Antarctic precipitation and climate-change predictions: horizontal resolution and margin vs plateau issues

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ABSTRACT. All climate models participating in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, as made available by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) as the Coupled Model Intercomparison Project 3 (CMIP3) archive, predict a significant surface warming of Antarctica by the end of the 21st century under a moderate (SRESA1B) greenhouse-gas scenario. All models but one predict a concurrent precipitation increase but with a large scatter of results. The models with finer horizontal resolution tend to predict a larger precipitation increase. Because modeled Antarctic surface mass balance is known to be sensitive to horizontal resolution, extrapolating predictions from the different models with respect to model resolution may provide simple yet better multi-model estimates of Antarctic precipitation change than mere averaging or even more complex approaches. Using such extrapolation, a conservative estimate of the predicted precipitation increase at the end of the 21st century is +30 kg m^{-2} a^{-1} on the grounded ice sheet, corresponding to a >1 mm a^{-1} sea-level rise. About three-quarters of this rise originates from the marginal regions of the Antarctic ice sheet with surface elevation below 2250 m. This is where field programs are most urgently needed to better understand and monitor accumulation at the surface of Antarctica, and to improve and verify prediction models.

1. INTRODUCTION

The North Polar region is already experiencing significant climatic and environmental changes, likely to be the result of increasing anthropogenic greenhouse-gas concentrations (Hegerl and others, 2007). In the Antarctic region, evidence of change remains weak or subcontinental in scale, but climate models unanimously predict large climate trends in the 21st century (Christensen and others, 2007). However, the models used in such predictions do not consistently reproduce the characteristics of the current Antarctic climate (Connolley and Bracegirdle, 2007). Climate change in Antarctica may result in significant change in the mass balance of the ice sheet, with impact on global sea level. Reliable models and optimal synthesis of available climate-change predictions for Antarctica are therefore needed.

Global sea level will fall by approximately 1 mm a^{-1} if accumulation at the surface of Antarctica increases by 20%, or approximately 30 kg m^{-2} a^{-1}, disregarding all other components of sea-level change (e.g. Gregory and Huybrechts, 2006). Antarctic accumulation, or positive surface mass balance (SMB), is the result of precipitation, evaporation, melt and run-off, and blowing snow (e.g. Eisen and others, 2008). Results of global climate reconstructions and predictions from a large range of climate models are archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) as the World Climate Research Program (WCRP) Coupled Model Intercomparison Project 3 (CMIP3) multi-model dataset (Meehl and others, 2007). These results have been the basis of much of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). On average, across the 43 available simulations for the SRESA1B greenhouse-gas emissions scenario (Nakiáenoviá and others, 2000), precipitation on the grounded Antarctic ice sheet is predicted to increase by 26.4 kg m^{-2} a^{-1} (see section 3) through the 21st century. However, there are large differences between the results from the different models and simulations, which range from –4.3 kg m^{-2} a^{-1} (a precipitation decrease) to as much as +77.7 kg m^{-2} a^{-1} (section 3). The standard deviation between all simulations is 16.0 kg m^{-2} a^{-1}, corresponding to 0.5 mm a^{-1} of sea-level change uncertainty.

Advanced statistical methods to rate model performance with respect to atmospheric dynamics in order to extract best multi-model estimates of climate and hydrology changes have been proposed (Uotila and others, 2007). Here, a larger set of models and simulations from the CMIP3 archive and a simpler approach taking into account the sensitivity of precipitation to model resolution are used in a model synthesis. In addition, the partitioning between central and peripheral contributions of Antarctic precipitation to future sea-level change is evaluated. The current distribution of precipitation on the Antarctic ice sheet is very inhomogeneous. It is much lower on the high plateau than closer to the coast. Whether such spatial contrast also affects precipitation change is assessed here.

2. DATA AND METHODS

The IPCC AR4 model results from 15 different climate-modeling groups are obtained from the PCMDI CMIP3 archive (Meehl and others, 2007). A list of participating groups and models and of model characteristics can be found in Meehl and others (2007). For the SRESA1B scenario, results from 24 different models (some modeling groups running several models or model versions) are archived. While, for most models, only one simulation is available for a given greenhouse-gas change scenario, some models provide more than one to characterize their own

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internal variability and sensitivity to initial conditions. Altogether, there are 49 simulations available that cover the full 21st century or more in the SRESA1B scenario. Here, only their 21st-century data are used, although some models run longer simulations with fixed greenhouse-gas concentrations beyond the end of the 21st century. Although 20th-century hindcasts are also available in the CMIP3 archive (SRES 20CM3 scenario), we concentrate on the 21st century (SRESA1B) for simplicity and because all models do not necessarily run all scenarios. In all statistics, averages and regressions, no account is taken of the fact that some simulations originate from the same model and all runs are considered independent. In fact, results indicate that there may be as much difference between different realizations of the same model as between different models. The generic term 'multi-model' will be used for 'multi-simulations'.

Models vary in terms of treatment of the climate-system physics and in terms of resolution. The meridional resolution ranges from 1.2° to 4°, with an average of 2.5°. Horizontal resolution is generally not perfectly isotropic, particularly at high latitudes where meridians converge. Here, since the Antarctic ice sheet has a broad axial symmetry, meridional resolution is taken as a measure of horizontal resolution. However, using mean resolution instead would not significantly affect the results and conclusions. The monthly-mean total precipitation, whether liquid or solid (variable PR in the CMIP3 archive), is used. Although liquid precipitation occurs in Antarctica, it is very infrequent. In addition, much of the liquid water deposited at the surface is more likely to refreeze than run off, thus contributing to accumulation. Runoff, whether from precipitation or melting, is not expected to account for a significant fraction of the Antarctic SMB in the 21st century (Gregory and Huybrechts, 2006; Krinner and others, 2007). In addition to total precipitation, surface air temperature (TAS) and precipitable water (PRW) are also extracted from the CMIP3 archive and presented to tentatively interpret precipitation-change results. Some evaluation of evaporation/sublimation (HFLS) is also reported.

A 0.5° (longitude) × 0.25° (latitude) grounded Antarctic ice map (personal communication from C. Ritz, 2007) is used to mask out that part of the precipitation field of each model which does not contribute to sea-level change. Similarly, a 1/6° topography dataset (Krinner and others, 2007) is used to mask in or out model precipitation in various surface elevation ranges. Both masks are first interpolated on each model grid and then applied, avoiding interpolation of the precipitation itself which may be affected by strong gradients. Calculation/averaging of the mean precipitation on the grounded ice sheet is performed for each model after masking. The mean precipitation is evaluated and averaged over the first and last 20 years of the 21st century in the SRESA1B simulations. Difference between the two periods thus yields a precipitation-change estimate over ~80 years from the early part to the end of the current century. Other climate variables are treated similarly.

In addition to the IPCC coupled model results, simulations and predictions from a high-resolution atmosphere-only general circulation model (GCM), LMDZ4 (Hourdin and others, 2006), are also used in the present work. Description and setting of the model are described by Krinner and others (2007). Sea-surface boundary conditions for the end of the 20th and 21st centuries are provided by the 20CM3 and SRESA1B coupled model simulations of one of the CMIP3 models archived at PCMDI, namely the IPSL-CM4 model. How sea-surface boundary conditions are best interpolated from a coupled model on a different and much coarser grid is discussed by Krinner and others (2008). The atmosphere-only model grid is stretched in order to increase resolution in the Antarctic region (Krinner and others, 1997). As a result, the mean meridional resolution is 0.6° south of 60° S, finer than any of the models in the PCMDI CMIP3 archive. Simulations are available over 20 years at the end of the 20th and 21st centuries, and simply interpolated to the early 21st century for comparison with the SRESA1B simulations from the CMIP3 archive. This is admittedly a first-order estimate, as climate change in this period is unlikely to be perfectly linear (section 4), if only because it is affected by significant stochastic natural variability. The present-day simulated surface temperature and SMB is in good agreement with the observations (Krinner and others, 2007).

There is virtually no reliable observation of precipitation on the Antarctic ice sheet to validate models for this variable. This is because precipitation is very hard to measure in Antarctica, both on the plateau where precipitation rates are very low and in peripheral regions where measurement devices are strongly affected by blowing snow due to strong katabatic and synoptic winds. SMB is measured by various means (e.g. Magand and others, 2007; Eisen and others, 2008) and may be used as a first-order proxy for precipitation. Precipitation is expected to be on average larger than accumulation since evaporation/sublimation is generally a small negative term of the SMB (Genthon and Krinner, 2001; section 5) and so is melting followed by runoff. According to the latest compilation and interpolation of available SMB reports (Arthern and others, 2006), the mean SMB on the grounded ice sheet is $143 \pm 40\,\mathrm{kg\,m^{-2}\,a^{-1}}$. It is expected that the mean precipitation is somewhat larger than this, but to what extent is not known.

3. SENSITIVITY OF PRECIPITATION TO MODEL RESOLUTION

Many atmospheric processes take place at much finer resolution than current meteorological and climate models can explicitly resolve due to computational limitations. Thus, parameterizations of subgrid processes are largely used in such models, or the subgrid component of processes acting at various scales is simply ignored. This is often the case with topography-related processes which, in particular, directly affect precipitation through air-mass raising, adiabatic cooling and condensation. Thus, even the same model used at different resolution will not perform identically, with the finer resolution performing best over topographic regions (High Resolution Ten Year Climate Simulations – HIRETYCS: Centre National de Recherches Météorologiques, France (CNRM), http://www.cnrm.meteo.fr/hiretycs).

Figure 1 shows the annual mean simulated precipitation averaged over the grounded Antarctic ice sheet as a function of model meridional resolution for the early 21st century. The mean across all simulations is $239\,\mathrm{kg\,m^{-2}\,a^{-1}}$, with a standard deviation of $98\,\mathrm{kg\,m^{-2}\,a^{-1}}$. In one of the simulations, precipitation reaches $553\,\mathrm{kg\,m^{-2}\,a^{-1}}$ while in another it is as low as $147\,\mathrm{kg\,m^{-2}}$. Neither extreme is likely to be realistic, but there is no way of providing a definite objective assessment of Antarctic precipitation in the models. The mean simulated precipitation decreases with increasing (finer) resolution. A linear regression yields $P = 57R + 88$, significant at the 99% level (t test), with P the precipitation

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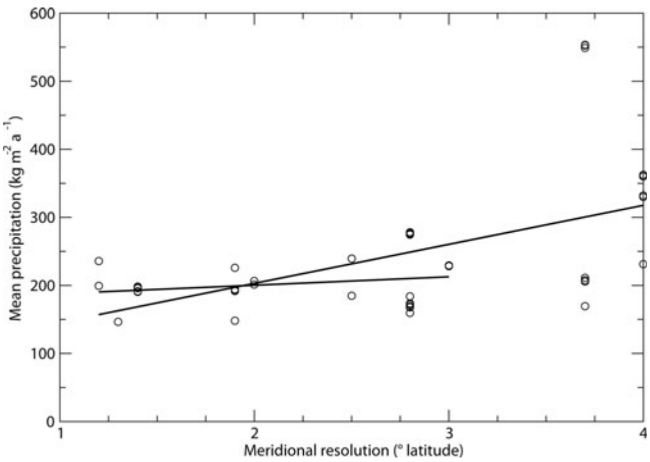

Fig. 1. Mean simulated precipitation on the grounded Antarctic ice sheet from the IPCC SRESA1B models for the early 21st century (circles) and linear regression (lines; full range and limited to models with spatial resolution finer than 3°).

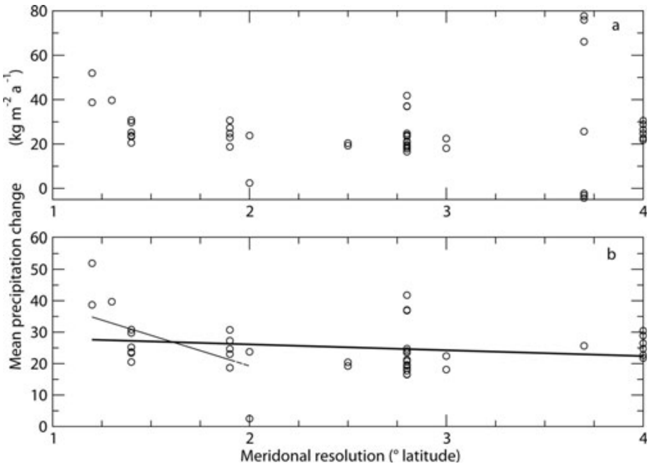

Fig. 2. Change of mean precipitation rate over the grounded Antarctic ice sheet from the early part to the end of the 21st century (80 years) as a function of model meridional resolution (circles) and linear regression: (a) all models; and (b) models predicting positive precipitation increase less than 60 kg m^{-2} a^{-1}, and linear regression for all such models and those models with resolution finer than 2°.

in kg m^{-2} a^{-1} and R the meridional resolution in degrees. However, this tendency is largely due to the contribution of the coarsest models. When limited to the models with resolution finer than 3°, no significant trend is found (Fig. 1).

Figure 2 shows the model precipitation change through the 21st century as a function of meridional model resolution. The mean multi-model predicted change is 26.4 kg m^{-2} a^{-1}. Most results lie between 10 and 50 kg m^{-2} a^{-1}. In one simulation a decrease of precipitation is obtained. This is unexpected: precipitation is expected to increase rather than decrease in response to climate warming due to increased atmospheric saturation vapor pressure and transport capacity. A decrease may result from particular atmospheric-circulation and moisture-advection pattern changes. One model predicts precipitation to increase by almost 80 kg m^{-2} a^{-1}. In Figure 2, the three simulations from this model lie above 60 kg m^{-2} a^{-1} and are considered outliers. If models predicting a precipitation decrease or increase of >60 kg m^{-2} a^{-1} are discarded as outliers, a linear regression over the remaining simulations (Fig. 2) yields a significant (>95%, t-test) decrease of precipitation with increasing coarseness: $p = 1.9R + 30$. The coarser models appear to underestimate precipitation increase and thus the contribution of Antarctic precipitation to moderating global sea-level rise in response to climate warming. While sensitivity of the mean precipitation to resolution is insignificant for models finer than 3° (see above), precipitation change does vary with resolution, even if only the higher-resolution models are retained and with the same regression as if all models are retained regardless of resolution. However, if only models finer than 2° are retained, then the regression is strongly modified (section 4; Fig. 2).

4. EXTRAPOLATING PRECIPITATION SENSITIVITY TO RESOLUTION

Poor models in terms of physics will produce poor results regardless of resolution. On the other hand, state-of-the-art higher-resolution meteorological and climate models yield better reconstructions of the Antarctic SMB (Genthon and Krinner, 2001; Gregory and Huybrechts, 2006; CNRM, http://www.cnrm.meteo.fr/hiretycs). To a large extent, this is because finer models better account for topographic effects. Although the Antarctic orography is relatively smooth, it largely determines the distribution of precipitation, with much higher snowfall in the peripheral coast-to-plateau regions than on the plateau itself (Arthern and others, 2006). It may be expected that such considerations also apply to predicting climate and particularly precipitation change. In that case, our results from section 3 indicate that the real precipitation increase by the end of the 21st century is likely to be larger than a simple multi-model average would suggest. Although there is no direct physics-based argument behind it, extrapolating an empirical precipitation–resolution relationship might yield a better multi-model estimate of precipitation change. If so, a first-order resolution-extrapolated estimate of the grounded Antarctic precipitation increase through the 21st century is given by using infinitely fine resolution (0°) in the linear regression found in section 3. The prediction of precipitation increase is 30 kg m^{-2} a^{-1} on the grounded Antarctic ice sheet, somewhat more than the simple multi-model average suggests (26.4 kg m^{-2} a^{-1}). Such an accumulation increase implies 1 mm a^{-1} of moderation of the sea-level rise by other contributions. Because the relation between precipitation and model resolution (Fig. 2) may be even steeper than the linear regression suggests, this value may be an underestimate.

The meridional resolution of the LMDZ4 atmospheric model used by Krinner and others (2007) reaches 0.6° over the Antarctic ice sheet, much finer than any of the models in the IPCC AR4 and of the order of the finest models ever used over Antarctica, even regional-only models. Using the regression above, it may be expected that LMDZ4 predicts a precipitation increase through the 21st century of 29 kg m^{-2} a^{-1}. In fact, the model predicts 49 kg m^{-2} a^{-1}, much more than anticipated, definitely much higher than the CMIP3 multi-model average, and even higher than almost all of the single simulations in the archive. Regressing precipitation on resolution for the models with resolution finer than 2° only (Fig. 2; $P = 19.5R + 58$), the prediction for a model with 0.6° resolution is 47 kg m^{-2} a^{-1}. This is very close to the prediction by LMDZ4, supporting the idea that

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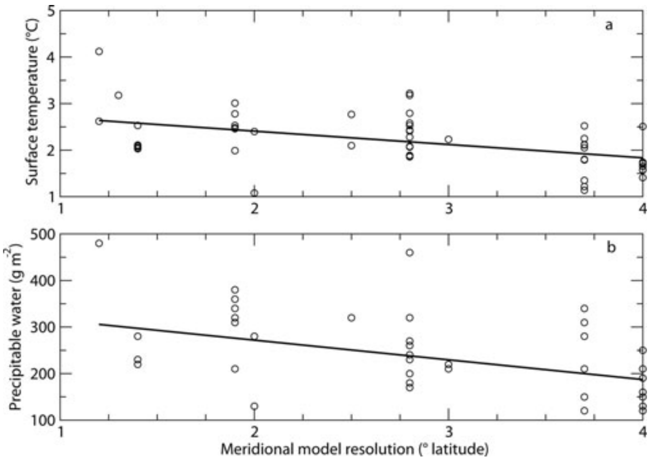

Fig. 3. Mean change of surface air temperature (a) and precipitable water (b) over the grounded Antarctic ice sheet from early part to the end of the 21st century as a function of model meridional resolution, including linear regressions.

the extrapolation of a linear regression over a broader range of resolutions above is probably conservative.

Uotila and others (2007) scaled 15 of the CMIP3 climate models according to their performance at reproducing circumpolar synoptic circulation patterns in the second half of the 20th century as identified using self-organizing maps and meteorological analyses for reference. They do not report a relation between model performance and spatial resolution. Synoptic dynamics may indeed be less directly sensitive to resolution than precipitation on the ice sheet. This is because coupling with the ocean and sea ice and the ability to accurately simulate both components and their coupling are more critical and less dependent on the resolution of the atmospheric model. Uolita and others (2007) evaluate net precipitation on the ice sheet, which they define as precipitation minus evaporation, $P-E$. The mean predicted increase of $P-E$ from the end of the 20th century to the end of the 21st century is $42\,\mathrm{kg\,m^{-2}\,a^{-1}}$. Considering that $P-E$ increases more during the first than during the second half of the period, it may be estimated that this reduces to approximately $25\,\mathrm{kg\,m^{-2}\,a^{-1}}$ from the early part to the end of the 21st century, our study period. Both precipitation and evaporation increase with warming, and the respective contribution of each component is not detailed. However, we can calculate the precipitation increase directly in the models selected by Uolita and others (2007). It amounts to $28\,\mathrm{kg\,m^{-2}\,a^{-1}}$, again more than a simple multi-model averaging would suggest, although less than a resolution-based extrapolation yields.

Figure 3 shows the change through the 21st century of the mean surface temperature and atmospheric precipitable water in the models. All models predict an increase of both variables. The multi-model average increase is 2.2°C and $219\,\mathrm{g\,m^{-2}}$ respectively. Again, inter-model variability is significant (std dev. = 0.56° and $27\,\mathrm{g\,m^{-2}}$), and a significant linear relationship with model resolution is found. If extrapolated to infinitely fine resolution, the best multi-model estimate of surface warming is almost 3°C and of increase of atmospheric moisture is $356\,\mathrm{g\,m^{-2}}$. The mean multi-model averaged precipitable water is $1.28\,\mathrm{kg\,m^{-2}}$, and the inter-model variability is weakly related to model resolution. Thus, a best estimate of the precipitable water increase through the 21st century is 28%. If the best estimate of surface temperature warming above is used, then the sensitivity of precipitable water to Antarctic warming is +9.3% $°\mathrm{C}^{-1}$. A similarly calculated sensitivity of precipitation to Antarctic warming is +13% $°\mathrm{C}^{-1}$, of the order of, yet slightly more than for, total precipitable water. This is consistent with the fact that greenhouse warming is larger in the lower atmospheric levels where much of the precipitable water lies and the precipitation originates from.

5. PERIPHERAL VS CENTRAL CONTRIBUTIONS OF ANTARCTIC PRECIPITATION AND SMB TO SEA-LEVEL CHANGE

Figure 4 shows the distribution of precipitation change from the end of the 20th century to the end of the 21st century in the LMDZ4 high-resolution model (Krinner and others, 2007). A relative change (Fig. 4a) is also reported in the supplementary material to chapter 11 of the IPCC AR4 report (Christensen and others, 2007, fig. S11.30) or in Gregory and Huybrechts (2006, fig. 1). Various details of the spatial distribution of precipitation change differ, illustrating particularities of a single model compared to a multi-model average. Yet, in common, all maps show little or no coast vs interior contrast and, if any, larger relative change on the plateau than in the peripheral regions. However, the real precipitation change is much larger on the periphery of the ice sheet (Fig. 4b). The illustration in the IPCC AR4 report may thus be misleading with respect to the contribution to sea-level change of precipitation in different parts of Antarctica.

Figure 5 shows the change of precipitation averaged over the grounded Antarctic ice sheet, separately for regions where the surface elevation is below or above 2250 m. The median elevation of the grounded Antarctic ice sheet is 2250 m (shown in Fig. 4). Thus the grounded surface above and below this elevation is the same ($\sim 7.5\times10^{6}\,\mathrm{km^2}$), and a given change of the SMB in one or the other part of Antarctica has the same impact on sea level. Figure 5 shows that the mean precipitation increase is about three times larger in the lower peripheral regions than on the interior Antarctic plateau, in relation to the warmer temperatures and saturation water pressure there. Thus, with respect to precipitation, the periphery of Antarctica is three times more important for sea-level issues than the interior. In addition, the slope of the linear regression between precipitation and model resolution is much steeper in the lower part of Antarctica. This is not surprising, as this is where the slopes are larger, topographic impact strongest, and model resolution to capture this impact most important. The results from the LMDZ4 high-resolution model are also reported in Figure 5. They fit nicely and confirm extrapolation from the coarser models, although on the higher side of the extrapolation for the lower-elevation part, possibly indicating that the marginal regions are even more important relative to the plateau than quantified here.

The early-century multi-model mean latent-heat flux at the surface of the grounded ice sheet is $2.05\,\mathrm{W\,m^{-2}}$, increasing to $2.29\,\mathrm{W\,m^{-2}}$ at the end of the 21st century. This converts into ablating <10% of the precipitation on average on the ice sheet. However, sublimation on the low-elevation ice-sheet periphery below 2250 m is more than six times that on the interior plateau due to warmer temperature and stronger winds, and sublimation increase through the

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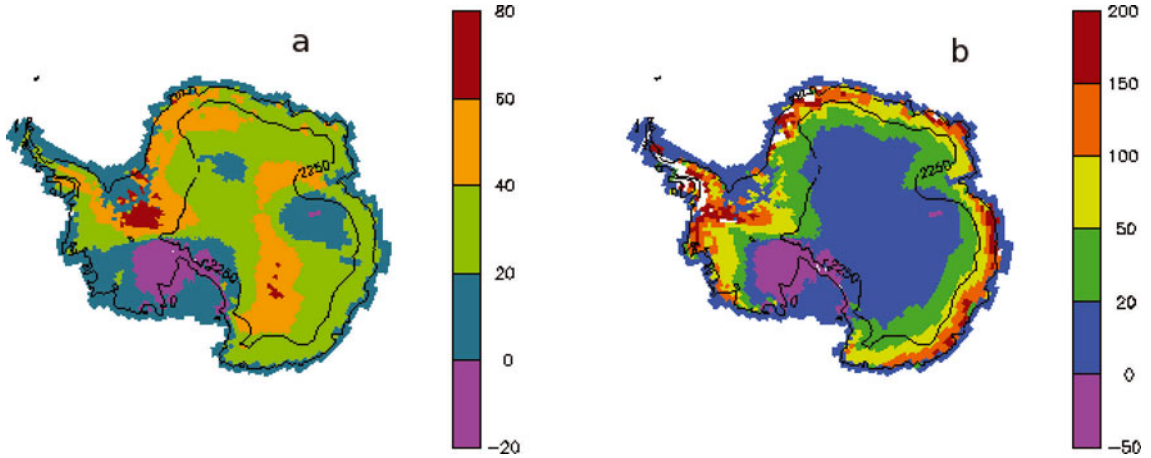

Fig. 4. LMDZ4 high-resolution prediction of (a) relative (%) and (b) absolute (kg m^{-2} a^{-1}) precipitation change from the late 20th to the late 21st century. The 2250 m elevation contour is also shown.

21st century is twice as much. Obviously, melt and runoff can only occur at low elevation where surface temperature may exceed 0°C. Wind erosion can only export blowing snow away from the ice sheet if occurring close to the coast. Thus all the terms of the mean Antarctic SMB and SMB change, including precipitation, have a much larger contribution at the periphery of the ice sheet than on the plateau. This is where models must be verified and improved in priority to increase confidence in their predictions of the contribution of the Antarctic SMB to sea-level change.

6. DISCUSSION AND CONCLUSION

The IPCC model results available from PCMDI as the CMIP3 archive show that change of precipitation on the Antarctic ice sheet with climate warming in the SRESA1B scenario may significantly contribute to moderating sea-level rise by other components of sea-level change like thermal expansion of the oceans or melting and changing flow of continental ice. However, both the simulated mean precipitation and its predicted change with climate are sensitive to model resolution. Considering that finer-resolution models are likely more realistic, an extrapolation of a linear regression to an infinitely fine resolution is the preferred way of extracting common information, rather than a simple multi-model average. Then, a conservative estimate of relative sea-level fall due to Antarctic precipitation at the end of the 21st century is about 1 mm a^{-1}. Although high resolution alone will not make a poor model perform well over Antarctica, increasing the spatial resolution of the models, even everything else kept unchanged, should improve our confidence in the results. Regional limited-area models, stretched-grid GCMs and additional computer resources are keys to this prospect.

The peripheral part of the grounded Antarctic ice sheet with surface elevation below 2250 m contributes ~3 times more to the relative sea-level fall due to precipitation than the interior plateau. This is a marginal region to about 250 km from the coast, where the processes of snow accumulation are complex due to strong winds and blowing snow, proximity to the ocean, and frequent occurrence of low-pressure systems. Although most of the manned Antarctic stations are located on the coasts rather than on the plateau, little is currently being done to efficiently monitor the accumulation in this crucial region, beyond the very close proximity of the stations. A better understanding and monitoring of accumulation in the coast-to-plateau region is crucial to better evaluate and improve the models used to predict Antarctic SMB changes and related contribution to sea level. Coast-to-plateau monitoring transects like that of the GLACIOCLIM SurfAce Mass Balance of Antarctica (GLACIOCLIM-SAMBA) observatory (http://www.lgge.obs.ujf-grenoble.fr/~christo/glacioclim/samba) should be extended to other parts of Antarctica and should deploy more efforts to evaluate the various contributions to the SMB, in particular precipitation.

ACKNOWLEDGEMENTS

We acknowledge the modeling groups for making their simulations available for analysis, and PCMDI for collecting and archiving the CMIP3 model output. The WCRP CMIP3 multi-model dataset is supported by the Office of Science, US Department of Energy. This research was supported by

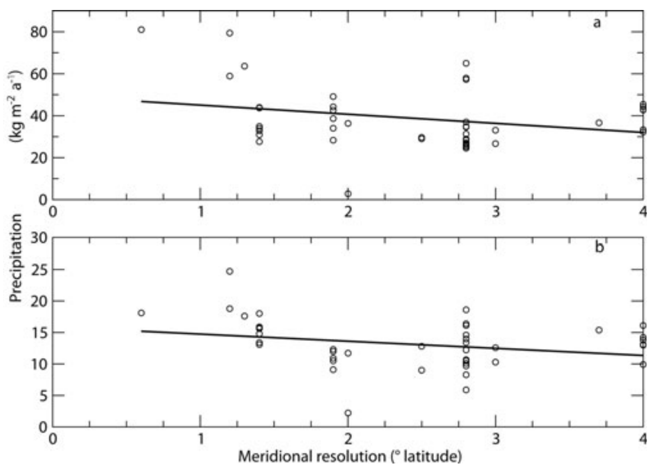

Fig. 5. Change of mean precipitation rate from the early part to the end of the 21st century (80 years) as a function of model meridional resolution (circles) and linear regressions: (a) in the 0–2250 m surface elevation fraction of the grounded Antarctic ice sheet; and (b) above 2250 m. Model results are from the IPCC AR4 archive at PCMDI, except for the finest-resolution model which is the scaled LMDZ4 atmospheric GCM (see text for details).

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Institut National des Sciences de l'Univers (INSU, France) program LEFE-CHARMANT. The LMDZ4 model was run on the computer facilities of MIRAGE at Université Joseph Fourier in Grenoble, France. Comments and suggestions by T. Neumann, K. Fujita and two anonymous reviewers are acknowledged.

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