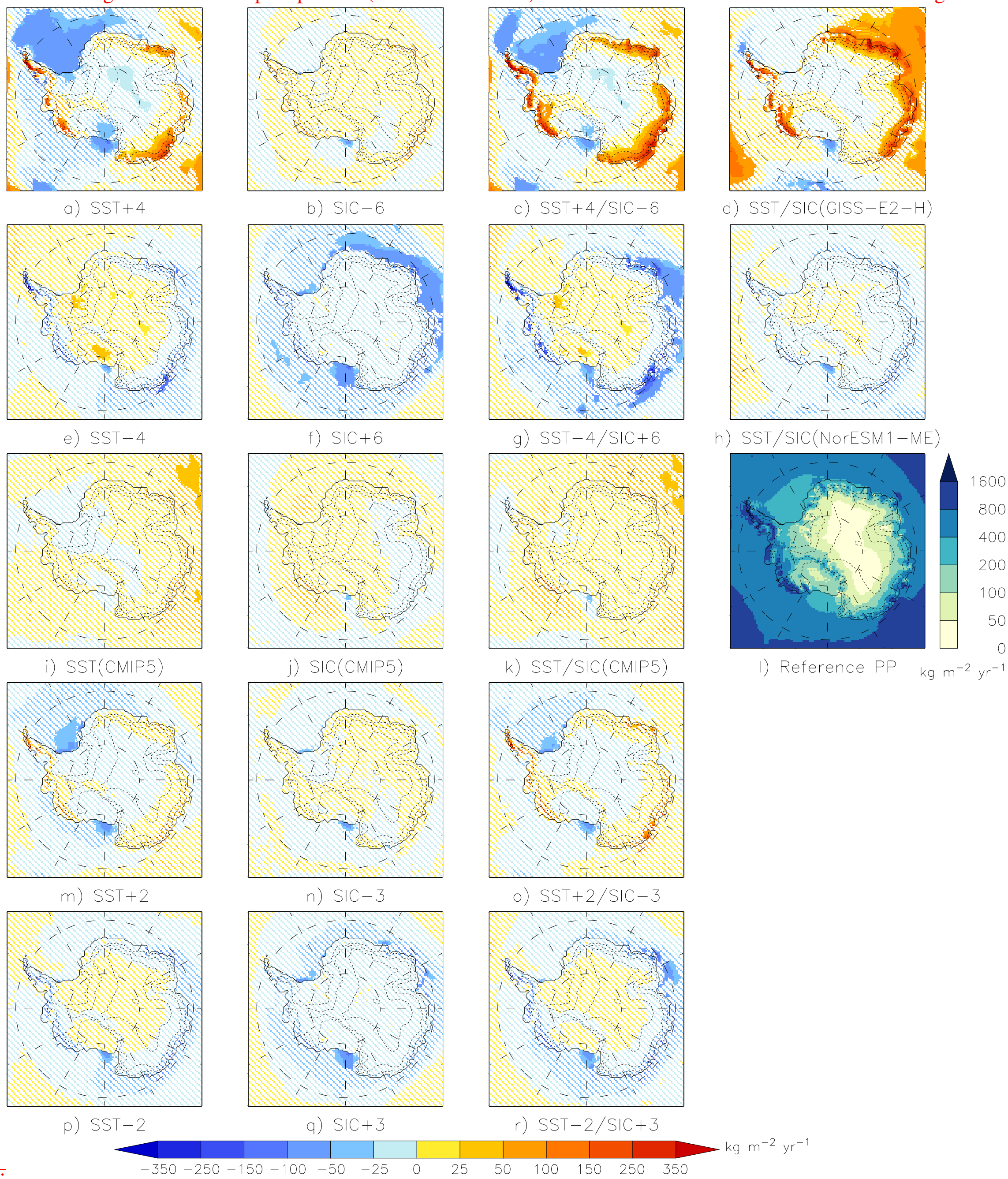


Figure S3. a: Mean SMB simulated by MAR over 1979 – 2015 from Agosta et al.(2018). b: Comparison between the ~~reference simulation and (~~MAR SMB at a ~~) SST+4,~~ 35 km resolution from Agosta et al. (~~b~~2018) ~~SIC-6,~~ and the MAR SMB at a 50 km resolution (~~e~~this study)~~SST+4/SIC-6, (d) SST/SIC(GISS-E2-H), (e) SST-4, (f) SIC+6, (g) SST-4/SIC+6, (h) SST/SIC(NorESM1-ME), (i) SST(CMIP5), (j) SIC(CMIP5), (k) SST/SIC(CMIP5), (~~. Units are kg m~~) SST+2,~~ $^{-2}$ yr^{-1}. Non-significant anomalies (~~n) SIC-3, (o) SST+2/SIC-3, (p) SST-2, (q) SIC+3, (r) SST-2/SIC+2 experiments~~i.~~Difference less~~ e., lower than the interannual variability) are ~~considered as non-significant and are dashed~~hatched.~~l) Mean annual SMB (kg m^{-2} y^{-1}) simulated by MAR forced by ERA-Interim over 1979 – 2015.~~

~~Same as Fig. ?? but for total precipitation (rainfall + snowfall) over the Antarctic ice sheet and the surrounding~~



~~ocean.~~

Figure S4. Difference in mean annual total precipitation (rainfall + snowfall) (kg m^{-2} y^{-1}) between the reference simulation and (a) SST+4, (b) SIC-6, (c) SST+4/SIC-6, (d) SST/SIC(GISS-E2-H), (e) SST-4, (f) SIC+6, (g) SST-4/SIC+6, (h) SST/SIC(NorESM1-ME), (i) SST(CMIP5), (j) SIC(CMIP5), (k) SST/SIC(CMIP5), (m) SST+2, (n) SIC-3, (o) SST+2/SIC-3, (p) SST-2, (q) SIC+3, (r) SST-2/SIC+2 experiments. Difference less than the interannual variability are considered as non-significant and are dashed. l) Mean annual SMB (kg m^{-2} y^{-1}) simulated by MAR forced by ERA-Interim over 1979 – 2015.

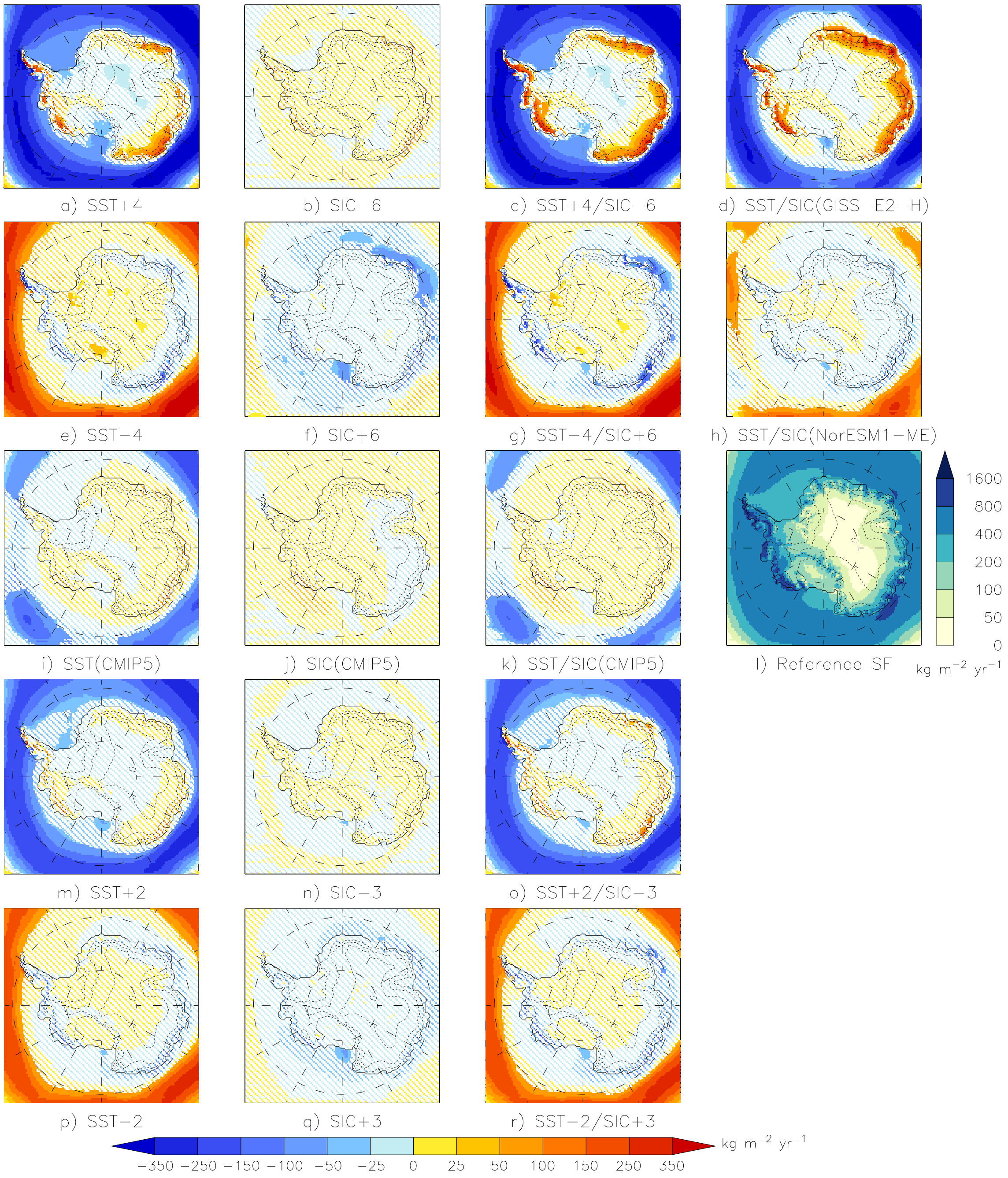


Figure S5. Same as Fig. ~~??~~ S4 but for snowfall over the ice sheet and the surroudning ocean.

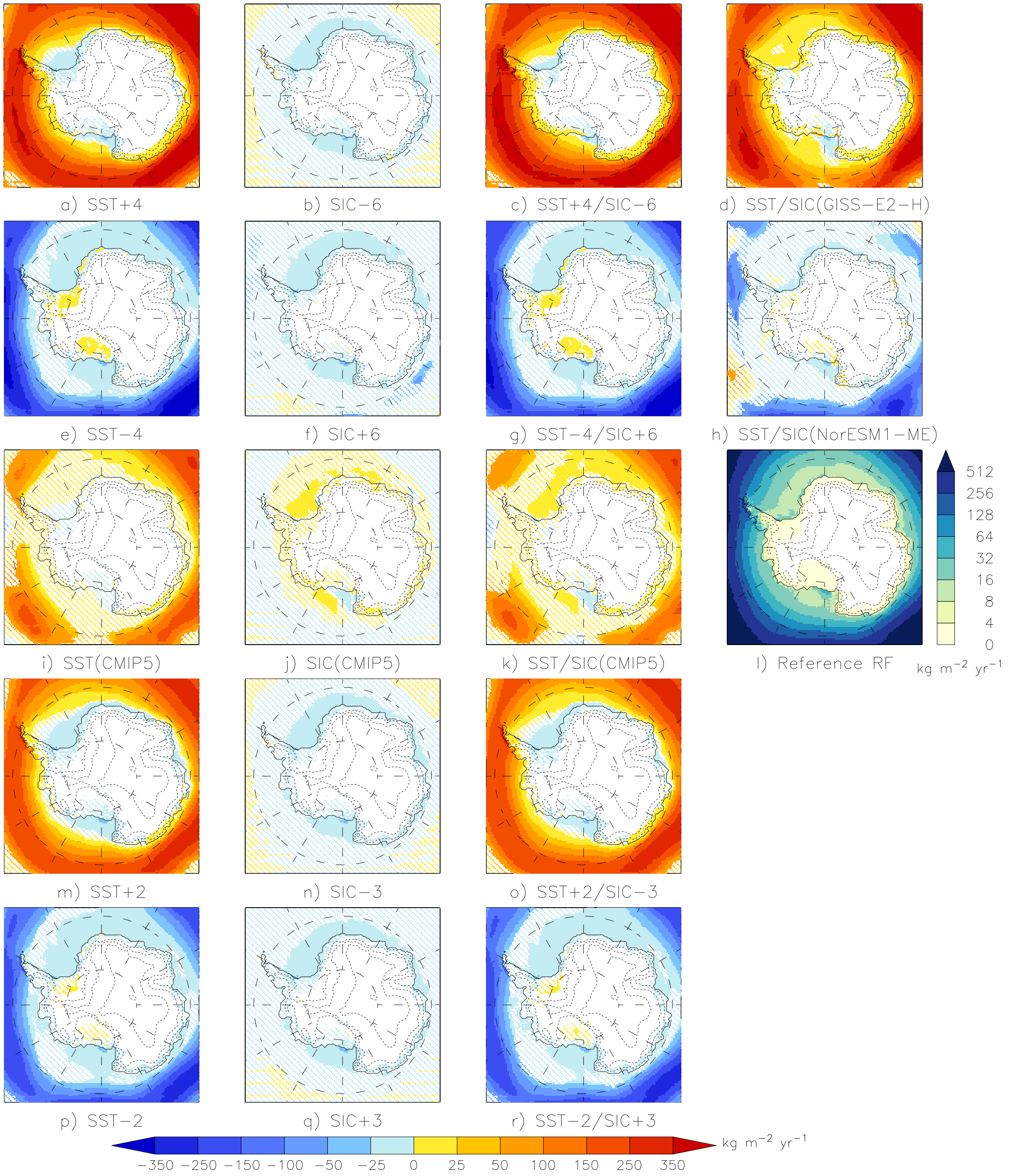


Figure S6. Same as Fig. ~~??~~ S4 but for rainfall over the ice sheet and the surroudning ocean. ~~Withe~~ White areas over the ice sheet indicates that there is no rainfall.

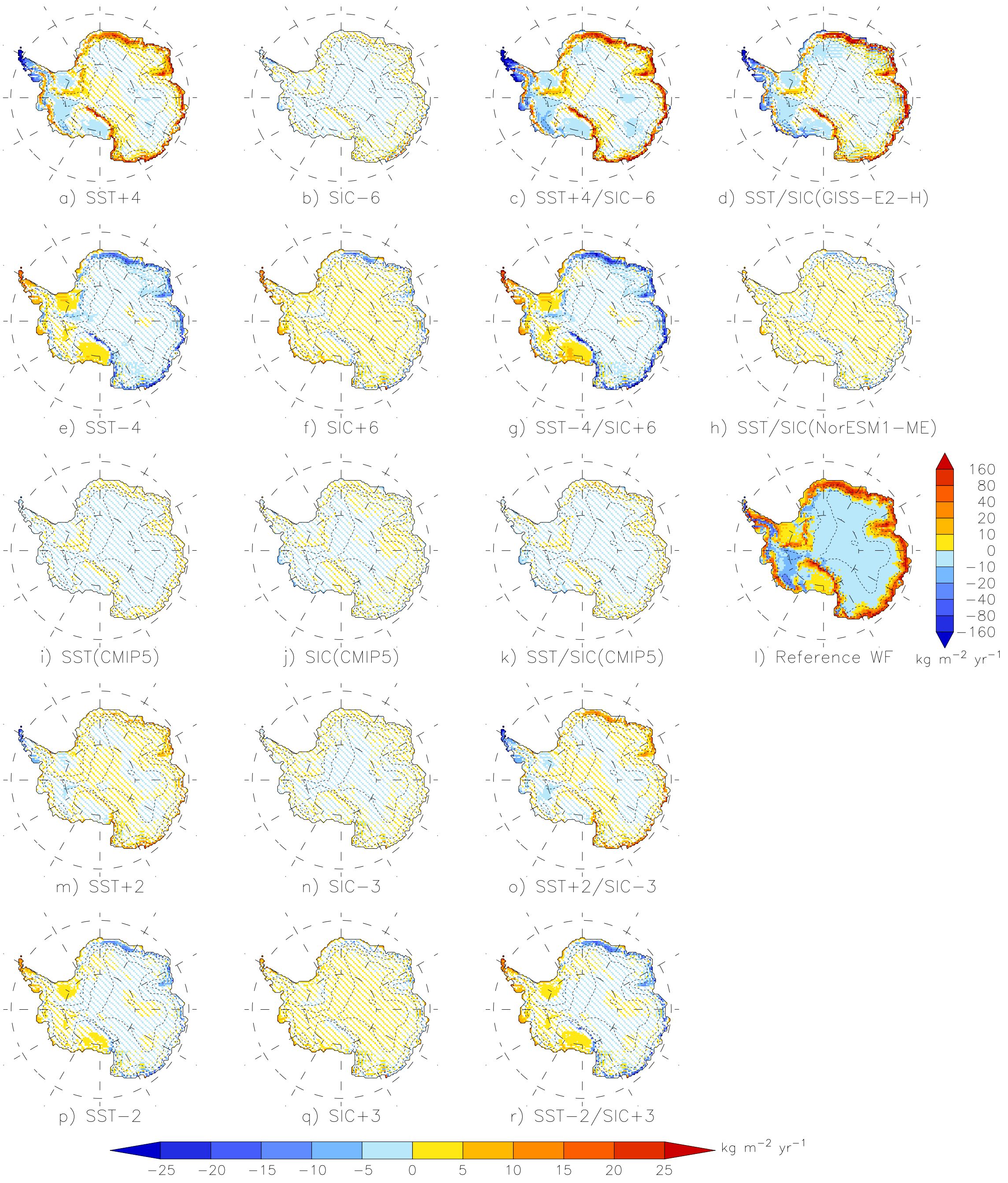


Figure S7. Same as Fig. ~~??~~ S4 but for waterfluxes (sublimation mines deposition) at the ice sheet surface. Positive fluxes indicates sublimation while negative fluxes are representative of deposition processes.

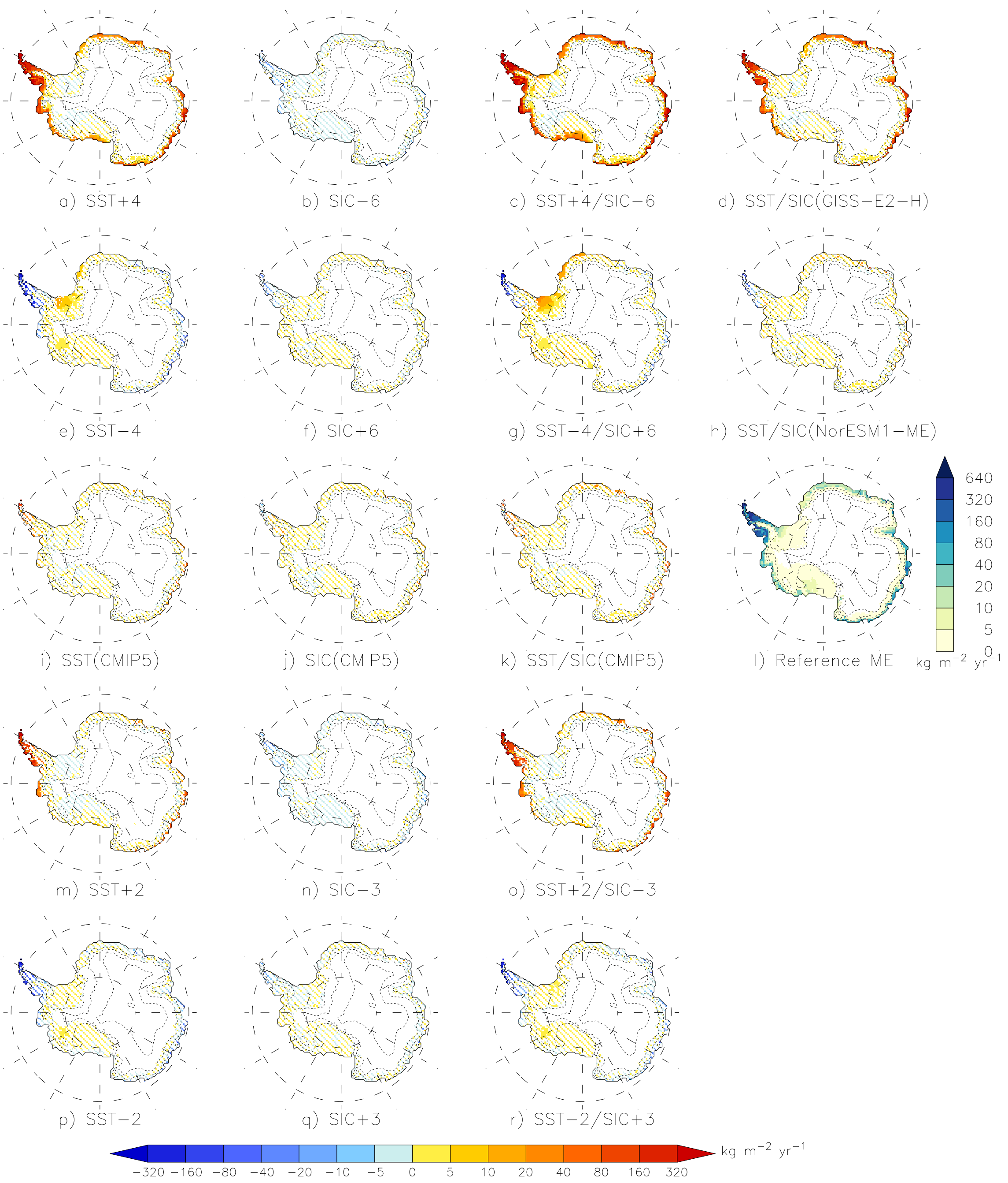


Figure S8. Same as Fig. ~~??~~ S4 but for meltwater production at the surface. ~~Withe~~ White areas over the ice sheet indicates that melt never occurs.

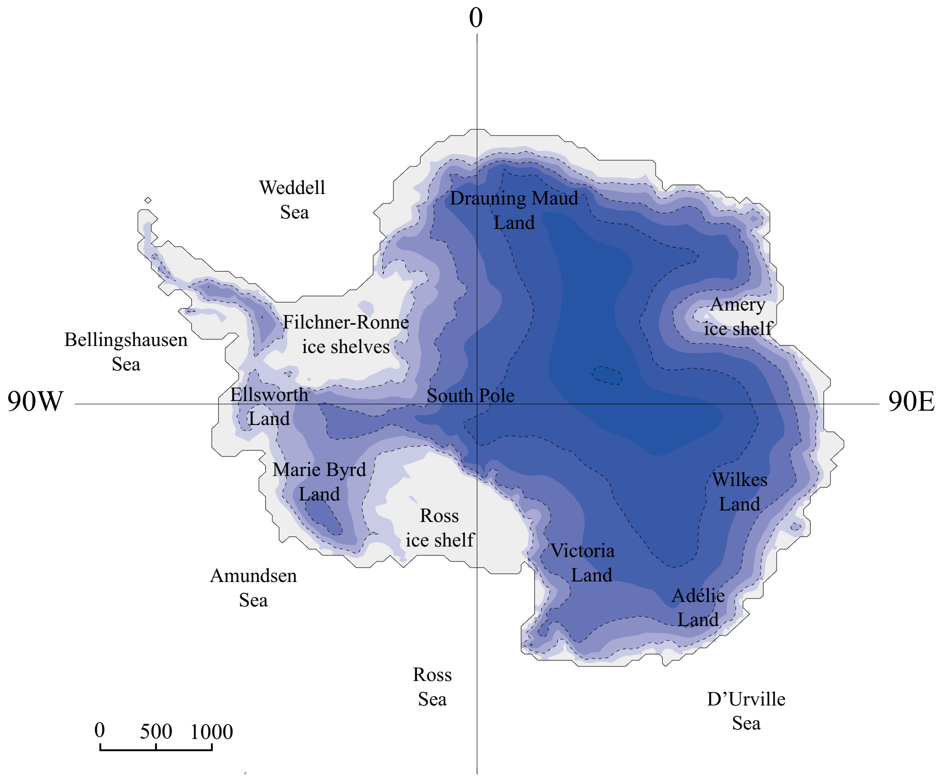


Figure S9. The Antarctic ice sheet and surrouding seas. Elevation contours are shown every 1000 m.

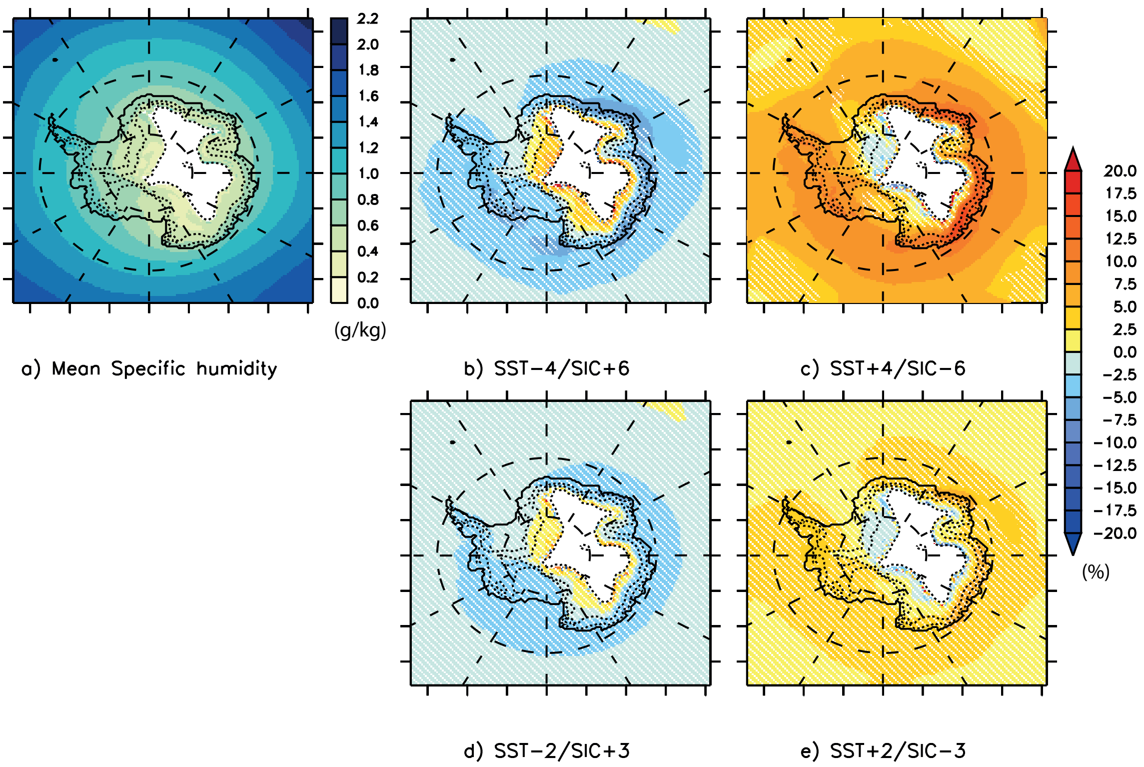


Figure S10. a: Mean specific humidity modelled by MAR over 1979–2015 at 700 hPa (Units: g/kg). Difference in mean specific humidity (%) between the reference simulation and (b) SST-4/SIC+6, (c) SST+4/SIC-6, (d) SST-2/SIC+3, (e) SST+2/SIC-3 experiments. Differences lower than the interannual variability are considered as non-significant and are dashed.

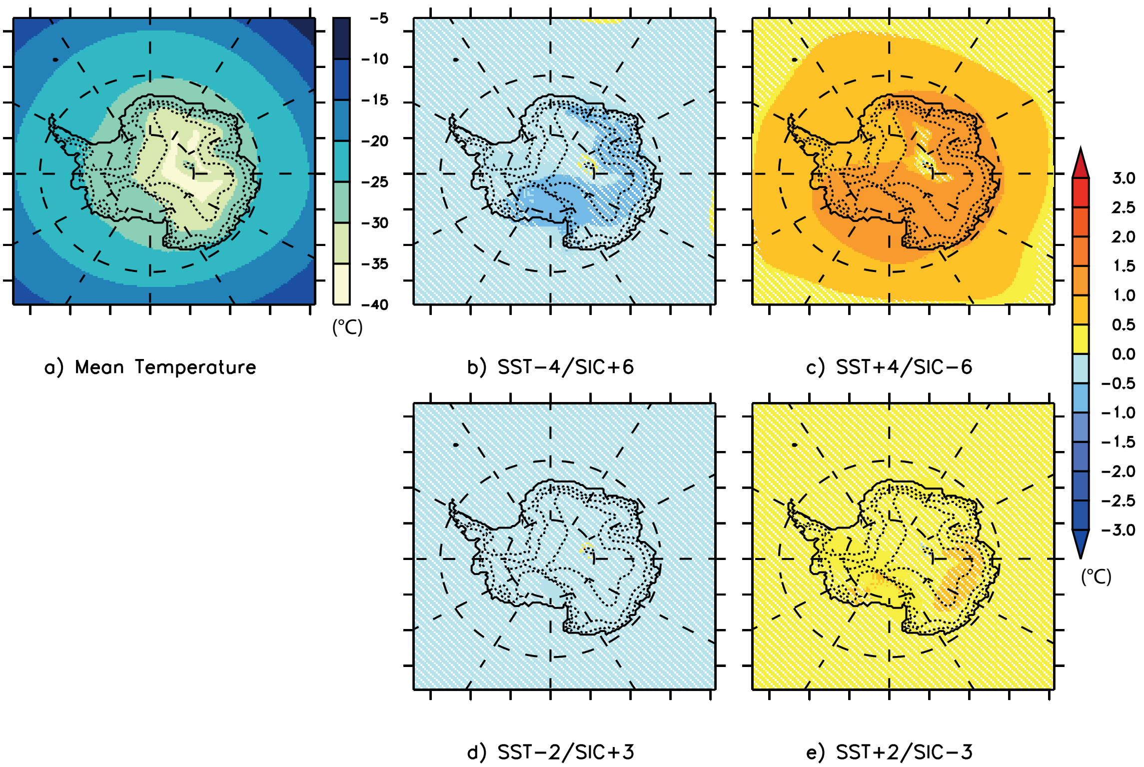


Figure S11. a: Mean air temperature modelled by MAR over 1979–2015 at 600 hPa (Units: °C). Difference in mean air temperature (°C) between the reference simulation and (b) SST-4/SIC+6, (c) SST+4/SIC-6, (d) SST-2/SIC+3, (e) SST+2/SIC-3 experiments. Differences lower than the interannual variability are considered as non-significant and are dashed.

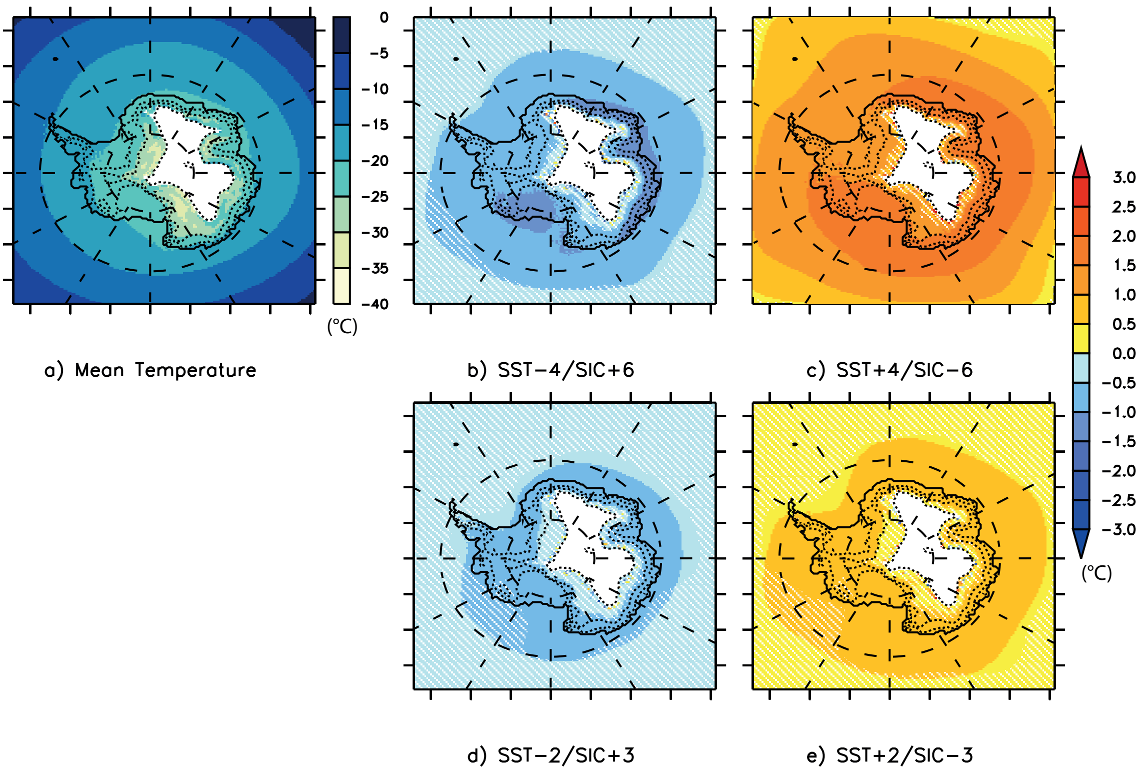


Figure S12. Same as Fig. S11 but 700 hPa.

Table S1. Top: Annual mean integrated (Gt yr^{-1}) and standard deviation (Gt yr^{-1}) total precipitation (rainfall and snowfall), snowfall and rainfall ver the whole AIS (including grounded and not grounded ice) for the reference simulation (1979–2015). Bottom: Difference of annual mean total precipitation (rainfall and snowfall), snowfall and rainfall (Gt yr^{-1} and %) between each sensitivity test and the reference simulation (1979–2015). Anomalies larger than the inter-annual variability are considered as significant and are displayed in bold.

Mean (Gt y^{-1})	Total precipitation	Snowfall	Rainfall
Reference	2678 ± 110	2658 ± 109	20± 3
Anomaly (Gt y^{-1})	Total precipitation	Snowfall	Rainfall
SST-4	-64	-61	**-3**
SST-2	-89	-85	**-4**
SST+2	+50	+45	**+5**
SST+4	**+162**	**+137**	**+25**
SIC+6	**-170**	**-166**	**-4**
SIC+3	-107	-104	**-3**
SIC-3	+25	+28	**-3**
SIC-6	+91	+93	-2
SST-4/SIC+6	**-136**	**-133**	**-3**
SST-2/SIC+3	**-129**	**-125**	**-4**
SST+2/SIC-3	**+133**	**+126**	**+7**
SST+4/SIC-6	**+344**	**+304**	**+40**
SST/SIC-Nor	-105	-102	**-3**
SIC-CMIP	+36	+35	+1
SST-CMIP	+80	+79	+1
SST/SIC-CMIP	+105	+104	+1
SST/SIC-GIS	**+368**	**+353**	**+15**