



LETTER

Anthropogenic impact on Antarctic surface mass balance, currently masked by natural variability, to emerge by mid-century

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Abstract

Global and regional climate models robustly simulate increases in Antarctic surface mass balance (SMB) during the twentieth and twenty-first centuries in response to anthropogenic global warming. Despite these robust model projections, however, observations indicate that there has been no significant change in Antarctic SMB in recent decades. We show that this apparent discrepancy between models and observations can be explained by the fact that the anthropogenic climate change signal during the second half of the twentieth century is small compared to the noise associated with natural climate variability. Using an ensemble of 35 global coupled climate models to separate signal and noise, we find that the forced SMB increase due to global warming in recent decades is unlikely to be detectable as a result of large natural SMB variability. However, our analysis reveals that the anthropogenic impact on Antarctic SMB is very likely to emerge from natural variability by the middle of the current century, thus mitigating future increases in global sea level.

1. Introduction

The mass balance of the Antarctic ice sheet is of critical scientific and societal concern due to its central role in regulating global sea level. Over the 1992–2011 period, Antarctica is estimated to have lost mass at an average rate of $-71 \pm 53 \text{ Gt yr}^{-1}$ (Shepherd *et al* 2012), with evidence for higher rates of mass loss toward the end of the period (e.g., $-81 \pm 37 \text{ Gt yr}^{-1}$ during 2005–2010). This recent acceleration of ice sheet mass loss is thought to be due to the acceleration of outlet glaciers in several key sectors of the ice sheet, in particular on the Antarctic Peninsula (Rignot *et al* 2004, Domack *et al* 2005, Wouters *et al* 2015), and in the Amundsen Sea sector of West Antarctica (Rignot 2011, Shepherd *et al* 2012, Velicogna *et al* 2014). In contrast, Antarctic surface mass balance (SMB) (essentially the difference between snowfall and sublimation) has exhibited no significant trend in recent decades (Monaghan *et al* 2006a, 2006b, van den Broeke *et al* 2006, Lenaerts *et al* 2012). This is despite the fact that both global and regional climate models

robustly project increases in Antarctic SMB in response to global warming (Krinner *et al* 2007, Uotila *et al* 2007, Monaghan *et al* 2008b, Ligtenberg *et al* 2013, Frieler *et al* 2015). In the current work, we show that this apparent discrepancy between models and observations can be reconciled by taking into account the large variability in SMB (associated primarily with variability in snowfall) generated naturally (or internally) within the Antarctic climate system.

The remainder of this paper is organized as follows. Section 2 describes the model and observational data that are employed in the present study, and discusses the methods used to compute spatiotemporal averages as well as temporal changes in these data. In section 3, we evaluate model-simulated Antarctic SMB in terms of climatology and projected response to anthropogenic climate warming during the twentieth and twenty-first centuries. Section 4 quantifies the anthropogenically-forced SMB increase in comparison to natural climate variability on different time-scales. Finally, conclusions are presented in section 5.

Table 1. CMIP5 simulations analyzed. For each model, the number of ensemble members n is indicated for the historical, RCP4.5 and RCP8.5 experiments. A single pre-industrial control (piControl) simulation from each model is analyzed, with the length of this simulation noted. The abbreviation ‘n/a’ denotes that data for a particular experiment were not available.

Model	Historical n	RCP4.5 n	RCP8.5 n	piControl length (yrs)
ACCESS1-0	1	1	1	225
ACCESS1-3	1	1	1	495
bcc-csm1-1	3	1	1	495
bcc-csm1-1-m	3	1	1	360
BNU-ESM	1	n/a	1	540
CanCM4	10	10	n/a	n/a
CanESM2	5	5	5	990
CCSM4	6	6	6	495
CESM1-CAM5	30	15	30	n/a
CESM1-WACCM	7	3	3	180
CMCC-CESM	1	n/a	1	270
CMCC-CM	1	1	1	315
CMCC-CMS	1	1	1	n/a
CSIRO-Mk3-6-0	10	5	10	495
FGOALS-g2	5	n/a	1	675
GFDL-CM3	5	1	1	495
GFDL-ESM2G	3	1	1	495
GFDL-ESM2M	1	1	1	495
GISS-E2-H	5	5	1	225
GISS-E2-R	6	5	2	270
HadCM3	10	10	n/a	n/a
HadGEM2-CC	3	1	3	225
HadGEM2-ES	4	1	4	225
inmcm4	1	1	1	495
IPSL-CM5A-LR	5	4	4	990
IPSL-CM5A-MR	1	1	1	270
IPSL-CM5B-LR	1	1	1	270
MIROC5	5	1	3	180
MIROC-ESM	3	1	1	495
MIROC-ESM-CHEM	1	1	1	225
MPI-ESM-LR	3	3	3	990
MPI-ESM-MR	3	3	1	990
MPI-ESM-P	2	n/a	n/a	1125
MRI-CGCM3	3	1	1	495
NorESM1-M	3	1	1	495

2. Model and observational data: description, averaging and trend analysis

We evaluated simulations from 35 coupled atmosphere-ocean general circulation models (GCMs) that were included in phase 5 of the Coupled Model Intercomparison Project (CMIP5; see table 1). Model-simulated monthly precipitation, evaporation/sublimation, and surface air temperature (SAT) were acquired from four different CMIP5 experiments (Taylor *et al* 2012): the historical experiment, nominally covering the period 1850–2005; the RCP4.5 and RCP8.5 experiments for the period 2006–2100; and the pre-industrial control experiment that varies in length between models from about 200 years to over 1000 years (see table 1). All available ensemble members from each CMIP5 model are used. In cases where multimodel means are computed, we first calculate ensemble-average values for each individual model so as to weight all models equally. Note that we employ the version of CESM1-CAM5 that was used in

the Large Ensemble project (Kay *et al* 2015), even though the model configuration is somewhat different than that used in CMIP5. However, for simplicity, we refer to all 35 models (i.e., including CESM1-CAM5) collectively as the CMIP5 models.

For comparison with CMIP5 results, we employ simulated Antarctic SMB from the RACMO2.3 regional atmospheric model (van Wessem *et al* 2014). RACMO2.3 has a horizontal resolution of 27 km and is forced by ERA-Interim reanalysis data at the ocean and lateral boundaries. For the current work, we acquired climatological and annual-mean Antarctic SMB data from RACMO2.3 for the period 1979–2013. Additionally, in order to evaluate CMIP5 simulations of Antarctic temperature, we employ observed monthly SAT for 1960–2005 based on four different temperature reconstructions (Schneider *et al* 2012).

Annually-averaged (and annually-integrated) quantities in the present study are calculated from monthly-mean data assuming that the year runs from June through May. This is done in order to avoid

breaking up the Antarctic summer melt season. Antarctic-mean SAT in both models and observations is computed by area weighting using the cosine of latitude.

Temporal changes in all quantities are based on linear trend analysis, using ordinary least-squares linear regression. Estimated uncertainties in these changes account for autocorrelation of the regression residuals following Santer *et al* (2000). Thus, trend uncertainties are calculated as

$$\pm \frac{s_{\varepsilon} t_{\text{crit}}}{(N_e - 1)^{1/2} s_x}, \quad (1)$$

where s_{ε} is the standard deviation of the regression residuals, s_x is the standard deviation of the x variable (time), N_e is the effective sample size, and t_{crit} is the critical t -value for $N_e - 2$ degrees of freedom (95% confidence).

3. Simulated Antarctic SMB: climatology and response to anthropogenic forcing

3.1. Climatological mean SMB

Before discussing the historical and future changes in Antarctic SMB simulated by the CMIP5 models, we demonstrate that these models are able to capture the key features of the climatological mean SMB for the present day. Observationally-constrained estimates of the present-day SMB for the grounded Antarctic ice sheet range between 1768 Gt yr⁻¹ (Arthern *et al* 2006) and 2076 Gt yr⁻¹ (van de Berg *et al* 2006). For the CMIP5 models, the corresponding climatological mean SMB computed from the pre-industrial control (piControl) simulations is 2509 ± 544 Gt yr⁻¹ (multi-model mean and 1-sigma range). Thus, even though the models overestimate the Antarctic SMB by 21%–42% on average (see also Palermé *et al* 2016), the simulated SMB distribution overlaps significantly with the observationally-constrained estimates.

We additionally compare spatial patterns of Antarctic SMB in CMIP5 with simulations from the RACMO2 regional atmospheric model. RACMO2 has been used extensively for Antarctic SMB studies (e.g., van den Broeke *et al* 2006, Shepherd *et al* 2012, Ligtenberg *et al* 2013, van Wessem *et al* 2014, Frieler *et al* 2015), and has been shown to have a high level of skill in simulating SMB when validated against *in situ* observations (van de Berg *et al* 2006, Lenaerts *et al* 2012, van Wessem *et al* 2014). As shown in figure 1, the spatial patterns of climatological and annual-mean Antarctic SMB in CMIP5 and RACMO2 agree reasonably well, with a spatial correlation coefficient of $r = 0.77$. Both the regional and global models simulate maximum SMB values along the periphery of the ice sheet, with SMB decreasing dramatically over the ice sheet interior, and reaching its minimum values over the high plateau of East Antarctica. The CMIP5 models tend to overestimate SMB over most of interior Antarctica, and underestimate SMB along the

steep margins of the ice sheet where they lack the resolution to properly simulate orographic enhancements in precipitation.

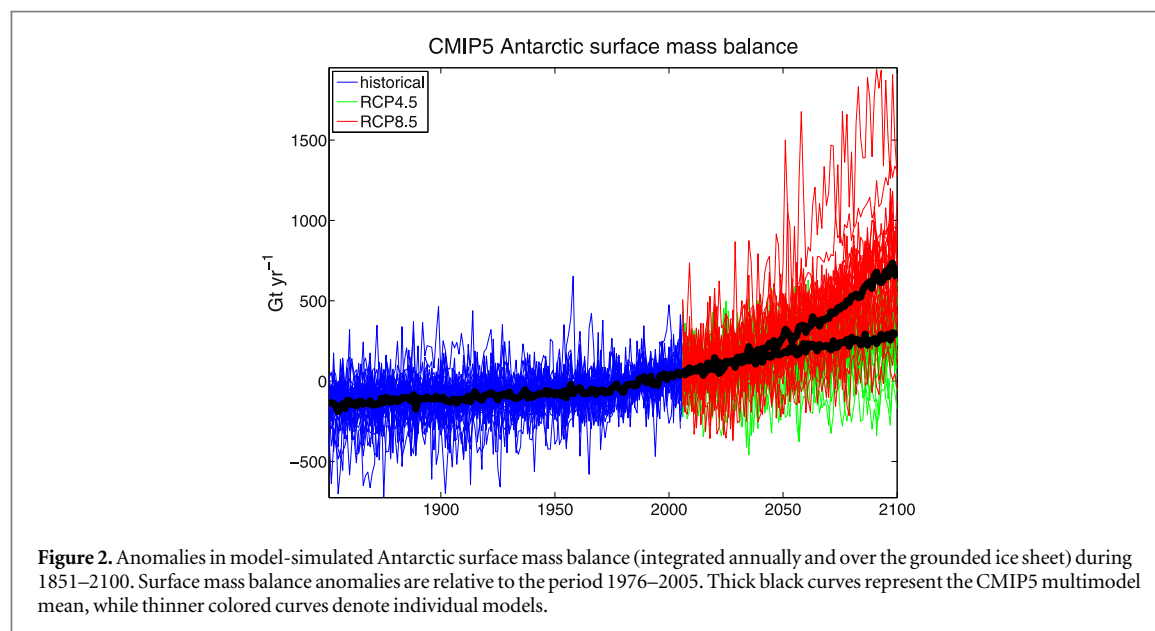
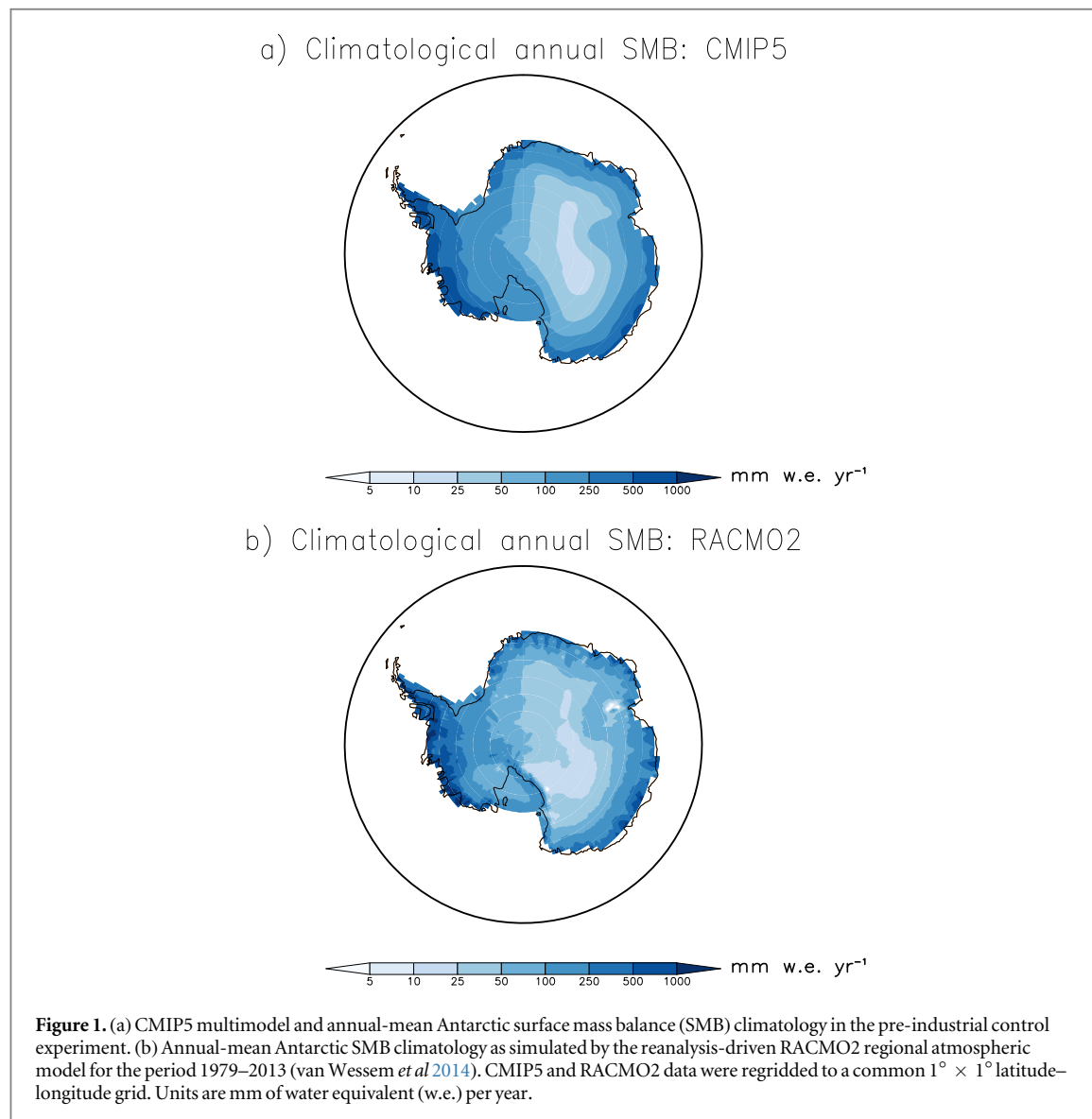
Overall, these results indicate that the CMIP5 models are able to capture the general features of the climatological mean Antarctic SMB. Perhaps even more relevant for the present study, we show in section 4 that these models also realistically simulate SMB interannual variability.

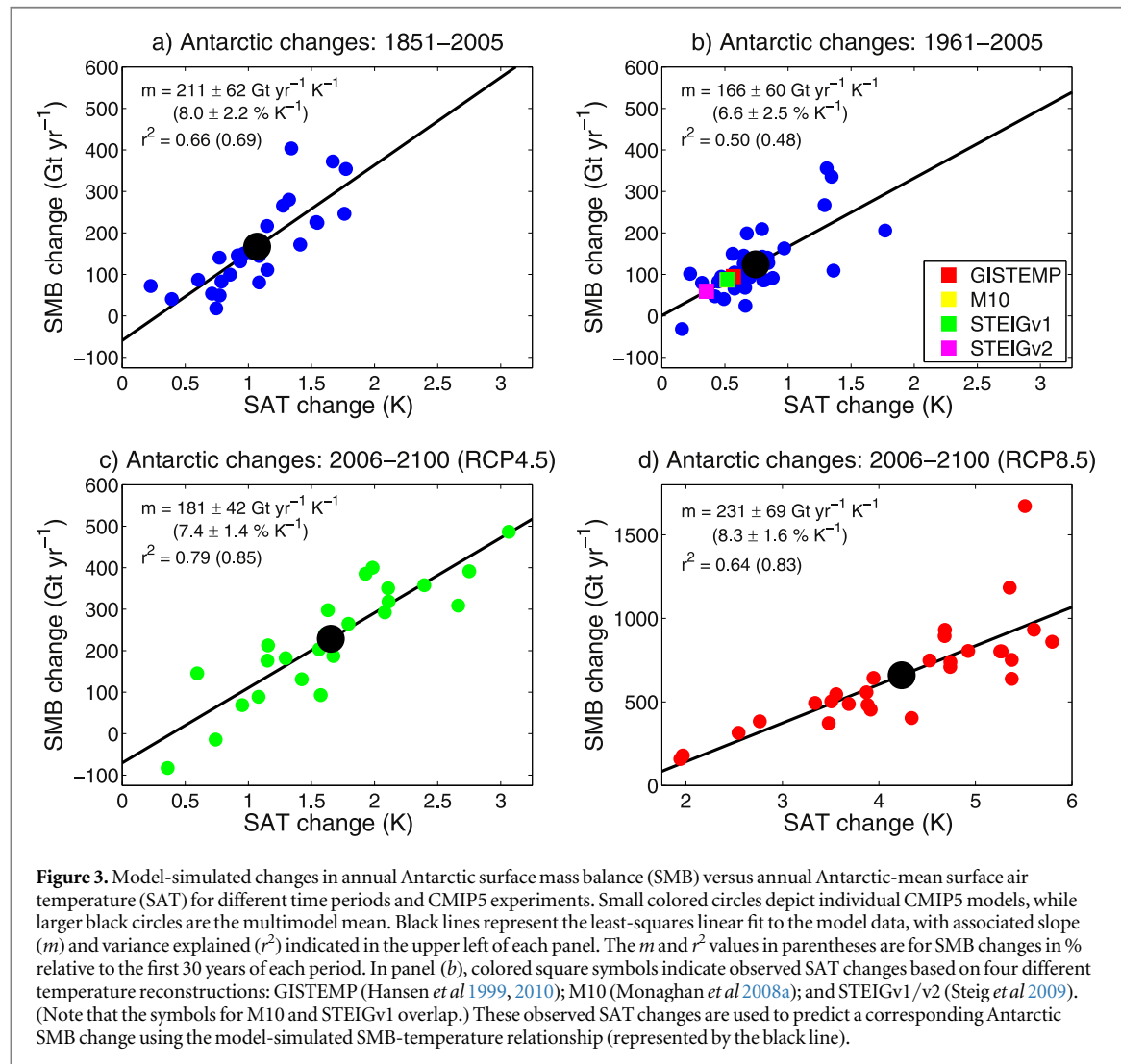
3.2. Historical and future SMB changes

We now turn our attention to the CMIP5 simulated changes in Antarctic SMB in the historical and future RCP experiments. Figure 2 shows the simulated SMB (i.e., precipitation minus evaporation/sublimation), integrated annually and over the grounded ice sheet, for the period 1851–2100. A clear upward trend in SMB is evident, particularly during the twenty-first century under the RCP8.5 emissions scenario. Even in the historical simulations, however, the modeled SMB increase is already significant from a global sea-level perspective. For the period 1851–2005, the multi-model mean Antarctic SMB (thick black curve in figure 2) increases by 160 Gt yr⁻¹, which is equivalent to 0.44 mm yr⁻¹ of global sea-level rise (GSLR). This represents about 14% of the observed rate of 3.2 mm yr⁻¹ GSLR during 1993–2010 (Church *et al* 2013), indicating a significant anthropogenic impact on Antarctic SMB even by the end of the twentieth century.

SMB increases in the CMIP5 models are largely due to increases in snowfall, with sublimation changes being much smaller in magnitude. These snowfall increases, in turn, are closely linked with increases in Antarctic air temperature, and the accompanying rise in atmospheric moisture content. Figure 3 illustrates the modeled relationship between SMB and temperature during the historical period (figures 3(a) and (b)), and during the twenty-first century under both the RCP4.5 (figure 3(c)) and RCP8.5 (figure 3(d)) emissions scenarios. Depending on the time period and emissions scenario considered, differences in Antarctic-mean warming between models explain anywhere from 50% (figure 3(b)) to ~80% (figure 3(c)) of the variance in the simulated SMB change. And, going beyond models, the presence of a strong relationship between Antarctic SMB and temperature is corroborated by a recent assessment (Frieler *et al* 2015) of ice-core data spanning the large temperature changes that occurred during the last deglaciation.

Given this strong relationship between SMB and temperature, we can compare modeled and observed Antarctic temperature changes over recent decades as a way of assessing indirectly whether there is observational evidence for the simulated SMB increase during this time. In figure 3(b), we plot along with the model results the observed Antarctic SAT change during 1961–2005 based on four different temperature



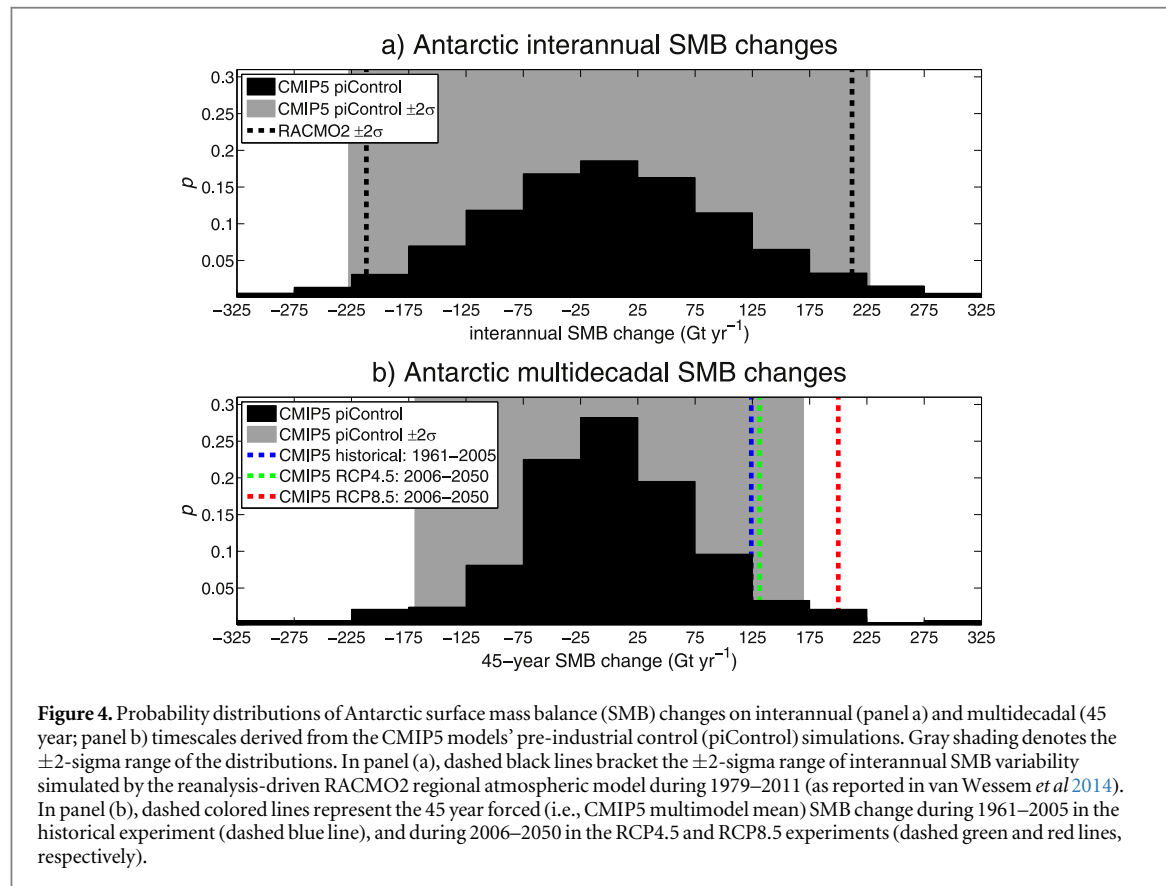


reconstructions (see Schneider *et al* 2012 for a description of these reconstructions). All reconstructions indicate that Antarctica has warmed over this period. This warming, while smaller than the multimodel mean (large black dot in figure 3(b)), is well within the distribution of individual models (small blue dots), thus providing some support for the simulated increase in SMB. Uncertainties in these observed SAT changes, however, are relatively large. For example, for the GISTEMP reconstruction (similar results apply to the other reconstructions), the 1961–2005 SAT change with 95% confidence interval is 0.567 ± 0.571 K. Using the modeled SMB-temperature relationship for this period, this translates into a SMB change of 94 ± 95 Gt yr⁻¹. (Note that the uncertainties stated here account only for SAT trend uncertainty, and not methodological uncertainty in the temperature reconstruction, or uncertainty in the SMB-temperature relationship.) These results are therefore in qualitative agreement with previous studies (Monaghan *et al* 2006a, 2006b, van den Broeke *et al* 2006, Lenaerts *et al* 2012) that found no statistically significant change in Antarctic SMB during the past several decades.

4. Importance of natural variability

One can ask whether the insignificant change in Antarctic SMB observed in recent decades implies that model projections of increasing SMB with global warming are incorrect. We argue that this is not the case, and that the apparent discrepancy between models and observations can be easily reconciled by considering the large SMB variations generated naturally within the Antarctic climate system.

Several previous studies (Monaghan *et al* 2006a, van den Broeke *et al* 2011, Horwath *et al* 2012, Lenaerts *et al* 2012, Wouters *et al* 2013, Mémin *et al* 2015) have emphasized that natural variability in Antarctic SMB is substantial on both interannual and interdecadal timescales. These studies did not, however, quantitatively compare this natural variability with the anthropogenically-forced SMB change over recent decades. This is necessary in order to determine whether we should expect the latter to be detectable—in a statistical sense—at this point in time. Figure 4 provides such a quantitative comparison, using the CMIP5 piControl simulations to represent natural



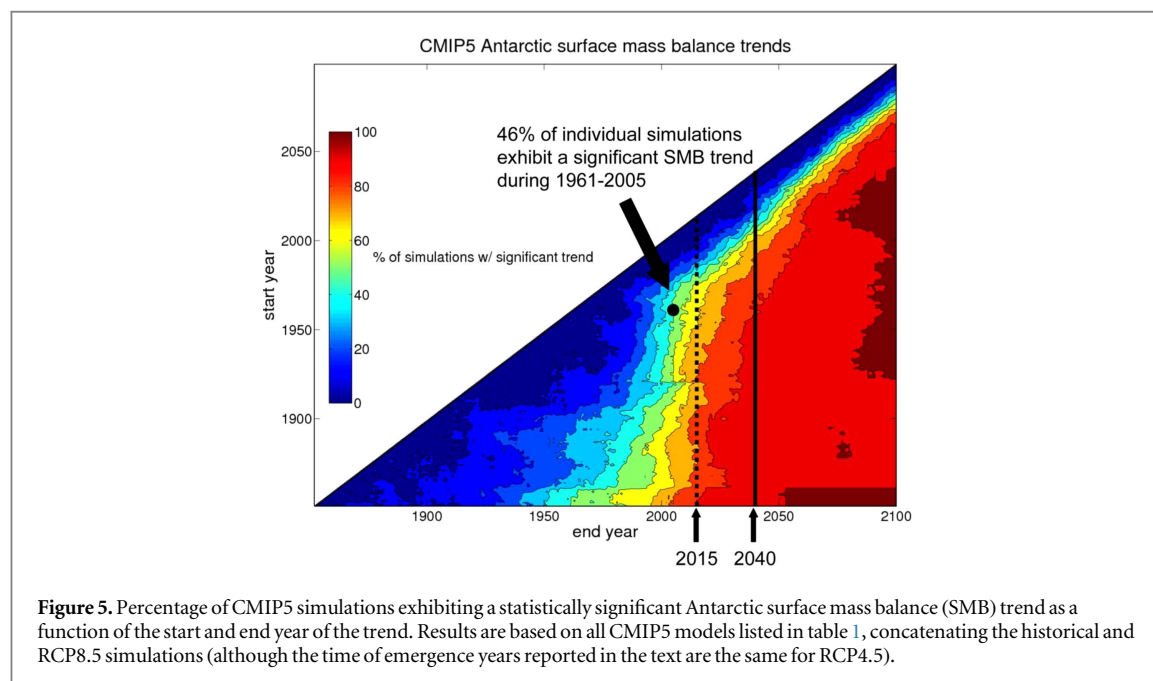
SMB variability. We remove any long-term drift from each simulation by subtracting the linear trend over the entire time series (although our results are not sensitive to this). In order to assess natural variability of Antarctic SMB on interannual timescales, each model's piControl simulation is then divided up into 9 year non-overlapping segments. We remove the 9 year mean from each segment, and use the resulting annual SMB anomalies to construct the probability distribution shown in figure 4(a), concatenating these anomalies for all 9 year periods and models.

We find that interannual SMB variability in the piControl simulations is in excellent agreement with the reanalysis-driven RACMO2 regional atmospheric model, as illustrated in figure 4(a). (Interannual SMB variability in RACMO2 has been shown to agree favorably with estimates based on GRACE satellite data; see Shepherd *et al* 2012 and van Wessem *et al* 2014.) In the CMIP5 models, the interannual SMB standard deviation is found to be 114 Gt yr^{-1} , compared to 106 Gt yr^{-1} in RACMO2 (van Wessem *et al* 2014). This good agreement offers clear evidence that the CMIP5 models are realistically simulating natural variability. However, it is important to point out that since the climatological mean SMB in the CMIP5 models is overestimated (see section 3.1), extreme low and high SMB years in these models are likely to be associated with larger absolute SMB values than extreme years in RACMO2.

The large interannual variations in Antarctic SMB will introduce large uncertainties in SMB trends on longer timescales. For the 1961–2005 period considered above, we can estimate a trend uncertainty associated with interannual variability by replacing s_e in equation (1) with the CMIP5 interannual SMB standard deviation of 114 Gt yr^{-1} . Additionally, we use $N_e = 39$ in equation (1), which is the CMIP5 multimodel mean over this period. This yields a trend uncertainty of $\pm 2.86 \text{ Gt yr}^{-2}$ (95% confidence interval), or, equivalently, $\pm 126 \text{ Gt yr}^{-1}$ for the total 45 year SMB change. For comparison, the forced (i.e., multimodel mean) SMB change over the same time period is $+124 \text{ Gt yr}^{-1}$, which is therefore not yet detectable above the noise of interannual variability.

The prospects of detecting a statistically significant SMB change decrease further when one considers the possibility that the forced response could have been masked (or offset) by multidecadal natural variability. We quantify the likelihood of this using the probability distribution of 45 year SMB changes in the CMIP5 piControl simulations (figure 4(b)). To construct this distribution, each model's piControl simulation is divided up into 45 year non-overlapping segments. SMB changes are then computed for each of these individual time periods. Finally, all 45 year SMB changes from the 31 models are combined in order to generate the probability distribution.

Based on figure 4(b), there is a 6% likelihood that the forced SMB change during 1961–2005 (dashed



blue line) could have been masked entirely by natural variability, and an 18% likelihood that at least half of the forced change could have been masked. (Since the forced SMB change during this period is an increase of $+124 \text{ Gt yr}^{-1}$, this would require SMB *decreases* due to natural variability of at least -124 and -62 Gt yr^{-1} , respectively.) Similar results apply for the 2006–2050 period under RCP4.5, as the forced response in this case is about the same ($+131 \text{ Gt yr}^{-1}$; dashed green line). Under the higher-end RCP8.5 emissions scenario, the 2006–2050 forced SMB change ($+200 \text{ Gt yr}^{-1}$; dashed red line) is outside the 2-sigma range from the piControl simulations (gray shading). This is roughly equivalent to saying that this change is outside the range of natural variability at the 95% confidence level. Accordingly, by the year 2050, the likelihood that the forced response would be masked entirely by natural variability is a mere 2%, and the likelihood that even half of the forced response would be masked is only 9%.

These results suggest that the anthropogenic impact on Antarctic SMB will soon emerge above the noise of natural climate variability. In order to be more precise about this, and determine the specific time of emergence, we calculate SMB trends over all possible time periods within each individual CMIP5 simulation. We then compute the percentage of simulations that exhibit a statistically significant SMB trend as a function of the start and end year of the trend (figure 5). For a given start year, the *likely* time of emergence is defined as the first end year when at least 66% of individual simulations display a significant SMB trend. Similarly, we regard the anthropogenic climate change signal as being *very likely* to emerge from natural variability when at least 90% of individual simulations display a significant trend. These

quantitative thresholds that are used here to define *likely* and *very likely* are chosen to be compatible with those used in the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5; IPCC 2013).

For the 1961–2005 period (black dot in figure 5), a total of 46% of the individual CMIP5 simulations exhibit a statistically significant SMB trend. This confirms our earlier result that the forced SMB response over this period is not yet well separated from natural variability. However, when the SMB trend is extended forward in time by a mere decade, to the year 2015 (dashed black line), we find it likely that the forced response would emerge from natural variability. Emergence of the anthropogenic climate change signal becomes very likely when the trend is extended to 2040 (solid black line).

Given that observed Southern Hemisphere climate change is poorly constrained prior to the start of the satellite era in 1979, we repeated the above analysis using this later year as a starting point for the SMB trends. This only slightly delays the likely and very likely time of emergence until 2021 and 2050, respectively.

5. Conclusions

Our results suggest that the anthropogenic impact on Antarctic SMB will very likely emerge from natural variability by the middle of the current century. The associated SMB increases will have a mitigating effect on GSLR. In the CMIP5 multimodel mean under RCP8.5, this mitigated GSLR reaches 79 mm by the year 2100 (relative to 1986–2005). It has been estimated, however, that as much as 35% of the twenty-first century SMB increase over Antarctica

could be offset by increased dynamic ice loss, which is an expected response to higher snowfall near the grounding line of the ice sheet (Winkelmann *et al* 2012). Even if we assume this to be the case, the remaining 51 mm of mitigated GSLR, representing the net effect of SMB increases, constitutes a significant fraction of the projected GSLR contribution from other dynamic processes over Antarctica (e.g., ice shelf thinning/destabilization due to oceanic and atmospheric warming). For example, the median estimate for this dynamic contribution, as reported in the IPCC AR5 (Church *et al* 2013), is 80 mm of GSLR by the year 2100 (again relative to 1986–2005). This implies, therefore, that more than 60% of the dynamic mass loss from Antarctica during the remainder of the current century could be compensated for by a net mass gain at the ice sheet surface. While the precise degree of compensation is highly uncertain, it suffices to say that the balance of different processes determining Antarctica's net contribution to GSLR will be decidedly different over the next several decades than it has been in the recent past.

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