Effect of prescribed sea surface conditions on the modern and future Antarctic surface climate simulated by the ARPEGE AGCM

Julien Beaumet[1], Michel Déqué[2], Gerhard Krinner[1], Cécile Agosta[3], and Antoinette Alias[2]

[1]Univ. Grenoble Alpes, CNRS, IGE, F-38000, Grenoble, France
[2]CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France
[3]Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, F-91198 Gif-sur-Yvette, France

Correspondence to: Julien Beaumet (Julien.Beaumet@univ-grenoble-alpes.fr)

Abstract. Owing to increase in snowfall, the Antarctic Ice Sheet surface mass balance is expected to increase by the end of current century. Assuming no associated response of ice dynamics, this will be a negative contribution to sea-level rise. However, the assessment of these changes using dynamical downscaling of coupled climate models projections still bears considerable uncertainties due to poorly represented high southern latitudes atmospheric circulation and sea surface conditions (SSC), that is sea surface temperature and sea-ice concentration.

This study evaluates the Antarctic surface climate simulated by a global high-resolution atmospheric model, and assesses the effects on the simulated Antarctic surface climate of two different SSC data sets obtained from two coupled climate models projections. The two coupled models from which SSC are taken, MIROC-ESM and NorESM1-M, simulate future Antarctic sea ice trends at the opposite ends of the CMIP5 RCP8.5 projections range. The atmospheric model ARPEGE is used with a stretched grid configuration in order to achieve an average horizontal resolution of 35 kilometers over Antarctica. Over the 1981-2010 period, ARPEGE is driven by the SSC from MIROC-ESM, NorESM1-M CMIP5 historical runs, and by observed SSC. These three simulations are evaluated against the ERA-Interim reanalyses for atmospheric general circulation as well as the MAR regional climate model, and *in-situ* observations for surface climate.

For late 21st century, SSC from the same coupled climate models forced by the RCP8.5 emission scenario are used both directly and bias-corrected with an anomaly method which consists in adding the future climate anomaly from coupled models projections to the observed SSC with taking into account the quantile distribution of these anomalies. We evaluate the effects of driving the atmospheric model by the bias-corrected instead of the original SSC. For the simulation using SSC from NorESM1-M, no significantly different climate change signals over Antarctica as a whole are found when bias-corrected SSC are used. For the simulation driven by MIROC-ESM SSC, a significant additional increase in precipitation and in winter temperatures for the Antarctic Ice Sheet is obtained when using bias-corrected SSC. For the range of Antarctic warming found (+3 to +4 K), we confirm that snowfall increase will largely outweigh increases in melt and rainfall. Using the end members of sea ice trends from the CMIP5 RCP8.5 projections, the difference in warming obtained ($\sim$ 1 K) is much smaller than the spread of the CMIP5 Antarctic warming projections. This confirms that the errors in representing the Southern Hemisphere atmospheric circulation in climate models are also determinant for the diversity of their projected late 21st century Antarctic climate change.

1 Introduction

Projected 21st century increase of the Antarctic surface mass balance (SMB) due to higher snowfall rates are expected to partly compensate for eustatic sea level rise (SLR) due to opposite changes in almost all other components affecting global sea level (Agosta et al., 2013; Ligtenberg et al., 2013; Lenaerts et al., 2016). However, the acceleration of ice flow and the interactions between oceans and ice shelves are expected to lead to an overall positive Antarctic contribution to SLR (Pollard et al., 2015; Ritz et al., 2015). Uncertainties in ice dynamics and surface mass balance trends are large and influence each other (e.g., Winkelmann et al., 2012; Barrand et al., 2013). It is therefore crucial to produce high-quality Antarctic climate projections for the end of the current century with reduced uncertainties, yielding trustworthy estimates of the contribution of the Antarctic Ice Sheet (AIS) SMB and useful driving data for ice dynamics and ocean-ice shelves interaction model studies.

Detection of an anthropogenic climate change signal is more challenging in high southern latitudes than in the Arctic. While some parts of West Antarctica and of the Antarctic Peninsula (AP) have experienced one of the world's most dramatic warming in the second part of the 20th century (Vaughan et al., 2003; Bromwich et al., 2013), there was no significant recorded temperatures trend in East Antarctica as a whole (Nicolas and Bromwich, 2014) except for some coastal regions that experienced a cooling in autumn over the 1979-2014 period (Clem et al., 2018). Moreover, the observed strong warming trend in the AP has shown a pause or even a reversal for 13 years in the beginning of the 21st century (Turner et al., 2016). Contrary to the dramatic sea ice loss observed in the Arctic (e.g., Stroeve et al., 2012), significant positive trends have been observed in the Antarctic sea ice extent (SIE) since the 1970s (Comiso and Nishio, 2008; Turner et al., 2015, e.g.), although a record of sea ice loss was observed in 2016/7 (Turner et al., 2017). Most of the Coupled Atmosphere-Ocean Global Circulation Models (AOGCM or CGCM), such as those participating the Coupled Model Intercomparison Project, Phase 5 (CMIP5, Taylor et al., 2012) struggle to reproduce the seasonal cycle of SIE around Antarctica, and very few of them were able to reproduce the positive trend observed at the end of the 20th century (Turner et al., 2013). This is problematic because Krinner et al. (2014) showed that atmospheric model simulations of the Antarctic climate are very sensitive to the prescribed sea surface conditions (SSC), that is, sea surface temperatures (SST) and sea-ice concentration (SIC). Additionally, the amount of sea ice present in historical AOGCM climate simulations is strongly correlated to the projected absolute sea ice decrease for the 21st century (Agosta et al., 2015; Bracegirdle et al., 2015), which is linked itself to the strengthening of the westerly wind maximum (Bracegirdle et al., 2018). It is expected that the signal due to the current anthropogenic climate change will take over the natural variability of Antarctic climate by the middle of the twenty-first century (Previdi and Polvani, 2016). Favier et al. (2017) and Lenaerts et al. (2019) provide more complete reviews of the current understanding of the regional climate and surface mass balance of Antarctica and of the key-processes that determine their evolution.

The dynamical downscaling of climate projections such as those provided by coupled models from the CMIP5 ensemble is generally produced using Regional Climate Models (RCM). The marginal importance of atmospheric deep convection for Antarctic precipitation does not require dynamical downscaling at very high resolutions. Therefore the use of a cloud resolving atmospheric model configurations is not particularly relevant for Antarctic climate projections. However, the added value of higher horizontal resolutions, such as the CORDEX-like simulations (Giorgi and Gutowski, 2016) at 0.44°, with respect to driving climate projections at coarser resolution (1 to 2°) from the CMIP5 ensemble is significant near the AIS margins, as the steep topography induces a strong precipitation gradient between wet coastal regions and dry inland East Antarctic Plateau (EAP). Below 1000 m above sea level (a.s.l), the origin of precipitation on the AIS is mostly orographic (e.g., Orr et al., 2008). For present-day climate, Lenaerts et al. (2016, 2018) found no significant differences in area integrated SMB and coastal-inland snowfall gradient between simulations with the RACMO model run at 5.5 and 27 km horizontal resolution. Genthon et al. (2009) similarly found reduced impact of the model grid resolution when excluding very coarse ($> 4°$) model of the CMIP3 ensemble. For future climate projections however, much larger precipitation increases were reported when using climate models at higher horizontal resolutions (Genthon et al., 2009; Agosta et al., 2013). The modelling of strong katabatic wind blowing at the ice sheet surface is also generally improved with a better representation of the topography (e.g., van Lipzig et al., 2004).

In this study, we use CNRM-ARPEGE, the atmosphere general circulation model (AGCM) from Météo-France, with a stretched grid allowing an average horizontal resolution of 35 km over the Antarctic continent, to dynamically downscale multiple coupled climate simulations. As a global atmospheric model, ARPEGE is driven by prescribed SSC, but does not require any lateral boundary conditions. This method has some advantages over the more commonly used limited-area RCM method which depends, for future climate projection, on the quality of the representation of the climate of the region of interest by the driving GCM used at lateral boundaries. When using stretched grid AGCMs, it is possible to use observed SSC at the present and model-generated SSC anomalies for projections (e.g., Krinner et al., 2008). When such an anomaly method is used, it is not required that the AOGCM used as a driver for SSC perfectly represents the atmospheric general circulation and its variability in the region of interest. Using a stretched grid GCM also allows us to better take into account potential feedback and teleconnections between the high-resolution region we are interested in, and other regions of the world. Several studies showed that AGCMs produce a better representation of atmospheric general circulation and a better spatial distribution of precipitation when driven by observed SSC instead of simulated SSC (Krinner et al., 2008; Ashfaq et al., 2011; Hernández-Díaz et al., 2017). Consistently, these studies also showed that AGCM projections driven with bias-corrected SSC, instead of SSC directly taken from coupled model output, yielded significantly different results.

In this work, a bias-correction of SSC using a quantile mapping method for SST and an analog method for SIC is achieved following the recommendations described in Beaumet et al. (2019). We drive the ARPEGE AGCM (Déqué et al., 1994) with both observed and simulated (from coupled models) SSC for the recent past (1981-2010). For future climate projections (late 21^{st} century), we drive the model with SSC directly taken from two coupled models and with corresponding bias-corrected SSC. One aim of this paper is to evaluate the capability of ARPEGE at high resolution to represent the current Antarctic climate. Additionally, we quantify the sensitivity of present and future simulations of this AGCM to the prescribed SSC. The results are compared to similar studies (Krinner et al., 2008, 2014), that used the global atmospheric model LMDZ with a coarser resolution than the one used in this study, in the aim of analyzing the impact of prescribed SSC on the Antarctic climate simulated by AGCMs.

In Section 2.1, we present a short analysis of CMIP5 SST and SIE in the Antarctic region, which were used as a basis to select the coupled model providing SSC forcing for our simulations. In Section 2.2, we present more in detail the ARPEGE model set-up used in this study. In section 3.1, we assess the ability and limitations of CNRM-ARPEGE to represent current Antarctic climate. Results and comparisons for Antarctic future climate projections are detailed in section 3.2.

2 Data and Methods

2.1 Sea Surface Conditions in CMIP5 AOGCMs

Sea surface conditions have been identified as key drivers for the evolution of the climate of the Antarctic continent (Krinner et al., 2014; Agosta et al., 2015). In this study, SSC obtained from CMIP5 projections are bias-corrected using recommendations from Beaumet et al. (2019) before being used as surface boundary conditions for the atmospheric model. The bias-correction methods used for SST ans SIC mostly relies on anomalies methods, which consists in adding the anomalies coming from a coupled model projection to the observed SSC while taking into account the quantile distribution of these anomalies. Besides, the analog method for sea-ice recombines analog candidates from a library of observed and simulated SIC maps in order to reproduce SIE and sea-ice area computed using the anomaly method. Therefore, the importance of the realism of each CMIP5 model for the reconstruction of oceanic conditions around Antarctica in their historical simulation is reduced. There is however a limitation in the previous statement, as the analog method used to bias-correct SIC runs into trouble when the bias is so large that sea ice completely disappears over wide areas for too long. Besides this caveat, the choice of CMIP5 AOGCMs used in this study was guided by compliance to desired characteristics of the climate change signal rather than by the skills of the models in reproducing SSC in the historical periods.

Therefore, we identified CMIP5 models with the strongest and weakest climate change signal by the end of the 21st century considering only SSC in the Southern Ocean, in order to span the uncertainty range associated with model response. We computed the relative evolution of integrated winter SIE over the whole Southern Ocean between the historical simulation (reference period: 1971-2000) and their RCP8.5 projection (reference period: 2071-2100) for 21 AOGCMs from CMIP5 experiment. The CMIP5 ensemble was reduced to 21 members because we discarded models sharing the same history of development and high code comparability. The model list is the same as in Krinner and Flanner (2018) and can be seen in the Fig. 1 legend. We also looked at the mean summer SST increase South of 60°S for the same reference periods. In order to be consistent with periods of maximum (minimum) SIE, seasons considered in this analysis are shifted, and late winter (summer) corresponds here to the period August-September-October, ASO (February-March-April, FMA).

The results of the computation can be seen in Fig. 1, which displays the relative late winter (ASO) decrease in SIE in the RCP8.5 projections as a function of the value of the late winter SIE in the historical simulation. The four models with the strongest SIE decrease are CNRM-CM5 (-62.4 %), GISS-E2-H (-53.4 %), inmcm4 (-47.9%) and MIROC-ESM (-45.2 %). Because of the above-mentioned limitation of the bias-correction method, the first three GCMs cannot be selected due to a large negative bias of winter and spring SIE. We therefore selected MIROC-ESM as representative for models projecting a decrease in sea ice around Antarctica. Conversely, MIROC5 shows the lowest decrease (-1.5%) followed by NorESM1-M (-13,6%). For

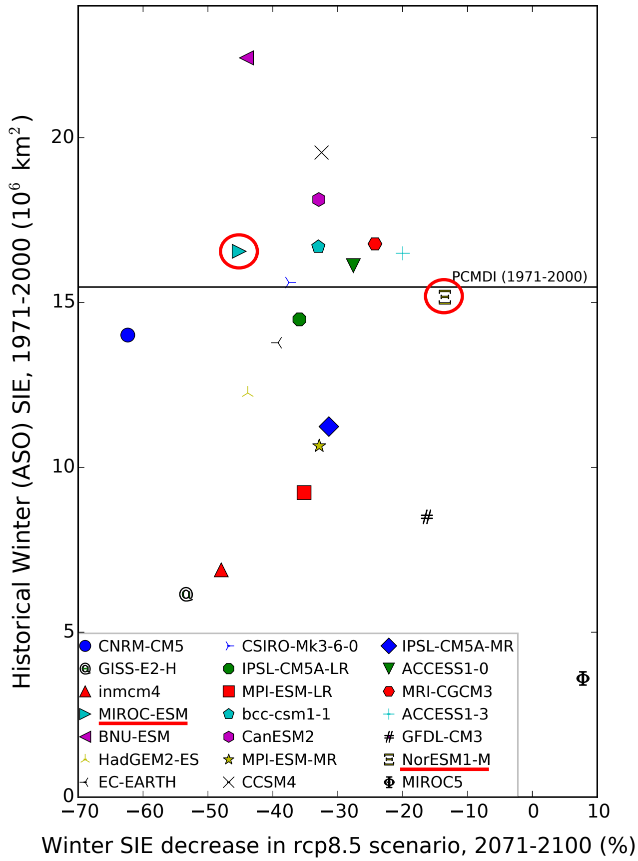

Figure 1. Historical Antarctic winter (August-September-October: ASO) sea ice extent (SIE, in millions of km^2) as function of the relative decrease of winter SIE in the RCP8.5 projection for the period 2071-2100 with respect to the reference period 1971-2000. The mean winter SIE in the observations for the historical reference period is indicated by the horizontal black line (PCMDI 1971-2000). Model selected for this study are highlighted in red.

the same reasons of limitations of the bias correction method, we dismissed MIROC5 and kept NorESM1-M as representative for a weak climate change signals in the SSC around Antarctica. The impact of primarily considering changes in winter SIE rather than in late summer SST is limited as the climate change signal for these two variables are strongly correlated (R^2=0.96). For late summer SSTs, MIROC-ESM shows the 6$^{\text{th}}$ largest increase (+1.8 K), while NorESM1-M exhibits the second lowest (+0.4 K).

2.2 CNRM-ARPEGE set-up

We use version 6.2.4 of AGCM ARPEGE, a spectral primitive equation model from Météo-France, CNRM (Déqué et al., 1994). The model is run at T255 truncation with a 2.5 zoom factor and a pole of stretching at 80°S and 90°E. With this set-

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

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

ting, the horizontal resolution in Antarctica ranges from 30 km near the stretching pole on the Antarctic Plateau to 45 km at the northern tip of the Antarctic Peninsula. At the Antipodes, near the North Pole, the horizontal resolution decreases to about 200 km. In this model version, the atmosphere is discretized into 91 sigma-pressure vertical levels. The surface scheme is SURFEX-ISBA-ES (Noilhan and Mahfouf, 1996) which contains a three-layer snow scheme of intermediate complexity (Boone and Etchevers, 2001) that takes into account the evolution of the surface snow albedo, the heat transfer through the snow layers and the percolation and refreezing of liquid water in the snow pack. Over the ocean, we use a 1D version of sea ice model GELATO (Mélia, 2002) which means that no advection of sea ice is possible. The sea ice thickness is prescribed following the empirical parametrization used in Krinner et al. (1997, 2010) and described in Beaumet et al. (2019). The use of GELATO is therefore limited to the computation of heat and moisture fluxes in sea ice covered regions and also allows taking into account for the accumulation of snow on top of sea ice.

We performed an AMIP-style control simulation for the period 1981-2010 in which CNRM-ARPEGE is driven by observed SST and SIC coming from PCMDI data set (Taylor et al., 2000). CNRM-ARPEGE was also forced by the original SSC coming from the historical simulations of MIROC-ESM and NorESM1-M (1981-2010) and from projections under the radiative concentration pathway RCP8.5 (Moss et al., 2010) carried out with the same two models (2071-2100). In each ARPEGE simulation, the first two years are considered as a spin-up phase for the atmosphere and the soil or snowpack, and are therefore discarded from the analysis. The characteristics of the different ARPEGE simulations presented in this paper are summarized in Table 1.

2.3 Model Evaluation

The ability of ARPEGE model to reproduce atmospheric general circulation of the Southern Hemisphere is assessed by comparing sea level pressure (SLP) and 500 hPa geopotential height (Z500) poleward of 20°S to those of ERA-Interim reanalysis (ERA-I). For surface climate of the Antarctic continent, several studies have shown that (near)-surface temperatures from ERA-I are not reliable (Bracegirdle and Marshall, 2012; Jones and Harpham, 2013; Fréville et al., 2014), as the reanalysis is not constrained by a sufficient number of observations and because the boundary layer physics of the model fails to successfully reproduce strong temperature inversions near the surface that characterize the climate of the EAP. As a consequence, near-surface temperatures in Antarctica from ARPEGE simulations are evaluated using observations from the SCAR READER data base (Turner et al., 2004) as well as temperatures from a MAR RCM simulation in order to increase the spatial coverage of the model evaluation. MAR (Gallée and Schayes, 1994) has been one of the most successful RCMs in reproducing the surface climate of large ice sheet such as Greenland (Fettweis et al., 2005; Lefebre et al., 2005) and Antarctica (Gallée et al., 2015; Amory et al., 2015; Agosta et al., 2018). For Antarctica, outputs of the MAR simulation (version 3.6 of the model) driven by ERA-I have been evaluated against *in-situ* observations for surface pressure, 2 m temperatures, 10 m wind speed and surface mass balance in Agosta et al. (2018) and Agosta (2018). MAR skills for temperatures and SMB are excellent for most of Antarctica. However, a systematic 3-5 K cold bias over large ice shelves (Ross and Ronne-Filchner) throughout the year and a 2.5 K warm bias over the Antarctic Plateau in winter are worth mentioning.

In this evaluation, we compare ARPEGE near-surface temperatures, to those of an ERA-I driven MAR simulation (hereafter MAR-ERA-I) at a similar horizontal resolution of 35 kilometres (Agosta et al., 2018). The SMB of the grounded AIS and its components from ARPEGE simulations are compared to the outputs of the same ERA-Interim driven MAR simulation. We also performed an evaluation of ARPEGE snowfall rates using a model independent data set such as the CloudSAT climatology for Antarctic snowfall (Palerme et al., 2014). However, because this data set is only available for a very short period of time (2007-2010) and is representative of snowfall rates about 1200 m above the surface, the results from this comparison have to be considered with extreme caution and are therefore only shown in the supplementary material (see C2).

In this study, the statistical significance at the 5% level of the difference between two samples of independent mean ($\overline{\mathrm{A}} - \overline{\mathrm{B}}$) is admitted when it verifies the following condition :

$$|\,\overline{\mathrm{A}} - \overline{\mathrm{B}}\,| > \frac{1.96 \star ((\mathrm{STD_A} + \mathrm{STD_B}) \star 0.5) \star \sqrt{2}}{\sqrt{\mathrm{n}-2}} \tag{1}$$

where $\mathrm{STD_A}$ and $\mathrm{STD_B}$ are the standard deviation of sample A and B and n is the size of the sample (usually 30 in this study, because of 30 years simulations).

3 Results

3.1 Simulated Present Climate

In this section, ARPEGE simulation are evaluated using mostly ERA-I reanalyses for atmospheric general circulation south of 20° S and polar-oriented RCMs as well as READER *in-situ* data for the surface climate of the ice sheet.

3.1.1 Atmospheric General Circulation

The differences between mean SLP from the 1981-2010 ARPEGE simulation driven by observed SSC (called ARP-AMIP in the remainder of this paper, see Table 1) and mean SLP from ERA-I can be seen in Fig. 2a. The general pattern is an under-estimation of SLP around 40°S, especially in the Pacific sector (up to 6 to 10 hPa) and an overestimation around Antarctica

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

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

(generally between 4 and 8 hPa), especially in Amundsen/Ross Sea sector. Mean SLP differences for ARPEGE simulations driven by NorESM1-M (ARP-NOR-20) and MIROC-ESM (ARP-MIR-20) historical SSC can be seen respectively in Fig. 2b and Fig. 2c. The pattern and the magnitude of the errors are similar to those of the ARP-AMIP simulation in summer (DJF). The seasonal root mean square errors (RMSE) for each simulation are summarized in Table 2. In winter (JJA), spring (SON) and autumn (MAM) the errors are substantially larger in ARP-NOR-20 and ARP-MIR-20 than in ARP-AMIP (up to 50% larger). The patterns of the errors and the ranking of simulation scores are similar for the 500hPa geopotential height (*not shown*).

The mean atmospheric general circulation in each simulation has also been compared and evaluated against ERA-I by analyzing the latitudinal profile of the 850 hPa zonal mean eastward wind component (referred to as westerly winds in the following), as well as the strength (m s^{-1}) and position (° of southern latitude) of the zonal mean westerly wind maximum (Fig. 3). In this figure, results are only presented for the annual average, as the differences between simulations or with respect to ERA-I do not depend much on the season considered (*not shown*). ARP-AMIP and ARP-MIR-20 better simulate the westerly wind maximum strength than ARP-NOR-20, with an underestimation of this maximum of about 1.5 m s^{-1} compared to ERA-I. The equatorward bias on the position of the westerly wind maximum is 1.6° in ARP-NOR-20, while it is up to 3 to 5° in ARP-AMIP and ARP-MIR-20.

3.1.2 Near-surface Temperatures

Screen level (2 m) air temperatures (T_{2m}) from ARP-AMIP simulation are compared to those from MAR-ERA-I simulation and READER data base in winter (JJA) and summer (DJF) for the reference period 1981-2010 (Fig. 4). In this analysis, stations from the READER data base for which less than 80% of valid observations were recorded for the reference period were not used. Altitude differences between corresponding ARPEGE grid point and stations have been accounted for by correcting modelled temperatures with a 9.8 K km^{-1} dry adiabatic lapse rate similarly as in Bracegirdle and Marshall (2012). Errors of the T_{2m} in ARP-AMIP simulation for each weather station and each season are presented in supplementary material (Table B1). The ARP-AMIP T_{2m} are much warmer than MAR-ERA-I on the ridge and the western part of the Antarctic Plateau in winter as well as on on the large Ronne and Ross ice shelves. Consistently with its atmospheric circulation errors in this area, ARPEGE is colder than MAR-ERA-I on the Southern and Western part of the Antarctic Peninsula, especially in winter. We can also mention a moderate (1 to 3 K) but widespread warm bias on the slope of the EAP and on the west side of the West Antarctic

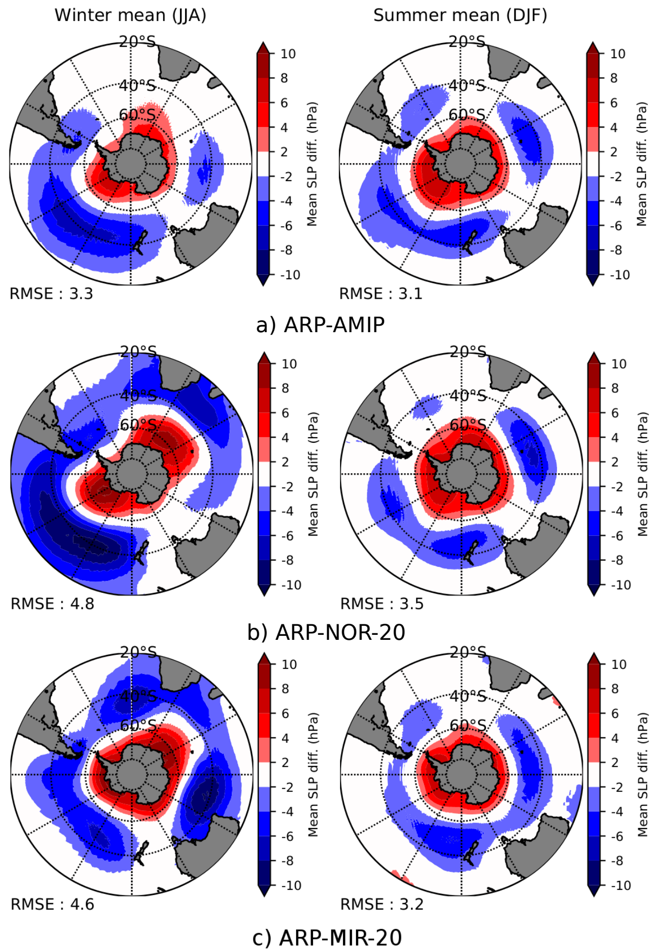

Figure 2. Difference between ARPEGE simulations and ERA-I mean SLP for the reference period 1981-2010 in winter (JJA, left) and summer (DJF, right). Value of the RMSE are given below the plots.

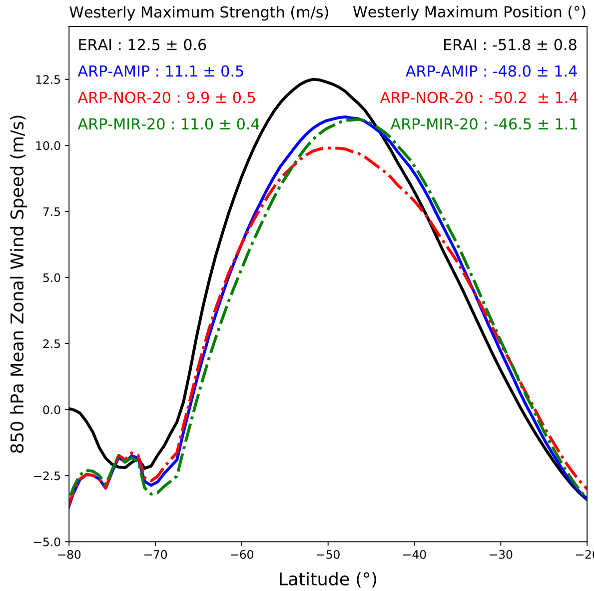

Figure 3. Mean latitudinal profile of 850 hPa eastwards wind component (reference period : 1981-2010) for ARP-AMIP (grey), ARP-MIR-20 (dashed green), ARP-NOR-20 (dashed red) and ERA-Interim (black). Yearly mean ± one standard deviation of strength (m.s^{-1}, upper left) and latitude position (°, upper right) of the 850 hPa westerly wind maximum.

Ice Sheet (WAIS) in summer. Except for some coastal stations of East Antarctica, T_{2m} errors in the ARP-AMIP simulation are very similar in the comparisons with MAR-ERA-I and READER data base.

Considering errors on near-surface temperatures of the Antarctic Plateau as large as 3 to 6 K for ERA-I reanalysis in all seasons (Fréville et al., 2014), skills of the ARP-AMIP simulation in this region are comparable to those of many AGCM or even climate reanalyses. The systematic error for Amundsen Scott station is for instance not significant at the 5% level in any season except autumn (MAM). The large discrepancies between ARPEGE and MAR over large ice shelves are further investigated in the supplementary material(B3). Although a part (3-5K) of this large discrepancy in winter (ARPEGE up to 12 K warmer than MAR over the center of Ross Ice Shelf) comes from a cold bias in MAR identified in the comparison with the in-situ observations (Agosta, 2018), the majority of ARPEGE errors on large ice shelves appears to come from specificities in the representation of stable boundary layers over these large and flat surfaces. As a consequence, the surface climate over the large ice shelves simulated by ARPEGE should at this stage be used with circumspection. Considering the model lower skills on the floating ice shelves, integrated SMB and temperature changes are mostly presented and discussed for the grounded AIS in the remainder of the paper.

Large negative biases in ARP-AMIP for some coastal stations of East Antarctica (Casey, Davis, Mawson, Mc Murdo), especially in winter, are likely due to effects of the local topography that cannot be captured at a 35 kms horizontal resolution.

Table 3. Mean seasonal T_{2m} differences (in K) for the grounded AIS with respect to the ARP-AMIP simulation. Differences significant at p=0.05 are presented in bold.

Simulations	DJF	MAM	JJA	SON
ARP-NOR-20	-0.1	**0.4**	**1.2**	**0.9**
ARP-MIR-20	**-1.5**	-0.2	0.3	**-0.7**

Besides, ARPEGE temperatures are representative for a 35x35 km^2 inland grid point, whereas many weather stations are located very close to the shoreline. The large cold bias at Rothera station on the Peninsula is likely a combination of the effects of poorly represented local topography in the model and of errors on the simulated atmospheric general circulation. Contrary to the continent's interior, the average 35 kms horizontal resolution used in this study is insufficient to capture many local topographic features of the coastal areas and of the AP, which challenges the comparisons with *in-situ* measurements in these areas.

Regarding T_{2m} in ARPEGE simulations forced by NorESM1-M and MIROC-ESM historical SSC, the skills of the ARPEGE model are particularly impacted over the AP and, to a lesser extent, over the EAP (see Fig. B1). Over coastal East Antarctic stations, most of the errors in T_{2m} are likely due to local topography effects, or inadequacies of the physics of the atmospheric model, as the skills of the atmospheric model shows few variations in the three simulations. The use of SSC from NorESM1-M and MIROC-ESM instead of observed SSC also impacts the simulated temperatures at the continental scale. Differences for ARP-NOR-20 and ARP-MIR-20 in T_{2m} for the grounded AIS with respect to the ARP-AMIP simulation are presented in Table 3. For the ARP-MIR-20, differences of -0.7 K in spring and -1.5 K in summer were found significant. For ARP-NOR-20, differences ranging from 0.4 K to 1.2 K in autumn, winter and spring are significant as well.

3.1.3 Surface Mass Balance

In this study, SMB from ARPEGE simulations is defined as the total precipitation minus the surface snow sublimation/evaporation minus the surface run-off. Differences between ARP-AMIP and MAR-ERA-I total precipitation, snow sublimation and SMB (in mm of water equivalent per year) for the reference period 1981-2010 can be seen in Fig. 5. As differences in runoff are restricted to the ice shelves and some very localized coastal areas, their spatial distribution is not displayed in this figure. Yearly mean SMB, total precipitation, sublimation, run-off, rainfall and melt, integrated over the whole grounded AIS for the different ARPEGE simulations, for MAR and RACMO2 driven by ERA-Interim reanalyses and from other studies are presented in Table 4.

Precipitation integrated over the grounded AIS in ARP-AMIP ad ARP-MIR-20 is very close to the values from MAR-ERA-I and RACMO2-ERA-I. However, higher surface sublimation (and run-off) in ARPEGE simulation yields lower estimates of the grounded AIS integrated SMB. Integrated SMB over the ice sheet using ARPEGE however concurs independent estimates from satellite data (e.g., Vaughan et al., 1999; Arthern et al., 2006). Precipitation is generally much higher in ARPEGE with respect to MAR over many coastal areas such as the Ross sector of Marie Byrd Land, in Dronning Maud and in the northern

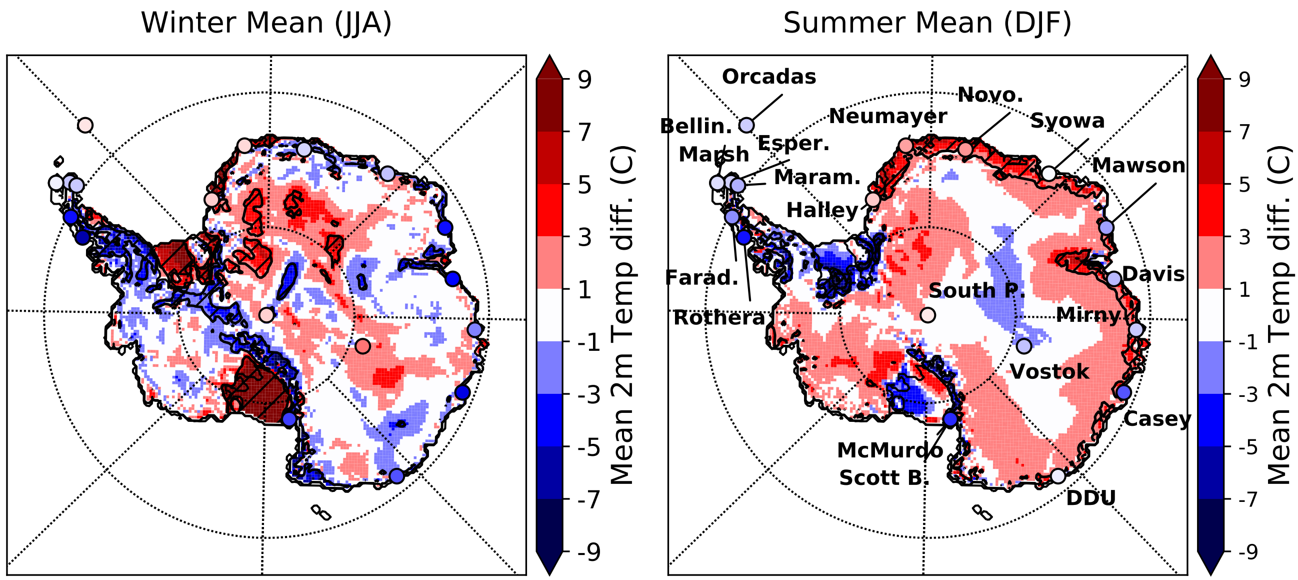

Figure 4. T_{2m} differences between ARP-AMIP and MAR-ERA-I (Agosta et al., 2018) simulations in winter (JJA, *left*) and summer (DJF, *right*) for the reference period 1981-2010. Circles are T_{2m} differences between ARP-AMIP and weather stations from the READER data base, stations names are shown on the right side pannel ("Bellin." = Bellingshausen,"DDU"= Dumont D'Urville, "Esper." = Esperanza, "Farad." = Faraday, "Maram." = Marambio, "Novo." = Novolerevskaya, "South P." = South Pole-Amundsen Scott). Black hatched areas is where $\mid \mathrm{ARPEGE} - \mathrm{MAR} \mid = 1\mathrm{MAR}\sigma$.

and eastern part of the AP. On the other hand, precipitation is lower in ARP-AMIP in the western part of the Peninsula, in the inland part of central WAIS and in the interior and lee-side of the TransAntarctic Mountains. Sublimation integrated over the grounded AIS is about three times higher in ARP-AMIP than in MAR-ERA-I. Differences mostly come from coastal areas and the peripheral ice sheet. This is consistent with ARP-AMIP being systematically 1 to 3 K warmer than MAR-ERA-I in summer in those areas. The inter-annual variability is very high in the simulated ARPEGE runoff, in accordance with MAR-ERA-I. A closer look at the values of rainfall, surface snow melt and runoff in the three present-day ARPEGE simulations in Table 4 shows that about 1/3 of the liquid water input into the snow pack (rainfall + surface snow melt) does not refreeze and therefore leaves the snow pack in the end. In MAR-ERA-I and in RACMO2-ERA-I, this ratio is about 1/20. This means that although the snow surface scheme SURFEX-ISBA-ES used in ARPEGE is in principle able to explicitly account for storage and refreezing of liquid water in the snow-pack, the retention capacity of the Antarctic snow-pack appears to be largely underestimated when compared to MAR and RACMO2. For these reasons, projected changes in melt rates are preferably presented and discussed in section 3.2, while changes in run-off are *not shown* due to the suspected lower skill of ARPEGE for this variable and strong non-linearities expected in changes in surface run-offs in a warming climate.

Simulation	SMB	Precip.	Subli.	Run-Off	Rain	Melt
ARP-AMIP	1970±96	2268±94	277±17	22±14	10±2	52±32
ARP-NOR-20	**2188±101**	**2484±100**	275±12	21±14	10±2	52±27
ARP-MIR-20	1996±84	2267±92	**257±18**	**14±9**	10±3	**34±21**
MAR-ERA-I[1]	2158±106	2260±104	84±10	3±2	16±3	45±15
RACMO2-ERA-I[1]	2117±92	2268±99	136±4	2±2	3±1	61±21
RACMO2-ERA-I[2](entire ice sheet)	2596±121	2835±122	228±11	5±2	6±2	88±24
CESM-hist[3]	2280±131	2433±135	68±6	86±21	5±2	203±41
Vaughan et al. (1999)	1811					

Table 4. Mean Grounded AIS SMB and its component (Gt yr^{-1}) ± one standard deviation of the annual mean for the reference period 1981-2010. Variables from ARP-NOR-20 and ARP-MIR-20 that are significantly different from the value in ARP-AMIP at p=0.05 level are in **bold**. [1]MAR and RACMO2 driven by ERA-I and ARPEGE statistics for 1981-2010 over the grounded AIS are computed using MAR grounded ice mask (area = 12.37 10^6 km^2) as in Agosta et al. (2018). Sublimation values for RACMO2 include drifting snow sublimation, while only surface sublimation is accounted in MAR and ARPEGE statistics.[2]RACMO2 statistics are given for the total Ice Sheet and the period 1979-2005 from Lenaerts et al. (2016), sublimation includes drifting snow sublimation. [3]Community Earth System Model historical simulation (1979-2005), values for the total ice-sheet from Lenaerts et al. (2016)

In the ARP-MIR-20 simulation, snow sublimation, run-off and melt were found significantly lower than in ARP-AMIP, which is consistent with this simulation being 1.5 K cooler in summer (DJF). The effect of driving ARPEGE by biased SSC for the modelling of Antarctic precipitation is discussed in supplementary material (see Sec. C1).

3.2 Climate change signal

In this section, we present the climate change signal obtained in ARPEGE RCP8.5 projections driven by SSC from NorESM1-M and MIROC-ESM. For ARPEGE projections realized using original SSC from the two coupled models (ARP-NOR-21 and ARP-MIR-21), the reference simulations for the historical period are the ARPEGE simulations performed with historical SSC coming from the respective coupled model (ARP-NOR-20 and ARP-MIR-20). For projections realized with bias-corrected SSC (ARP-NOR-21-OC and ARP-MIR-21-OC), the reference simulation for the historical period is ARP-AMIP (observed SSC). The primary goal here is to evaluate the effect on the climate change signals for Antarctica simulated by ARPEGE AGCM associated with SSC forcings coming from two end values of the CMIP5 RCP8.5 ensemble in terms of sea ice retreat, as well as the effect of the bias correction of SSC.

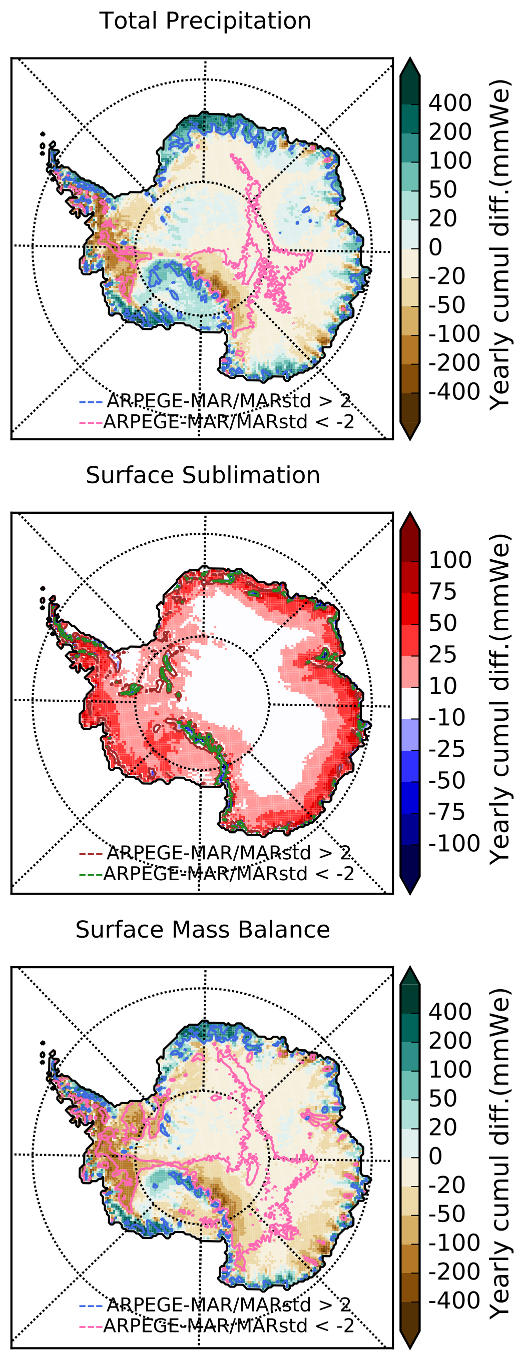

Figure 5. Total precipitation (*top*), Sublimation/Evaporation (*centre*) and SMB (*bottom*) for ARP-AMIP minus MAR-ERA-I difference (mm.we yr^{-1}) for the reference period 1981-2010. Pink (brown) and blue (green) contour lines represents areas where ARPEGE-MAR absolute differences are respectively larger than 2 MAR standard deviation of the annual mean (2σ).

Table 5. Changes in mean yearly Southern westerly wind maximum strength (ΔJSTR, m/s) and position (ΔJPOS, °) for the different ARPEGE projections. Changes significantly different using bias-corrected SSC are shown in **bold**.

Simulations	ΔJSTR (m/s)	ΔJPOS (°)
ARP-NOR-21	1.7	-0.8
ARP-NOR-21-OC	1.5	**-2.2**
ARP-MIR-21	1.9	-3.7
ARP-MIR-21-OC	2.0	-3.8

3.2.1 Atmospheric General Circulation

Climate change signals in mean SLP for the different RCP8.5 projections realized with ARPEGE can be seen in Fig. 6. All projections show a pressure increase at mid-latitudes (30-50 °S) and a decrease around Antarctica. This corresponds to a strengthening of the mid to high latitude pressure gradient (positive phase of the SAM) and a poleward shift of the circum-Antarctic low pressure belt towards the continent, which are generally the expected consequences of 21st century radiative forcing (Kushner et al., 2001; Arblaster and Meehl, 2006). This pattern (increase at mid-latitude, decrease around Antarctica) is sharper in projections realized with MIROC-ESM SSC.

Differences in the climate change signal between ARP-NOR-21-OC and ARP-NOR-21 are smal (Fig. 6a). Differences in SLP changes are larger in the projections realized with MIROC-ESM SSC : in those with non bias-corrected SSC (ARP-MIR-21), the intensification of the low pressure systems around Antarctica in winter is clearly organized in a 3-wave pattern (Fig. 6b). In ARP-MIR-21-OC, the JJA pressure decrease is rather organized in a dipole with one maximum of pressure decrease centered the eastern side of the Ross Sea and the other west of the Weddell Sea. As a result, the 3-wave pattern is clearly noticeable in the difference between the two climate change signals (Fig. 6b, *right*). Late 21st century changes in westerly wind maximum latitude position and strength at 850 hPa are shown in Table 5. When compared to the variability in the reference historical simulations, each climate change signal is significant at the 5% level. Regarding the changes in westerly winds maximum strength, the difference between the two projection using NorESM1-M SSC are limited. However, we can mention a 1.4° larger southward displacement of the westerly wind maximum position in the projection using bias-corrected SSC (significant at the 5% level). Differences in changes in position and strength are not significant between ARP-MIR-21 and ARP-MIR-21-OC. Compared to projections realized with SSC from NorESM1-M, these projections show a slightly larger increase in westerlies maximum strength and a much larger poleward shift, although this difference is reduced when comparing projections with bias-corrected SSC.

3.2.2 Near-surface temperatures

The mean yearly T_{2m} increase for the grounded AIS using SSC from NorESM1-M RCP8.5 projection is 2.9±1.0 K using original SSC (ARP-NOR-21) and 2.8±0.8 K using bias-corrected SSC (ARP-NOR-21-OC). For projections using SSC from MIROC-ESM, these temperatures increases are respectively 3.8±0.7 K and 4.2±1.0 K. The differences in yearly T_{2m} increase

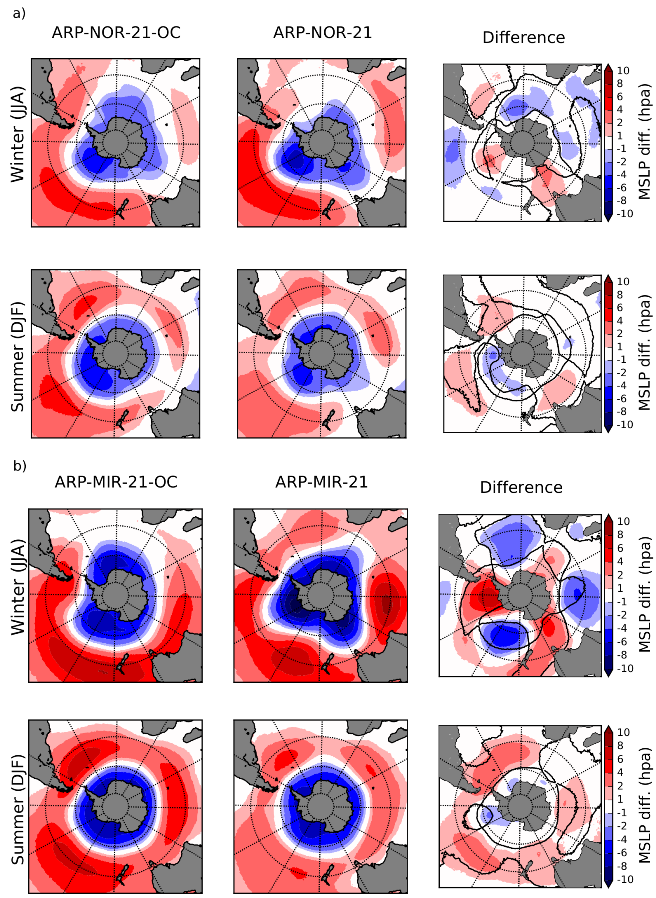

Figure 6. Climate change signal in SLP for ARPEGE RCP8.5 projections with bias-corrected SSC (*left*), original SSC (*center*) and difference (*right*). Climate change signal for winter (JJA) are displayed at the *top* of the subfigures and at the bottom for summer (DJF). Results for projections with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

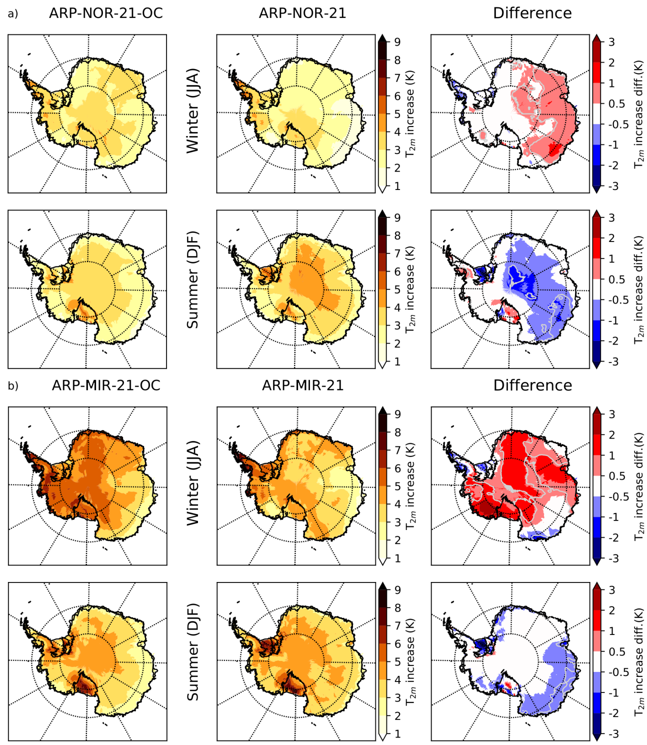

Figure 7. Climate change signal in T_{2m} for ARPEGE RCP8.5 projections for the late 21st century (2071-2100) with bias-corrected SSC (*left*), original SSC (*center*) and difference (*right*). Climate change signal for austral winter (summer) are displayed at the *upper* (*lower*) part of the figure.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

using bias-corrected SSC are found non significant in both cases. T_{2m} increase per season can be seen in Table 6. Only a +0.8 K difference in winter temperatures increase in ARP-MIR-21-OC with respect to the projection driven by original SSC is found significant. At the regional scale (Fig. 7b), this is materialized by large areas of 1 to 2 K stronger warming in the centre of the East Antarctic Plateau, Dronning Maud Land and the Ross Ice Shelf. The difference in warming in ARP-MIR-21-OC is the highest in Marie-Byrd Land (+2 K).

For projections using SSC from NorESM1-M, no seasonal differences were found significant at the AIS scale.

3.2.3 Precipitation and Surface Mass Balance

Absolute values and changes in grounded AIS SMB and its components for the late 21st are shown in Table 7. For the experiment realized with NorESM1-M SSC, precipitation and SMB changes (in both cases increases) are very similar (no significant differences), despite about 220 Gt.yr^{-1} more precipitation and accumulation in ARP-NOR-21 absolute values (significant at p=0.05, Table 7). No significant differences in absolute values or climate change signals were found for the other components

Table 6. Mean seasonal T_{2m} increase (K) for the grounded AIS for the different ARPEGE RCP8.5 projection for late 21^{st} century (reference period: 2071-2100) with respect to their historical reference simulation (reference period: 2071-2100). Climate change signal in projections with bias-corrected SSC significantly different at p=0.05 level are presented in bold.

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

of SMB for projections with NorESM1-M SSC.

For the experiment performed with MIROC-ESM SSC, absolute values and increase in precipitation are about 170 Gt.yr^{-1} (7 %) stronger in the projection with bias-corrected SSC. The total precipitation increase is +8.8% K^{-1} in ARP-MIR-21-OC, compared to a 7.9% K^{-1} increase in ARP-MIR-21. For SMB and precipitation, both absolute values and climate changes signals were found significantly different in ARP-MIR-21-OC than in ARP-MIR-21.

In all projections, the sublimation increases by about 20 to 30% with respect to the corresponding values in the historical period. Surface melt increases by about a factor 2 to 3 in projections with NorESM1-M SSC and by factors from 5 to 6 in projections with MIROC-ESM SSC. Increases in SMB remain essentially determined by the increases in precipitation. As a consequence, we only present here the spatial distribution of changes in precipitation in Antarctica in Fig. 8. In all projections, the largest absolute precipitation increases occur in the coastal regions of West Antarctica and in the west of the Peninsula. In simulations with MIROC-ESM SSC, precipitation increase is also very large in the Atlantic sector of coastal East Antarctica. The difference between total precipitation increases in ARP-NOR-21 and ARP-NOR-21-OC (Fig. 8a) is small in most regions of Antarctica, except for a stronger increase (or weaker decrease) in Marie-Byrd Land, and a weaker increase in Adélie Land in ARP-NOR-21-OC. For the simulations with MIROC-ESM SSC (Fig. 8b), we can clearly identify an alternation of three regions of higher or lower precipitation increases. This tri-pole pattern can easily be linked to the 3-wave pattern in SLP change in ARP-MIR-21, clearly different than the pattern in MSLP change in ARP-MIR-21-OC (Fig. 6b). Here again, Marie Byrd Land and Adélie Land are among the areas where large differences are found between simulations with or without bias-corrected SSC. Winter and spring (and to a lesser extent autumn) are the seasons mostly responsible for differences in precipitation changes between the simulations with MIROC-ESM original SSC. The relative mean precipitation changes (in %) and the associated standard deviation for the four RCP8.5 projections realized in this study can be seen in Fig. 9.

Table 7. Absolute values, absolute (Gt yr^{-1}) and relative climate change signal (in %) for Mean SMB and components for the grounded AIS for the different ARPEGE RCP8.5 projection (2071-2100). Climate change signals and absolute values significantly different at p=0.05 level in projections with bias-corrected SSC are displayed in bold.

Simulations	SMB	Tot. PCP	Surf. Sublim.	Rainfall	Melt
ARP-NOR-21	2543±143	2965±167	340±28	26±6	196±102
CC change (Gt yr^{-1})	355±196	481±196	65±26	16±8	144±81
Rel. change	16%	19%	24%	164%	276%
ARP-NOR-21-OC	**2334±181**	**2742±176**	331±21	27±7	184±82
CC change (Gt yr^{-1})	364±195	474±179	55±26	17±8	132±137
Rel. change	19%	21%	20%	171%	252%
ARP-MIR-21	2508±98	2940±131	332±24	46±12	248±120
CC change (Gt yr^{-1})	512±132	673±135	75±18	31±10	248±120
Rel. change (%)	26%	30%	29%	377%	628%
ARP-MIR-21-OC	**2637±156**	**3108±202**	345±29	52±15	306±144
CC change (Gt yr^{-1})	**667±202**	**840±227**	68±23	42±15	254±118
Rel. change	34%	37%	25%	416%	484%

4 Discussion

4.1 Evaluation of ARPEGE climate model : reconstruction of historical climate

The atmospheric model ARPEGE correctly captures the main features of the atmospheric circulation around Antarctica. The three local minima in SLP and 500 hPa geopotential heigh located around 60°W, 90°E and 180 °E are well reproduced in the ARP-AMIP simulation (see Fig. **??**). However, there is a positive SLP bias in the seas around Antarctica, particularly in the ASL sector, and a negative bias at mid-latitudes (30-40 °S), especially in the Pacific sector. This bias structure in the Southern Hemisphere is present in many coupled and atmosphere-only GCMs. Its consequence is an equatorward bias on the position of the surface jet associated with westerly winds (Bracegirdle et al., 2013). The errors of our high resolution ARPEGE on atmospheric general circulation in the high southern latitudes are typical of many lower resolution climate simulation and in the same order of values as the errors of the CMIP5 CNRM-CM5 and ARPEGE (AMIP) simulations found in Bracegirdle et al. (2013). Even though simulations realized with different versions of the model are to be compared with care, our results suggest that here the use of higher resolution did not improved the representation of the high southern latitude atmospheric circulation, contrary to the results of Hourdin et al. (2013) who used LMDZ model.

The use of observed SSC (ARP-AMIP) rather than SSC from NorESM1-M and MIROC-ESM substantially improves the simulated mean SLP in the Southern Hemisphere in all seasons but summer. This confirms at a higher resolution results from previous studies realized at coarser resolution which have shown that the use of observed rather than modeled SSC to drive atmosphere-only model clearly improves the skill of the atmospheric models (Krinner et al., 2008; Ashfaq et al., 2011;

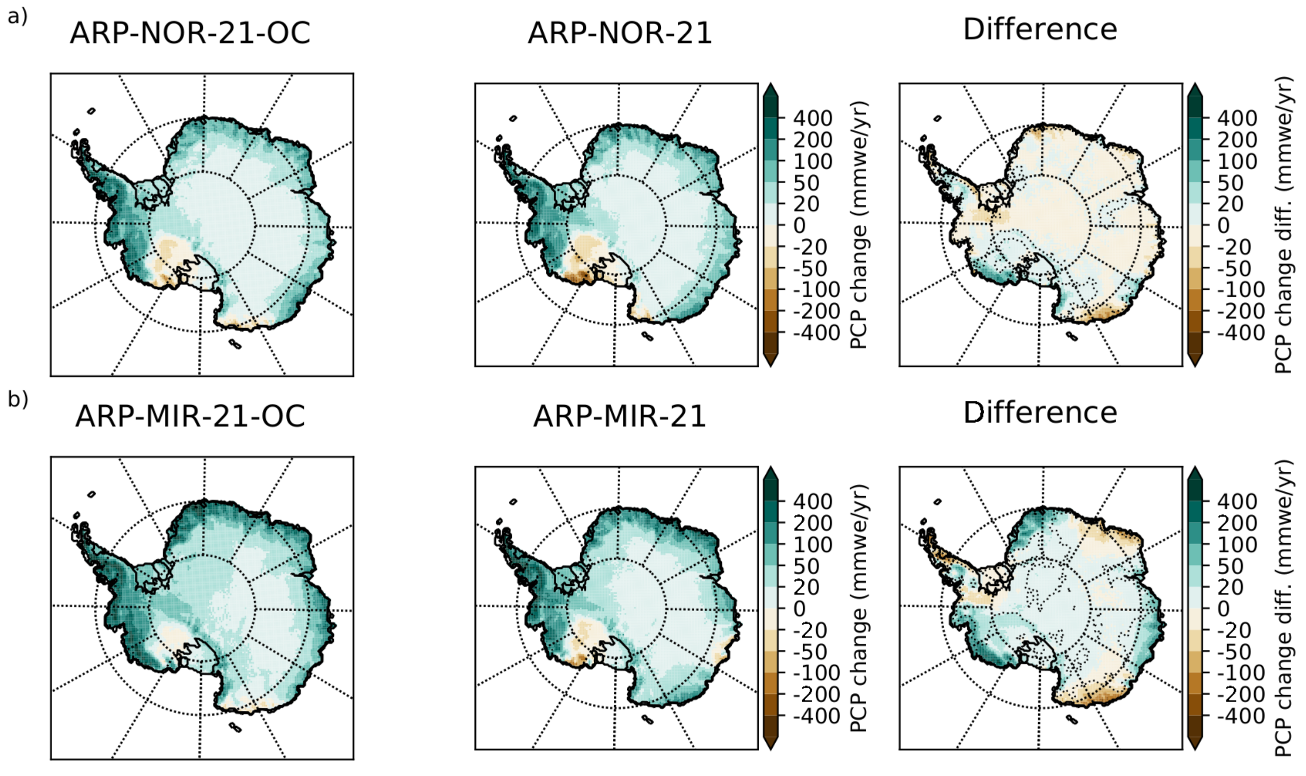

Figure 8. Climate change signal in total precipitation (mmwe yr^{-1}) for late 21st century (reference period: 2071-2100) in ARPEGE RCP8.5 projection with bias corrected SSC (*left*), original SSC (*center*) and difference (*right*). Results for projections with SSC from NorESM1-M are presented in subfigure (a) and from MIROC-ESM in subfigure (b). *Dotted lines* indicate where difference is 50% of the precipitation change in the non bias-corrected SSC projection.

Hernández-Díaz et al., 2017).

Regarding surface climate, ARPEGE also reasonably reproduces Antarctic T_{2m} except over large ice shelves. The T_{2m} errors with respect to MAR-ERA-I are generally below 3 K over most of the grounded AIS. There is a substantial warm bias on the top the Antarctic Plateau in winter. However, these errors (+1.5 K at Amundsen-Scott, +3.4 K at Vostok) are to be compared with errors sometimes much larger in other GCMs or even in reanalyses (e.g. Bracegirdle and Marshall, 2012; Fréville et al., 2014). These errors are due to the fact that many climate models fail to capture the strength of the near-surface temperature inversion and the uncoupling with the upper atmosphere when extremely stable boundary layers are formed. The cold bias of ARPEGE in the Antarctic Peninsula, especially in winter, can largely be explained by atmospheric circulation errors, as these lead to an underestimation of mild and moist fluxes from the north-west towards the Peninsula.

The grounded AIS total precipitation in the ARP-AMIP simulation is extremely close to the estimates using the MAR or RACMO2 RCMs. However, the higher sublimation (and run-off) rates in the ARPEGE simulation compared to MAR and

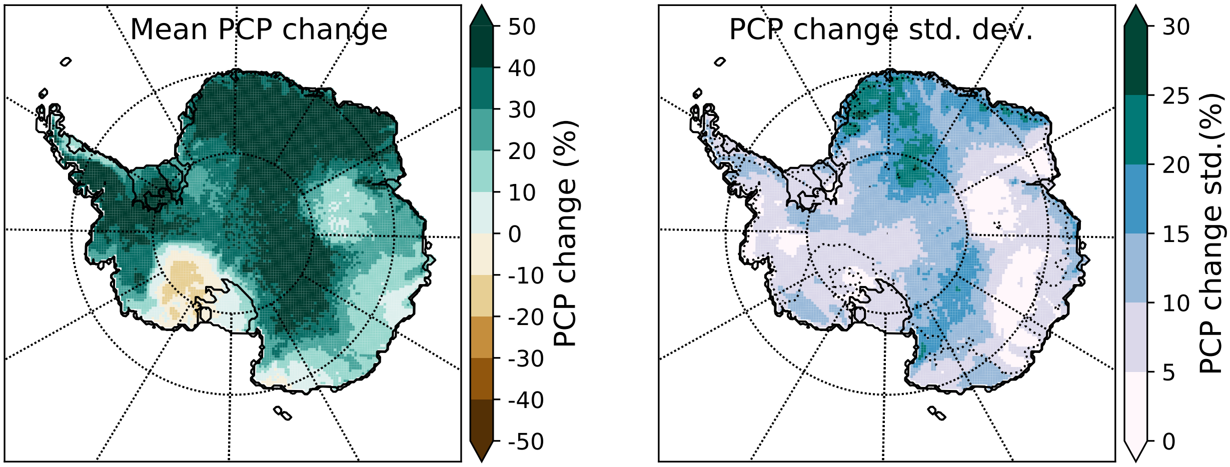

Figure 9. Mean (*left*) relative precipitation change (%) for late 21st century from the four ARPEGE RCP8.5 projections and associated standard deviation (*right*). *Dotted lines* indicate where standard deviation is 50% of the mean change.

RACMO2 yields lower SMB values for the grounded AIS. Nevertheless, estimates of the AIS SMB using ARPEGE concurs independent estimates using satellites data (e.g., Vaughan et al., 1999; Arthern et al., 2006). Many of the differences in the spatial distribution of precipitation rates between the ARP-AMIP simulation and MAR-ERA-I are linked to errors in atmospheric general circulations. These are for instance precipitation overestimates by ARPEGE over Marie-Byrd Land, the eastern part of the Peninsula and Dronning Maud Land, as well as precipitation underestimates over central West Antarctica and the west coast of the Peninsula.

4.2 Effects of Sea Surface Conditions

In the historical climate, we found that when driven by SSC from NorESM1-M instead of observed SSC, ARPEGE simulates significantly higher precipitation rates at the scale of the ice sheet (+218 Gt yr^{-1}, 2.2 σ). When driven by MIROC-ESM SSC, runoff and snow sublimation were found significantly lower than in the other two ARPEGE historical simulations due to cooler temperatures in spring and summer. In the following section, we discuss the effects of SSC on simulated climate change, the consistency of the atmospheric model response between historical and future climate as well as the implication of SSC selection for future Antarctic climate projections.

4.2.1 Climate change signals

NorESM1-M and MIROC-ESM were chosen in this study because they display very different RCP8.5 projections in terms of changes in sea ice around Antarctica (respectively -14% and -45% of winter SIE) at the end of the 21st century. The increase in SST below 50° S is much larger in MIROC-ESM (+ 1.8 K) than in NorESM1-M (+ 0.4 K). The separate effects of decreases in sea ice cover and increases in SST on Antarctic SMB has been assessed in Kittel et al. (2018) using the MAR RCM. Both result in an increase in Antarctic SMB (precipitation) that mostly takes places over coastal areas, as a result of the increase in evaporation and saturated water vapour pressure, and the decrease of the blanket effect of sea ice. van Lipzig et al. (2002) found similar results using the RACMO RCM. In this study, we confirm the high impact of SSC on Antarctic SMB with a global atmospheric model used at a resolution similar to those commonly used ($\sim$ 30-50 kms) for Antarctic studies using RCMs. van Lipzig et al. (2002) have also investigated the separate effect of the surface warming of the ocean and of the homogeneous warming of the atmospheric column at the border of the domain of integration, the latter being more important as a result of increased moisture advection towards the ice sheet over a thicker atmospheric column. These two studies carried out with RCMs driven by climate reanalyses do not account for the response of the atmospheric general circulation to changes in oceanic surface conditions and changes in radiative forcing as expected for the current century. This was done in Krinner et al. (2014) using LMDZ AGCM in a stretched-grid configuration who found that the effects of changes in SSC on Antarctic precipitation is much larger than the effect of changes in radiative forcings. As in Krinner et al. (2014), we find using an AGCM at a higher resolution that regional precipitation increases depend mostly on the SSC forcing. It was also found in this previous study that the thermodynamic component, that is the changes in precipitation for a given type of atmospheric circulation pattern (due to for instance higher moisture or heat transport as a result of higher SSTs) was more important than the dynamic one, that is the changes in precipitation due to changes in the relative frequencies of atmospheric circulation patterns (see e.g., Driouech et al., 2010) for the projected increase in Antarctic precipitation.

In the projections presented in this study, the Antarctic increase in annual mean T_{2m} and the relative increase in precipitation for late 21^{st} century are within the range of the CMIP5 RCP8.5 projetions ensemble (e.g., Palerme et al., 2017). Unsurprisingly, the warming obtained with projections using SSC from NorESM1-M (around +2.8K) belongs to the lower end of the values for RCP8.5 CMIP5 projections, a consequence of weaker changes in the Southern Ocean SSC in this projection. In projections using MIROC-ESM SSC, the increase in annual T_{2m} is around +4 K. The relative increase in precipitation in ARP-MIR-21-OC (+37%) belongs to the upper limit of the CMIP5 ensemble. As suggested by Krinner et al. (2010), the choice of the AOGCM providing SSC strongly influences the warming and precipitation increases obtained at the scale of the Antarctic continent. Using NorESM1-M SSC and non-corrected MIROC-ESM SSC, the SMB (precipitation) increase obtained with ARPEGE ranges around 5.2 $\%.K^{-1}$ (6.6 and 7.9 $\%.K^{-1}$). This is within the range of values obtained in previous studies (Agosta et al., 2013; Ligtenberg et al., 2013; Krinner et al., 2014; Bracegirdle et al., 2015; Frieler et al., 2015; Palerme et al., 2017). Using bias-corrected SSC from MIROC-ESM, the sensitivity of the precipitation to temperature increase (8.8 $\%\ K^{-1}$) is slightly above the higher end values of previous studies. Yet, this value is consistent with upper values of the CMIP5 ensemble (see Bracegirdle et al., 2015, Fig.3) which mostly come from AOGCMs with large SIE in their historical simulations, and consequently larger decrease in sea ice in their future climate projections (Agosta et al., 2015; Bracegirdle et al., 2015). This suggests that there are some non-linearities in the sensitivity of Antarctic precipitation change to regional warming, as it is also sensitive to the reduced blanket effect of sea ice. Consistent with findings from van Lipzig et al. (2002), we find that for regional warming within the + 3 to 4 K range, the increase in SMB is still largely dominated by precipitation increases, which remain much larger than the increase in surface melt and rain.

For the RCP8.5 simulation using SSC from NorESM1-M, the use of bias-corrected SSC has not yielded significantly different climate change signals with respect to the simulation using uncorrected SSC. For future projections with SSC from MIROC-ESM, using bias-corrected SSC led to significantly different climate change signals for many variables, especially in winter. In the projection with original MIROC-ESM SSC, the deepening of the low pressure zone around Antarctica is mainly organized in a three-wave pattern in JJA, while it shows a dipole in the projection with bias-corrected SCC. These differences lead to significantly different changes in atmospheric temperatures (0.8 K larger in ARP-MIR-21-OC in winter), the most dramatic difference being the larger (2 K) increase in west Marie-Byrd Land using bias-corrected SSC. Differences in atmospheric circulation are also unsurprisingly associated with significantly different changes in total precipitation. At the continental scale, the increase in moisture advection (approximated trough precipitation minus evaporation) is 9% larger in ARP-MIR-21-OC than in ARP-MIR-21. The consequences of the three-wave pattern decrease in SLP around Antarctica in ARP-MIR-21 are obvious with three regions of lower precipitations increases with respect to ARP-MIR-21-OC. At the regional scale, it is noteworthy that all projections agree on a (slight) precipitation decrease in Marie-Byrd Land and the western Ross Ice Shelf (see Fig. 9). The decrease in precipitation in this region is however mitigated when using both set of bias corrected SSC.

A lower increase or a slight precipitation decrease in Marie Byrd Land were also found in other studies (Krinner et al., 2008; Lenaerts et al., 2016). These results however bear uncertainties as many free AGCM (including ARPEGE) struggle to reproduce the depth and the variability of the Amundsen Sea Low. The changes in precipitation (and SMB) in this area are also extremely sensitive to the selected SSC. The changes in surface climate in the ASL area are extremely important for the SMB of the Antarctic Ice Sheet as a whole as glaciers of the Amundsen Sea Embayment are largely responsible for the positive contribution of the AIS to sea-level rise over recent years (e.g., Shepherd et al., 2018). The melting of ice shelves in this area is also expected to trigger the destabilization of glaciers located upstream (Rignot et al., 2013; Fürst et al., 2016; Deb et al., 2018).

Climate change signals for temperature and precipitation over large ice shelves (Ross and Ronne-Filchner) do not seem to substantially differ those from adjacent areas. Yet, as for the reconstruction of recent climate, projected climate change over these areas should be considered with caution, especially for near-surface temperatures.

4.2.2 Consistency of atmospheric model responses

The late winter (August to October, ASO) and late summer (February to April, FMA) errors of historical SST and SIC from NorESM1-M and MIROC-ESM with respect to observations are displayed in the supplementary material (Fig. A1). The same differences between SSC of their RCP8.5 projection and their bias-corrected equivalent are also shown. The differences in SSC used to drive the atmospheric model are, unsurprisingly, extremely similar between historical and future climate experiments. Has the introduction of the same SSC "biases" with respect to the observed or bias-corrected references yielded the same responses of the atmospheric model in the historical and future climates? The consistency of the response of the atmospheric model is considered here as being the key for having the same climate change signals.

For simulations using SSC from the NorESM1-M model, the consistency of the response of the atmospheric model is clear. The similarities in the differences between ARP-NOR-20 and ARP-AMIP with differences between ARP-NOR-21 and ARP-NOR-21-OC is clear for many climate variables (SLP, see Fig. D2a,c, 500 hPa geopotential, stratospheric temperatures, 500hPa zonal wind and near-surface atmospheric temperatures). In this perspective, the most interesting feature is that in both historical and future climate, the ARPEGE simulations forced by NorESM1-M original SSC are about 10% wetter at the Antarctic continental scale than their bias-corrected reference. The link here between the dynamical response of the atmospheric model and the SST biases of the NorESM1-M AOGCM seems physically consistent. NorESM1-M SSTs are indeed characterized by a warm bias in Southern hemisphere mid-latitudes (40-60°S) and a cool bias in the southern Tropics (see Fig. A2a,c), which cause a smaller meridional SST gradient. The response of the atmospheric model here is an increase in the moisture transport towards Antarctica (P-E larger by about 10%) and explains the additional $\sim$ 200 Gt.yr^{-1} (2 σ) of precipitation on the ice sheet in the simulations realized with NorESM1-M non-corrected SSC. The consistency of the response of the atmospheric model in historical and future climate explains the absence of significant differences in the climate change signals between experiments with the original NorESM1-M SSC and their bias-corrected reference.

The consistency of the response of the atmospheric model is less clear for the projections realized with SSC from MIROC-ESM. Some changes in the differences between simulations forced with original SSC and those forced by their bias-corrected references are noticeable in winter and autumn SLP (Fig. D2) and zonal wind speed (*not shown*). The main result here, as a consequence of these differences, is a total precipitation difference in the RCP8.5 experiment with bias-corrected SSC of about +180 Gt yr^{-1} ($\sim 1\sigma$), while there was almost no difference in total precipitation in the historical period between ARP-AMIP and ARP-MIR-20. Here, the link between biases in Southern Hemisphere SST from MIROC-ESM (see Fig. A1b,d) and the response of ARPEGE appears less clear. SSTs from MIROC-ESM are mainly characterized by a cold bias in the Tropics throughout the years. With respect to the ARP-AMIP simulation, ARP-MIR-20 is also characterized by cooler temperatures throughout the tropical troposphere, much lower upper tropospheric and stratospheric temperatures in Antarctica. This suggests that interactions between SST biases, tropical convection, and stratospheric meridional temperature gradients could also explain the response of the atmospheric model when forced by MIROC-ESM SSC.

4.2.3 Implication of Sea Surface Conditions selection

In many cases, it has been reported that selecting the best skilled models for a given aspect of the climate system helps in better constraining the associated uncertainties on the climate change signal (e.g., Massonnet et al., 2012). Here, because we use bias-correction of the SSC, this aspect has reduced importance. While performing a limited number of climate projections, we cover a large range of the uncertainties associated with the evolution of the Southern Ocean surface condition for the Antarctic climate because it was shown to be its primary driver (Krinner et al., 2014). This approach is supported by the fact that biases of large-scale atmospheric circulation of coupled climate models were shown to be highly stationary under strong climate change (Krinner and Flanner, 2018), and that the response of the ARPEGE atmospheric model to the introduction of the same SSC "bias" was shown to be mostly unchanged in future climate. The use of stretched grids AGCMs and polar-oriented RCMs to downscale future climate projections for Antarctica comports their own assets and drawbacks, and rather than opposed, they could be combined such as done for Africa in Hernández-Díaz et al. (2017). The warming signal for the AIS in the CMIP5 model ensemble RCP8.5 projection is evaluated to be 4$\pm$1 K (Palerme et al., 2017). By selecting NorESM1-M and MIROC-ESM, we explored the range of the Southern Hemisphere SIE changes among the CMIP5 ensemble. However, using these SSC, the ARPEGE AGCM simulates a warming in the range of 2.8 to 4.2K, which is in the lower half of the range simulated by the CMIP5 models. Bracegirdle et al. (2015) found that about half of the variance of the CMIP5 projection in RCP8.5 scenario for Antarctic temperature and precipitation is explained by historical biases and sea ice decreases by the late 21 st century. A non-negligible part of the uncertainties of Antarctic climate change is also linked to the representation of general circulation in the atmospheric model (Bracegirdle et al., 2013). This issue should therefore be assessed in future work.

5 Summary and Conclusion

This study presented the first general evaluation of the capability of the AGCM ARPEGE to reproduce atmospheric general circulation of the high southern latitudes and the surface climate of the Antarctic Ice Sheet. ARPEGE is able to correctly represent the main features of atmospheric general circulation, although we have shown a negative bias in sea-level pressures at mid-latitudes and a positive bias around Antarctica especially in the Amundsen Sea sector. Unsurprisingly, the use of observed sea surface conditions (ARP-AMIP simulation) rather than SSC from NorESM1-M and MIROC-ESM helped to improve the representation of sea-level pressures in the southern latitudes in all seasons but summer. ARPEGE is also able to correctly reproduce surface climate of Antarctica except for large ice shelves. The differences in T_{2m} with polar-oriented RCM MAR and *in-situ* observations is encouraging, especially given the large biases that are exhibited in other GCMs or even reanalyses when Antarctic surface climate is considered (Fréville et al., 2014; Bracegirdle and Marshall, 2012). Regarding precipitation, our estimates at the continental scale agree with estimates from other studies such as those using MAR or RACMO2, even though higher sublimation and run-off rates in ARPEGE yield smaller estimates of the grounded AIS SMB by about 150 Gt yr^{-1}) (1.5 σ). Concerning regional patterns, the distribution of precipitation in the ARP-AMIP simulation differs from the one in the MAR RCM mainly as a consequence of errors in atmospheric general circulation.

The future climate projections presented in this study are among the first Antarctic climate projections realized at a “high” (Cordex-like) horizontal resolution using a global atmospheric climate model. Concerning climate change signals, we evaluate the impact of using original and bias-corrected sea surface conditions from MIROC-ESM and NorESM1-M, which display opposite trends in their RCP8.5 projections for the Southern Ocean’s late 21st century SIE (respect. -45% and -14% for winter SIE). Using SSC from NorESM1-M model, no significant differences in yearly or seasonal mean T_{2m} increase, precipitation, or SMB changes were found when using bias-corrected SSC. When using SSC directly from MIROC-ESM model, the increase in precipitation is +30%, and it reaches +37% when using the corresponding bias-corrected SSC. This difference is statistically significant and is linked with clearly different dynamical and thermodynamical changes in SLP around Antarctica, occurring mainly in winter and spring. At the regional scale, large differences in T_{2m} and precipitation increases are found when using bias-corrected SSC both from NorESM1-M and MIROC-ESM.

The analysis of the climate projections further evidences the potential of the ARPEGE model for the study of Antarctic climate and climate change. When using SSC from NorESM1-M, we found a 10% higher precipitation rates at the continent scale (which is detrimental to the model skills for precipitation) with respect to the bias-corrected reference in both historical and future climate. These findings advocate once more for the use of bias-corrected SSC to drive climate projections using an

AGCM. Additionally, this method reduces the uncertainty of the baseline (historical) climate and the need for computational resources as only one historical simulation using observed SSC in needed.

In this study, we confirm the importance of the coupled model choice from which SSC projections are taken. By performing bias correction of SSC, we showed that not only the regional pattern of temperature and precipitation changes can be different but also the integrated changes in SMB and seasonal temperatures at the ice sheet scale. Unsurprisingly, projections using climate changes signal from MIROC-ESM SSC projections (larger decrease in sea ice) show higher increases in temperature and precipitation than the one using NorESM1-M SSC. This confirms the effect of sea ice decreases and SST increases on Antarctic temperatures and SMB in a "realistic" climate projection experiment. For the range of Antarctic warming obtained (+3 to +4 K), we confirm results from previous studies showing that the increase in SMB is largely dominated by increases in snowfall which remain much larger than the increase in melt and rainfall at the ice sheet scale. Considering changes in SIE at the two extreme end values from the CMIP5 ensemble, differences in Antarctic warming obtained ($\sim$ 1 K) are clearly smaller than the spread of CMIP5 projections for the AIS. This is consistent with the fact that a large part of the CMIP5 diversity for Antarctic climate projections comes from atmospheric model (errors) and associated uncertainties. Climate projections presented in this study still bear considerable uncertainties. These mostly come from ARPEGE errors (even when driven by observed SSC) on southern high latitudes general atmospheric circulation, which casts some doubt on the reliability of the projected Southern Hemisphere atmospheric circulation changes. As a consequence, in future work, we will assess the impact of AGCM atmospheric circulation errors by performing an ARPEGE simulation nudged towards the reanalysis and use the statistics of the model drift in this nudged simulation such as done in Guldberg et al. (2005) to perform an atmosphere bias-corrected ARPEGE historical simulation. Bias-corrected projections such as done in Krinner et al. (2019) can then also be assessed using the method presented in this study.

Acknowledgements. This study was funded by the Agence Nationale de la Recherche through contract ANR-14-CE01-0001-01 (ASUMA) and ANR-15-CE01-0003 (APRES3) and by the ESA Snow cci initiative. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups participating to CMIP5 for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

The Centre National de Recherches M'et'eorologique (M'et'e-France, CNRS) and associated colleagues are warm-fully thanks for providing resources and help to run ARPEGE model.

We also thank the Scientific Committee on Antarctic Research, SCAR and the British Antarctic Survey for the availability of the MET READER data base. We also want to thanks warmfully Michiel van den Broeke for providing access to the latest ERA-Interim driven RACMO2 outputs for Antarctica. We thanks Jan Lenaerts and anonymous referee for reviews and comments aiming at the improvement of the manuscript.

Author contributions. JB performed the ARPEGE simulation, analyzed the results and wrote most of the manuscript. GK and MD helped in analyzing the outputs of the simulations and discussing the results. CA provided MAR-ERA-I simulation, some scripts for interpolation on MAR grid and provided results for integration of surface mass balance on the grounded ice-sheet. AA and MD have helped in designing and running the ARPEGE experiment on CNRM supercomputers. All authors have contributed to the reviews and correction process of the manuscript.

Competing interests. The authors have no competing interests.

References

Agosta, C.: Added value of the regional climate model MAR compared to reanalyses for estimating the Antarctic surface climate, 1979-2017, https://doi.org/10.5281/zenodo.1256079, https://doi.org/10.5281/zenodo.1256079, 2018.

Agosta, C., Favier, V., Krinner, G., Gallée, H., Fettweis, X., and Genthon, C.: High-resolution modelling of the Antarctic surface mass balance, application for the twentieth, twenty first and twenty second centuries, Climate Dynamics, 41, 3247–3260, https://doi.org/10.1007/s00382-013-1903-9, 2013.

Agosta, C., Fettweis, X., and Datta, R.: Evaluation of the CMIP5 models in the aim of regional modelling of the Antarctic surface mass balance, The Cryosphere, 9, 2311–2321, https://doi.org/10.5194/tc-9-2311-2015, 2015.

Agosta, C., Amory, C., Kittel, C., Orsi, A., Favier, V., Gallée, H., van den Broeke, M. R., Lenaerts, J. T. M., van Wessem, J. M., and Fettweis, X.: Estimation of the Antarctic surface mass balance using MAR (1979–2015) and identification of dominant processes, The Cryosphere Discussions, 2018, 1–22, https://doi.org/10.5194/tc-2018-76, https://www.the-cryosphere-discuss.net/tc-2018-76/, 2018.

Amory, C., Trouvilliez, A., Gallée, H., Favier, V., Naaim-Bouvet, F., Genthon, C., Agosta, C., Piard, L., and Bellot, H.: Comparison between observed and simulated aeolian snow mass fluxes in Adélie Land, East Antarctica, The Cryosphere, 9, 1373–1383, https://doi.org/10.5194/tc-9-1373-2015, 2015.

Arblaster, J. M. and Meehl, G. A.: Contributions of External Forcings to Southern Annular Mode Trends, Journal of Climate, 19, 2896–2905, https://doi.org/10.1175/JCLI3774.1, 2006.

Arthern, R. J., Winebrenner, D. P., and Vaughan, D. G.: Antarctic snow accumulation mapped using polarization of 4.3-cm wavelength microwave emission, Journal of Geophysical Research: Atmospheres, 111, https://doi.org/10.1029/2004JD005667, 2006.

Ashfaq, M., Skinner, C. B., and Diffenbaugh, N. S.: Influence of SST biases on future climate change projections, Climate Dynamics, 36, 1303–1319, https://doi.org/10.1007/s00382-010-0875-2, 2011.

Barrand, N. E., Hindmarsh, R. C., Arthern, R. J., Williams, C. R., Mouginot, J., Scheuchl, B., Rignot, E., Ligtenberg, S. R., Van Den Broeke, M. R., Edwards, T. L., et al.: Computing the volume response of the Antarctic Peninsula ice sheet to warming scenarios to 2200, Journal of Glaciology, 59, 397–409, 2013.

Bazile, E., Traullé, O., Barral, H., Le Moigne, P., Genthon, C., Guidard, V., Couvreux, F., WU, A. H., SU, G. S., and FMI, T. V.: GABLS4: an intercomparison case to study the stable boundary layer with surface interactions on the Antarctic plateau., in: 21st Symposium on Boundary Layers and Turbulence, vol. 9, p. 2014, 2014.

Beaumet, J., Krinner, G., Déqué, M., Haarsma, R., and Li, L.: Assessing bias corrections of oceanic surface conditions for atmospheric models, Geoscientific Model Development Discussions, 12, 321–342, https://doi.org/10.5194/gmd-12-321-2019, https://hal.sorbonne-universite.fr/hal-02022662, 2019.

Boone, A. and Etchevers, P.: An Intercomparison of Three Snow Schemes of Varying Complexity Coupled to the Same Land Surface Model: Local-Scale Evaluation at an Alpine Site, Journal of Hydrometeorology, 2, 374–394, https://doi.org/10.1175/1525-7541(2001)002<0374:AIOTSS>2.0.CO;2, 2001.

Bracegirdle, T. J. and Marshall, G. J.: The Reliability of Antarctic Tropospheric Pressure and Temperature in the Latest Global Reanalyses, Journal of Climate, 25, 7138–7146, https://doi.org/10.1175/JCLI-D-11-00685.1, 2012.

Bracegirdle, T. J., Shuckburgh, E., Sallee, J.-B., Wang, Z., Meijers, A. J. S., Bruneau, N., Phillips, T., and Wilcox, L. J.: Assessment of surface winds over the Atlantic, Indian, and Pacific Ocean sectors of the Southern Ocean in CMIP5 models: historical bias, forcing response, and state dependence, Journal of Geophysical Research: Atmospheres, 118, 547–562, https://doi.org/10.1002/jgrd.50153, 2013.

Bracegirdle, T. J., Stephenson, D. B., Turner, J., and Phillips, T.: The importance of sea ice area biases in 21st century multimodel projections of Antarctic temperature and precipitation, Geophysical Research Letters, 42, 10,832–10,839, https://doi.org/10.1002/2015GL067055, 2015.

Bracegirdle, T. J., Hyder, P., and Holmes, C. R.: CMIP5 Diversity in Southern Westerly Jet Projections Related to Historical Sea Ice Area: Strong Link to Strengthening and Weak Link to Shift, Journal of Climate, 31, 195–211, https://doi.org/10.1175/JCLI-D-17-0320.1, 2018.

Bromwich, D. H., Nicolas, J. P., Monaghan, A. J., Lazzara, M. A., Keller, L. M., Weidner, G. A., and Wilson, A. B.: Corrigendum: Central West Antarctica among the most rapidly warming regions on Earth, Nature Geoscience, 7, 76, https://doi.org/http://dx.doi.org/10.1038/ngeo2016, 2013.

Clem, K. R., Renwick, J. A., and McGregor, J.: Autumn Cooling of Western East Antarctica Linked to the Tropical Pacific, Journal of Geophysical Research: Atmospheres, 123, 89–107, https://doi.org/10.1002/2017JD027435, 2018.

Comiso, J. C. and Nishio, F.: Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, Journal of Geophysical Research: Oceans, 113, https://doi.org/10.1029/2007JC004257, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JC004257, 2008.

Deb, P., Orr, A., Bromwich, D. H., Nicolas, J. P., Turner, J., and Hosking, J. S.: Summer Drivers of Atmospheric Variability Affecting Ice Shelf Thinning in the Amundsen Sea Embayment, West Antarctica, Geophysical Research Letters, 45, 4124–4133, 2018.

Déqué, M., Dreveton, C., Braun, A., and Cariolle, D.: The ARPEGE/IFS atmosphere model: a contribution to the French community climate modelling, Climate Dynamics, 10, 249–266, https://doi.org/10.1007/BF00208992, 1994.

Driouech, F., Déqué, M., and Sánchez-Gómez, E.: Weather regimes - Moroccan precipitation link in a regional climate change simulation, Global and Planetary Change, 72, 1 – 10, https://doi.org/https://doi.org/10.1016/j.gloplacha.2010.03.004, http://www.sciencedirect.com/science/article/pii/S0921818110000809, 2010.

Favier, V., Krinner, G., Amory, C., Gallée, H., Beaumet, J., and Agosta, C.: Antarctica-Regional Climate and Surface Mass Budget, Current Climate Change Reports, 3, 303–315, https://doi.org/10.1007/s40641-017-0072-z, 2017.

Fettweis, X., Gallée, H., Lefebre, F., and van Ypersele, J.-P.: Greenland surface mass balance simulated by a regional climate model and comparison with satellite-derived data in 1990–1991, Climate Dynamics, 24, 623–640, https://doi.org/10.1007/s00382-005-0010-y, https://doi.org/10.1007/s00382-005-0010-y, 2005.

Fréville, H., Brun, E., Picard, G., Tatarinova, N., Arnaud, L., Lanconelli, C., Reijmer, C., and van den Broeke, M.: Using MODIS land surface temperatures and the Crocus snow model to understand the warm bias of ERA-Interim reanalyses at the surface in Antarctica, The Cryosphere, 8, 1361–1373, https://doi.org/10.5194/tc-8-1361-2014, https://www.the-cryosphere.net/8/1361/2014/, 2014.

Frieler, K., Clark, P. U., He, F., Buizert, C., Reese, R., Ligtenberg, S. R. M., van den Broeke, M., Winkelmann, R., and Levermann, A.: Consistent evidence of increasing Antarctic accumulation with warming, Nature Climate Change, 5, https://doi.org/10.1038/nclimate2574, http://dx.doi.org/10.1038/nclimate2574, 2015.

Fürst, J. J., Durand, G., Gillet-Chaulet, F., Tavard, L., Rankl, M., Braun, M., and Gagliardini, O.: The safety band of Antarctic ice shelves, Nature Climate Change, 6, 479, 2016.

Gallée, H. and Schayes, G.: Development of a Three-Dimensional Meso-Y Primitive Equation Model: Katabatic Winds Simulation in the Area of Terra Nova Bay, Antarctica, Monthly Weather Review, 122, 671–685, https://doi.org/10.1175/1520-0493(1994)122<0671:DOATDM>2.0.CO;2, 1994.

Gallée, H., Preunkert, S., Argentini, S., Frey, M. M., Genthon, C., Jourdain, B., Pietroni, I., Casasanta, G., Barral, H., Vignon, E., Amory, C., and Legrand, M.: Characterization of the boundary layer at Dome C (East Antarctica) during the OPALE summer campaign, Atmospheric

Chemistry and Physics, 15, 6225–6236, https://doi.org/10.5194/acp-15-6225-2015, https://www.atmos-chem-phys.net/15/6225/2015/, 2015.

Genthon, C., Krinner, G., and Castebrunet, H.: Antarctic precipitation and climate-change predictions: horizontal resolution and margin vs plateau issues, Annals of Glaciology, 50, 55–60, https://doi.org/10.3189/172756409787769681, 2009.

Giorgi, F. and Gutowski, W. J.: Coordinated Experiments for Projections of Regional Climate Change, Current Climate Change Reports, 2, 202–210, https://doi.org/10.1007/s40641-016-0046-6, 2016.

Grazioli, J., Madeleine, J.-B., Gallée, H., Forbes, R. M., Genthon, C., Krinner, G., and Berne, A.: Katabatic winds diminish precipitation contribution to the Antarctic ice mass balance, Proceedings of the National Academy of Sciences, 114, 10 858–10 863, https://doi.org/10.1073/pnas.1707633114, 2017.

Guldberg, A., Kaas, E., Déqueé, M., Yang, S., and Vester, T.: Reduction of systematic errors by empirical model correction: impact on seasonal prediction skill, Tellus A, 57, 575–588, https://doi.org/10.1111/j.1600-0870.2005.00120.x, 2005.

Hernández-Díaz, L., Laprise, R., Nikiéma, O., and Winger, K.: 3-Step dynamical downscaling with empirical correction of sea-surface conditions: application to a CORDEX Africa simulation, Climate Dynamics, 48, 2215–2233, https://doi.org/10.1007/s00382-016-3201-9, 2017.

Hourdin, F., Foujols, M.-A., Codron, F., Guemas, V., Dufresne, J.-L., Bony, S., Denvil, S., Guez, L., Lott, F., Ghattas, J., et al.: Impact of the LMDZ atmospheric grid configuration on the climate and sensitivity of the IPSL-CM5A coupled model, Climate Dynamics, 40, 2167–2192, 2013.

Jones, P. D. and Harpham, C.: Estimation of the absolute surface air temperature of the Earth, Journal of Geophysical Research: Atmospheres, 118, 3213–3217, https://doi.org/10.1002/jgrd.50359, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/jgrd.50359, 2013.

King, J. C., Connolley, W. M., and Derbyshire, S. H.: Sensitivity of modelled Antarctic climate to surface and boundary-layer flux parametrizations, Quarterly Journal of the Royal Meteorological Society, 127, 779–794, https://doi.org/10.1002/qj.49712757304, 2001.

Kittel, C., Amory, C., Agosta, C., Delhasse, A., Doutreloup, S., Huot, P.-V., Wyard, C., Fichefet, T., and Fettweis, X.: Sensitivity of the current Antarctic surface mass balance to sea surface conditions using MAR, The Cryosphere, 12, 3827–3839, https://doi.org/10.5194/tc-12-3827-2018, 2018.

Krinner, G. and Flanner, M. G.: Striking stationarity of large-scale climate model bias patterns under strong climate change, Proc. Natl. Acad. Sci., in press., 115, 9462–9466, https://doi.org/10.1073/pnas.1807912115, 2018.

Krinner, G., Genthon, C., Li, Z.-X., and Le Van, P.: Studies of the Antarctic climate with a stretched-grid general circulation model, Journal of Geophysical Research: Atmospheres, 102, 13 731–13 745, https://doi.org/10.1029/96JD03356, http://dx.doi.org/10.1029/96JD03356, 1997.

Krinner, G., Guicherd, B., Ox, K., Genthon, C., and Magand, O.: Influence of Oceanic Boundary Conditions in Simulations of Antarctic Climate and Surface Mass Balance Change during the Coming Century, Journal of Climate, 21, 938–962, https://doi.org/10.1175/2007JCLI1690.1, 2008.

Krinner, G., Rinke, A., Dethloff, K., and Gorodetskaya, I. V.: Impact of prescribed Arctic sea ice thickness in simulations of the present and future climate, Climate Dynamics, 35, 619–633, https://doi.org/10.1007/s00382-009-0587-7, 2010.

Krinner, G., Largeron, C., Ménégoz, M., Agosta, C., and Brutel-Vuilmet, C.: Oceanic Forcing of Antarctic Climate Change: A Study Using a Stretched-Grid Atmospheric General Circulation Model, Journal of Climate, 27, 5786–5800, https://doi.org/10.1175/JCLI-D-13-00367.1, 2014.

Krinner, G., Beaumet, J., Favier, V., Déqué, M., and Brutel-Vuilmet, C.: Empirical Run-Time Bias Correction for Antarctic Regional Climate Projections With a Stretched-Grid AGCM, Journal of Advances in Modeling Earth Systems, 11, 64–82, https://doi.org/10.1029/2018MS001438, 2019.

Kushner, P. J., Held, I. M., and Delworth, T. L.: Southern Hemisphere Atmospheric Circulation Response to Global Warming, Journal of Climate, 14, 2238–2249, https://doi.org/10.1175/1520-0442(2001)014<0001:SHACRT>2.0.CO;2, 2001.

Lefebre, F., Fettweis, X., Gallée, H., Van Ypersele, J.-P., Marbaix, P., Greuell, W., and Calanca, P.: Evaluation of a high-resolution regional climate simulation over Greenland, Climate Dynamics, 25, 99–116, https://doi.org/10.1007/s00382-005-0005-8, 2005.

Lenaerts, J. T., Vizcaino, M., Fyke, J., van Kampenhout, L., and van den Broeke, M. R.: Present-day and future Antarctic ice sheet climate and surface mass balance in the Community Earth System Model, Climate Dynamics, 47, 1367–1381, https://doi.org/10.1007/s00382-015-2907-4, 2016.

Lenaerts, J. T., Ligtenberg, S. R., Medley, B., Van de Berg, W. J., Konrad, H., Nicolas, J. P., Van Wessem, J. M., Trusel, L. D., Mulvaney, R., Tuckwell, R. J., et al.: Climate and surface mass balance of coastal West Antarctica resolved by regional climate modelling, Annals of Glaciology, 59, 29–41, 2018.

Lenaerts, J. T. M., Medley, B., van den Broeke, M. R., and Wouters, B.: Observing and Modeling Ice Sheet Surface Mass Balance, Reviews of Geophysics, 57, 376–420, https://doi.org/10.1029/2018RG000622, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018RG000622, 2019.

Ligtenberg, S. R. M., van de Berg, W. J., van den Broeke, M. R., Rae, J. G. L., and van Meijgaard, E.: Future surface mass balance of the Antarctic ice sheet and its influence on sea level change, simulated by a regional atmospheric climate model, Climate Dynamics, 41, 867–884, https://doi.org/10.1007/s00382-013-1749-1, 2013.

Massonnet, F., Fichefet, T., Goosse, H., Bitz, C. M., Philippon-Berthier, G., Holland, M. M., and Barriat, P.-Y.: Constraining projections of summer Arctic sea ice, The Cryosphere, 6, 1383–1394, 2012.

Mélia, D. S.: A global coupled sea ice-ocean model, Ocean Modelling, 4, 137 – 172, https://doi.org/https://doi.org/10.1016/S1463-5003(01)00015-4, http://www.sciencedirect.com/science/article/pii/S1463500301000154, 2002.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., et al.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747, 2010.

Nicolas, J. P. and Bromwich, D. H.: New Reconstruction of Antarctic Near-Surface Temperatures: Multidecadal Trends and Reliability of Global Reanalyses, Journal of Climate, 27, 8070–8093, https://doi.org/10.1175/JCLI-D-13-00733.1, 2014.

Noilhan, J. and Mahfouf, J.-F.: The ISBA land surface parameterisation scheme, Global and Planetary Change, 13, 145 – 159, https://doi.org/https://doi.org/10.1016/0921-8181(95)00043-7, http://www.sciencedirect.com/science/article/pii/0921818195000437, soil Moisture Simulation, 1996.

Orr, A., Marshall, G. J., Hunt, J. C. R., Sommeria, J., Wang, C.-G., van Lipzig, N. P. M., Cresswell, D., and King, J. C.: Characteristics of Summer Airflow over the Antarctic Peninsula in Response to Recent Strengthening of Westerly Circumpolar Winds, Journal of the Atmospheric Sciences, 65, 1396–1413, https://doi.org/10.1175/2007JAS2498.1, 2008.

Palerme, C., Kay, J., Genthon, C., L'Ecuyer, T., Wood, N., and Claud, C.: How much snow falls on the Antarctic ice sheet?, The Cryosphere, 8, 1577–1587, https://doi.org/10.5194/tc-8-1577-2014, https://www.the-cryosphere.net/8/1577/2014/, 2014.

Palerme, C., Genthon, C., Claud, C., Kay, J. E., Wood, N. B., and L'Ecuyer, T.: Evaluation of current and projected Antarctic precipitation in CMIP5 models, Climate Dynamics, 48, 225–239, https://doi.org/10.1007/s00382-016-3071-1, https://doi.org/10.1007/s00382-016-3071-1, 2017.

Pollard, D., DeConto, R. M., and Alley, R. B.: Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure, Earth and Planetary Science Letters, 412, 112 – 121, https://doi.org/https://doi.org/10.1016/j.epsl.2014.12.035, 2015.

Previdi, M. and Polvani, L. M.: Anthropogenic impact on Antarctic surface mass balance, currently masked by natural variability, to emerge by mid-century, Environmental Research Letters, 11, 094 001, http://stacks.iop.org/1748-9326/11/i=9/a=094001, 2016.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B.: Ice-shelf melting around Antarctica, Science, 341, 266–270, 2013.

Ritz, C., Tamsin, E. L., Durand, G., Payne, A. J., Peyaud, V., and Hindmarsh, R. C. A.: Potential sea-level rise from Antarctic ice-sheet instability constrained by observations, Nature, 528, 115, https://doi.org/http://dx.doi.org/10.1038/nature16147, 2015.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., et al.: Mass balance of the Antarctic Ice Sheet from 1992 to 2017, Nature, 556, pages219–222, 2018.

Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., and Meier, W. N.: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations, Geophysical Research Letters, 39, n/a–n/a, https://doi.org/10.1029/2012GL052676, 2012.

Taylor, K., Williamson, D., and Zwiers, F.: The sea surface temperature and sea-ice concentration boundary condition for AMIP II simulations, p. 25 pp., 2000.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, Bulletin of the American Meteorological Society, 93, 485–498, 2012.

Turner, J., Colwell, S. R., Marshall, G. J., Lachlan-Cope, T. A., Carleton, A. M., Jones, P. D., Lagun, V., Reid, P. A., and Iagovkina, S.: The SCAR READER Project: Toward a High-Quality Database of Mean Antarctic Meteorological Observations, Journal of Climate, 17, 2890–2898, https://doi.org/10.1175/1520-0442(2004)017<2890:TSRPTA>2.0.CO;2, https://doi.org/10.1175/1520-0442(2004)017<2890:TSRPTA>2.0.CO;2, 2004.

Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., and Hosking, J. S.: An Initial Assessment of Antarctic Sea Ice Extent in the CMIP5 Models, Journal of Climate, 26, 1473–1484, https://doi.org/10.1175/JCLI-D-12-00068.1, 2013.

Turner, J., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J., and Phillips, T.: Recent changes in Antarctic Sea Ice, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 373, https://doi.org/10.1098/rsta.2014.0163, http://rsta.royalsocietypublishing.org/content/373/2045/20140163, 2015.

Turner, J., Lu, H., White, I., King, J. C., Phillips, T., Hosking, J. S., Bracegirdle, T. J., Marshall, G. J., Mulvaney, R., and Deb, P.: Absence of 21st century warming on Antarctic Peninsula consistent with natural variability, Nature, 535, –, https://doi.org/10.1038/nature18645, 2016.

Turner, J., Phillips, T., Marshall, G. J., Hosking, J. S., Pope, J. O., Bracegirdle, T. J., and Deb, P.: Unprecedented springtime retreat of Antarctic sea ice in 2016, Geophysical Research Letters, 44, 6868–6875, https://doi.org/10.1002/2017GL073656, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL073656, 2017.

van Lipzig, N. P. M., van Meijgaard, E., and Oerlemans, J.: Temperature Sensitivity of the Antarctic Surface Mass Balance in a Regional Atmospheric Climate Model, Journal of Climate, 15, 2758–2774, https://doi.org/10.1175/1520-0442(2002)015<2758:TSOTAS>2.0.CO;2, 2002.

van Lipzig, N. P. M., King, J. C., Lachlan-Cope, T. A., and van den Broeke, M. R.: Precipitation, sublimation, and snow drift in the Antarctic Peninsula region from a regional atmospheric model, Journal of Geophysical Research: Atmospheres, 109, https://doi.org/10.1029/2004JD004701, 2004.

van Wessem, J. M., van de Berg, W. J., Noël, B. P. Y., van Meijgaard, E., Amory, C., Birnbaum, G., Jakobs, C. L., Krüger, K., Lenaerts, J. T. M., Lhermitte, S., Ligtenberg, S. R. M., Medley, B., Reijmer, C. H., van Tricht, K., Trusel, L. D., van Ulft, L. H., Wouters, B., Wuite, J., and van den Broeke, M. R.: Modelling the climate and surface mass balance of polar ice sheets using RACMO2 – Part 2: Antarctica (1979–2016), The Cryosphere, 12, 1479–1498, https://doi.org/10.5194/tc-12-1479-2018, 2018.

Vaughan, D. G., Bamber, J. L., Giovinetto, M., Russell, J., and Cooper, A. P. R.: Reassessment of Net Surface Mass Balance in Antarctica, Journal of Climate, 12, 933–946, https://doi.org/10.1175/1520-0442(1999)012<0933:RONSMB>2.0.CO;2, 1999.

Vaughan, D. G., Marshall, G. J., Connolley, W. M., Parkinson, C., Mulvaney, R., Hodgson, D. A., King, J. C., Pudsey, C. J., and Turner, J.: Recent Rapid Regional Climate Warming on the Antarctic Peninsula, Climatic Change, 60, 243–274, 2003.

Winkelmann, R., Levermann, A., Martin, M. A., and Frieler, K.: Increased future ice discharge from Antarctica owing to higher snowfall, Nature, 492, 239, 2012.