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Spatial patterns of recent Antarctic surface temperature trends and the importance of natural variability: lessons from multiple reconstructions and the CMIP5 models

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Abstract The recent annually averaged warming of the Antarctic Peninsula, and of West Antarctica, stands in stark contrast to very small trends over East Antarctica. This asymmetry arises primarily from a highly significant warming of West Antarctica in austral spring and a cooling of East Antarctica in austral autumn. Here we examine whether this East–West asymmetry is a response to anthropogenic climate forcings or a manifestation of natural climate variability. We compare the observed Antarctic surface air temperature trends over two distinct time periods (1960–2005 and 1979–2005), and with those simulated by 40 models participating in Phase 5 of the Coupled Model Intercomparison Project (CMIP5). We find that the observed East–West asymmetry differs substantially between the two periods and, furthermore, that it is completely absent from the forced response seen in the CMIP5 multi-model mean, from which all natural variability is eliminated by the averaging. We also examine the relationship between the Southern Annular mode (SAM) and Antarctic temperature trends, in both models and reanalyses, and again conclude that there is little evidence of anthropogenic SAM-induced driving of the recent temperature trends. These results offer new, compelling evidence pointing to natural climate variability as a key contributor to the recent warming of West Antarctica and of the Peninsula.

Keywords Antarctic climate change · Climate variability · Coupled climate models

1 Introduction

Recent studies of Antarctic surface air temperature (SAT) trends over the past several decades have revealed that the Antarctic Peninsula and Western Antarctica are among the most rapidly warming regions on Earth (Turner et al. 2005; Chapman and Walsh 2007; Monaghan and Bromwich 2008; Steig et al. 2009; ODonnell et al. 2011; Bromwich et al. 2013; Nicolas and Bromwich 2014). These regions have also experienced increasing surface mass loss due to glacier retreat (Joughin et al. 2014; Rignot et al. 2014), with potentially severe consequences for global sea level rise. In contrast, East Antarctic SAT has experienced an insignificant, cooling trend (Schneider et al. 2012; Nicolas and Bromwich 2014). In the annual mean, this large spatial asymmetry in SAT trends between West and East Antarctica has become a hallmark of Antarctic climate change: yet, it remains poorly understood.

It is important to recall, however, that the annual mean asymmetry in Antarctic SAT trends arises, largely, from opposing trends in austral spring and autumn. Over the past several decades, significantly positive trends have been observed in West Antarctica in spring, and marginally significant negative trends have been observed in East Antarctica in autumn (Schneider et al. 2012). Hence, the causes leading to the annual mean asymmetry are likely to be complex, and might arise for different reasons in different seasons.

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Some of the cooling of East Antarctic and the warming of the Peninsula has been attributed to the recent positive trend in the Southern Annular Mode (SAM, Thompson and Solomon 2002; Marshall 2007; Nicolas and Bromwich 2014), which is believed to be anthropogenically forced in the austral summer season, the dominant forcing in this season being stratospheric ozone depletion (McLandress et al. 2011; Polvani et al. 2011; Thompson et al. 2011; Previdi and Polvani 2014; Schneider et al. 2015). Using a chemistry-climate atmospheric model, coupled to interactive ocean and sea ice models, McLandress et al. (2011) have suggested that ozone depletion may in fact have contributed to the spatial asymmetry between West and East Antarctica in austral summer. Yet, this is not the season with the largest observed cooling trends.

As for West Antarctica, many studies have highlighted the importance of the zonally asymmetric circulation, specifically the Amundsen Sea Low (ASL), in modulating the surface climate in this region (Hosking et al. 2013; Raphael et al. 2015). Specifically, the recent warming of West Antarctica has been associated with a deepening of the ASL (Ding et al. 2011; Schneider et al. 2012; Clem and Fogt 2015; Clem and Renwick 2015; Raphael et al. 2015; Schneider et al. 2015). Model simulations indicate a deepening of the ASL in austral summer over the historical period, which is likely linked to ozone depletion (Fogt and Zbacnik 2014; Fogt and Wovrosh 2015; Hosking et al. 2016). However, the broad warming of West Antarctica occurs primarily in spring, and this does not align with the seasonality of the deepening of the ASL in response to anthropogenic forcing reported in these studies.

Several other studies have emphasized the importance of tropical sea surface temperature (SST) variability for the West Antarctic region. In particular, both modeling and observational studies have shown that SST anomalies in the tropical Pacific excite Rossby waves trains that propagate into the ASL region of West Antarctica, and could therefore influence temperatures there (Ding et al. 2011; Schneider et al. 2012; Turner et al. 2013; Fogt and Wovrosh 2015; Clem and Fogt 2015; Clem and Renwick 2015). More recently, Atlantic SST anomalies have also been shown, in modeling studies, to be capable of significantly influencing Antarctic temperatures and sea ice, again via Rossby wave propagation and a deepening of the ASL (Simpkins et al. 2014; Li et al. 2015).

If SSTs are in fact an important player, one is led to ask to what degree the observed East–West asymmetry in the Antarctic SAT trend may be the result of natural, multi-decadal, climate variability, as opposed to a direct forced response to anthropogenic climate change. This is the question we wish to address in this paper. Several recent studies have shown that the climate of the Antarctic region might be highly variable, in both space and time, and that near-term detection of anthropogenically-forced trends in that region may be challenging (Hawkins and Sutton 2012; Polvani and Smith 2013; Simpkins et al. 2013; Thomas et al. 2013; Fan et al. 2014; Turner et al. 2015). Here, we adhere to the school of thought that recent multi-decadal trends in tropical Pacific (Meehl et al. 2011; Kosaka and Xie 2013; Dai et al. 2015) and Southern Ocean SSTs (Fan et al. 2014) are dominated by natural variability; however, we note that there are other schools of thought that consider the recent prolonged La-Nina state of tropical Pacific (Clement et al. 1996) and the recent cooling of Southern Ocean SSTs (Ferreira et al. 2015) to be anthropogenically forced.

In this study we seek to determine whether the asymmetric spatial patterns of recent Antarctic SAT trends are caused by natural variability or anthropogenic forcing. We do this by analyzing several widely available reconstructions of Antarctic SAT, as well as the extensive archive of the recently completed Phase 5 of the Coupled Model Intercomparison Project (CMIP5). We find that both observations and models offer clear evidence that the strong East–West asymmetry in SAT trends is quite likely a consequence of the natural variability of the climate system, and is not a direct fingerprint of anthropogenic forcings.

This paper is organized as follows. In Sect. 2, we outline the observationally-based datasets and model output used in the study and describe our methodology. In Sect. 3 we analyze the Antarctic SAT trends in the reconstructions over two different periods. In Sect. 4 we contrast these with and the trends seen in CMIP5 models, and place the observed and simulated trends within the context of natural climate variability. In Sect. 5 we examine the connection between the recent Antarctic temperature trends and trends in the Southern Annular Mode. Finally, a summary and discussion are presented in Sect. 6.

2 Methods

We use five observationally-based Antarctic SAT reconstructions: the Chapman and Walsh (2007) reconstruction (hereafter CHAPMAN), GISTEMP (Hansen et al. 2010), the updated Monaghan and Bromwich (2008), Monaghan et al. (2008) reconstruction (hereafter M10) and two alternative versions of the Steig et al. (2009) reconstruction (hereafter Steigv1 and Steigv2, following Schneider et al. (2012). See Schneider et al. (2012) for a detailed comparison of different Antarctic SAT observational products). We also use the ERA-Interim reanalysis (Dee et al. 2011) for selected diagnostics. Note that we do not use the ERA-Interim reanalysis to calculate SAT trends due to potentially spurious trends in the Antarctic region (see Nicolas

Table 1 Coupled Model Intercomparions Project Phase 5 (CMIP5) models used in this study, and the length of their preindustrial control integrations

CMIP5 Model	Length of preindustrial integration (years)
ACCESS1-0	250
ACCESS1-3	500
bcc-csm1-1	500
bcc-csm1-1-m	400
BNU-ESM	559
CanESM2	996
CCSM4	501
CESM1(BGC)	500
CESM1(CAM5-1-FV2)	n/a
CESM1(CAM5)	319
CESM1(FASTCHEM)	222
CESM1(WACCM)	200
CMCC-CESM	n/a
CMCC-CM	330
CMCC-CMS	n/a
CNRM-CM5	850
CSIRO-Mk3-6-0	500
FGOALS-g2	n/a
FIO-ESM	800
GFDL-CM3	500
GFDL-ESM2G	500
GFDL-ESM2M	500
GISS-E2-H	240
GISS-E2-R	850
HadCM3	n/a
HadGEM2-CC	240
HadGEM2-ES	575
inmcm4	500
IPSL-CM5A-LR	1000
IPSL-CM5A-MR	300
IPSL-CM5B-LR	300
MIROC4h	100
MIROC5	200
MIROC-ESM	531
MIROC-ESM-CHEM	255
MPI-ESM-LR	1000
MPI-ESM-MR	1000
MRI-CGCM3	500
NorESM1-M	501
NorESM1-ME	252

and Bromwich (2014) for a discussion of Antarctic SAT trends in different reanalysis products): instead, we only use the ERA-Interim reanalysis for estimates of the climatological mean and interannual variability of Antarctic SAT. It has been shown that ERA-Interim is one of the most reliable reanalysis products in the Antarctic region (Bracegirdle and Marshall 2012), yet substantial biases in SAT exist. ERA-Interim is warm-biased relative to stations in the interior of the continent and is cold-biased relative to the coastal stations (Bracegirdle and Marshall 2012; Jones and Lister 2015). Jones and Lister (2015) show that these biases largely cancel out when averaged over all manned and automatic weather stations; however, it is not clear whether this cancellation applies when averaging over all ERA-Interim Antarctic grid points.

We contrast these observational datasets with the SAT output of 40 Historical Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (Meinshausen et al. 2011). We also make use of output from 29 models that performed simulations with prescribed observed sea surface temperatures and sea ice following the Atmospheric Model Intercomparison Project protocol (hereafter AMIP5; Taylor et al. 2012). We use the first ensemble member for each of the CMIP5 and AMIP5 simulations (i.e., r1i1p1). Finally, we use the preindustrial integrations of the CMIP5 models, in order to contrast the observed and modeled Antarctic SAT trends with those naturally occurring in an unforced regime. Table 1 lists the CMIP5 models used in this study and the length (in years) of their preindustrial integrations. The AMIP5 models used in this study are: ACCESS1-0, ACCESS1-3, bcc-csm1-1, bcc-csm1-1-m, BNU-ESM, CanAM4, CCSM4, CESM1-CAM5, CMCC-CM, CNRM-CM5, CSIRO-Mk3-6-0, EC-EARTH, FGOALS-s2, GFDL-CM3, GFDL-HIRAM-C180, GFDL-HIRAM-C360, GISS-E2-R, HadGEM2-A, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-AGCM3-2H, MRI-AGCM3-2S, MRI-CGCM3, NorESM1-M.

It is important to note here that many CMIP5 models exhibit large biases in the Antarctic region in both their climatologies and their trends (Swart and Fyfe 2012; Turner et al. 2013; Hosking et al. 2013; Bracegirdle et al. 2015; Previdi et al. 2015; Schneider and Reusch 2015). While many of these biases tend to cancel out in the multi-model mean, some remain, such as the historical sea ice and wind-stress strength trends (Turner et al. 2013; Swart and Fyfe 2012). Whether the mismatch between the observed trends and the historical modeled trends represents true model bias, bias in the observations, or large natural variability remains unclear (Swart and Fyfe 2012; Zunz et al. 2012; Polvani and Smith 2013; Gagne et al. 2015).

To quantify the East–West asymmetry in SAT trends, we compute cosine-weighted area averages for West Antarctica (including the Peninsula) and East Antarctica separately (approximately following the definition in M10), as well as for the entire Antarctic continent. To avoid errors due to differing spatial resolutions, all of the reconstructions and model output are first interpolated onto an identical $2^\circ \times 2^\circ$ latitude-longitude grid, before computing any spatial averages. We also construct an unweighted mean observational Antarctic SAT trend using the five reconstructions, omitting missing values. This average is denoted as “OBS” throughout the paper.

We calculate linear trends and establish statistical significance in one of two ways: (1) for a single time series, such as an Antarctic SAT reconstruction, we use the method of Santer et al. (2000), which adjusts the sample size and degrees of freedom using the lag-1 autocorrelation of the regression residuals, or (2) for an ensemble of trends, such as the CMIP5 ensemble or the ensemble of reconstructions, we use a Student’s t-test to reject the null hypothesis that the ensemble mean trend is not different from zero.

To assess the degree to which natural variability may be contributing to the observed SAT trends, it is crucial to consider trends over different time periods: here, we have decided to consider two of them. The first, more recent, time period begins with the advent of extensive satellite data, the year 1979, and extends to the end of the overlap time period between the observational record and the CMIP5 historical period, the year 2005. Note here that ERA-Interim reanalysis and output from the AMIP5 integrations only extend back to 1979. The second, longer time period extends from 1960 to 2005, approximately starting at the beginning of the modern era of Antarctic observation, which began during the International Geophysical Year of 1957–1958. Note that all Antarctic SAT reconstructions extend back to 1960; however the Chapman reconstruction only extends forward to the year 2002.

3 Antarctic SAT trends in observations

We begin by showing the time series of the annual mean SAT reconstruction from M10 in Fig. 1, for each of the three regions separately: total, East and West Antarctica (blue curves in each panel). We consider the M10 reconstruction first, as it consists of *absolute* temperature values, whereas the other reconstructions consist of temperature anomalies. Note that the M10 reconstruction depends on the ERA-40 reanalysis to establish spatial zones of temperature coherence and is therefore subject to biases in the ERA-40 reanalysis (Monaghan et al. 2008; Schneider et al. 2012; Bracegirdle and Marshall 2012).

The key point here is that West Antarctica is considerably warmer than East Antarctica, over the entire 46-year period 1960–2005, reflecting the different geography of the two regions. As a simple comparison, we plot on the same figure the 1979–2005 average SAT values for ERA-Interim: these are shown as straight red lines in each panel (we only plot the mean value over the entire period to make it clear that we do not wish to use ERA-Interim to compute any trends). In both datasets, the mean SAT of East Antarctica is roughly 20 K colder than in the West part of the continent. The black curves and gray shading in Fig. 1, show the CMIP5 models, which roughly capture the key climatological temperature differences between East and West Antarctica: they will be discussed in much detail in the next section.

We now proceed to discuss the recent observed annual mean SAT trends which are, in fact, difficult to discern in Fig. 1. To bring them out, and also to give a full visual representation of the observed trends, we plot the annual mean SAT trends for all the five reconstructions in Fig. 2. Note that over the period 1979–2005 all reconstructions show a clear spatial asymmetry in their trends, with West Antarctica experiencing warming and East Antarctica experiencing cooling (with the exception of Steigv1). This is also true for the recent Antarctic SAT reconstruction of Nicolas and Bromwich (2014), which is not included in this study. While the finer spatial features of the trends are not identical, the general picture is the same. Table 2 lists the area-averaged temperature trends for each region (total, East and West) and for each season. In the annual mean, only West Antarctica shows statistically significant warming trends.

As mentioned in the Introduction, the spatial asymmetry in Antarctic SAT trends in the annual mean is, to a large degree, a manifestation of opposing trends in different seasons (spring and autumn). Figure 3 is identical to Fig. 2 except that it now shows the trends for austral autumn, March-April-May (MAM): in this season all reconstructions show a cooling of East Antarctica (Table 2). Cooling in the West is weaker and the warming of the Peninsula appears to be non-robust across reconstructions in this season. On the other hand, Fig. 4 shows the SAT trends for austral spring, September-October-November (SON), where we see a clear and statistically significant warming of West Antarctica over the 1979–2005 time period in the reconstructions and no significant trends in the East (Table 2). This seasonal asymmetry in SAT trends is also clearly evident in the Nicolas and Bromwich (2014) reconstruction, with cooling in the East in MAM and significant warming in the West in SON.

To summarize what the observations show, we now combine the five reconstructions and, in the left column of Fig. 5 (panels a, d and g), we show the annual mean, MAM and SON (respectively) SAT trends for the unweighted mean of the five reconstructions, denoted by the acronym OBS. We clearly see the spatial asymmetry in the annual mean, resulting from the signature cooling in MAM and warming in SON. When we calculate the statistical significance of the area-averaged OBS trend using method (2) discussed in Sect. 2 (Table 2), we find that the cooling in East Antarctica in MAM and the warming in West Antarctica in SON are statistically significant. Since the different reconstructions qualitatively agree on the spatial patterns of

Table 2 Total, East and West Antarctic surface air temperature (SAT) trends (in K dec^{-1}) for the satellite era (1979–2005) for five observationally-based reconstructions, CHAPMAN, GISTEMP, M10, Steigv1 and Steigv2, and for the unweighted mean of the five reconstructions, OBS

Region	Data set	Time period	MAM	JJA	SON	DJF	ANN
Total	CHAPMAN	1979–2002	*−0.42 ± 0.48*	0.09 ± 0.58	0.17 ± 0.30	−0.14 ± 0.33	−0.08 ± 0.25
	GISTEMP	1979–2005	−0.23 ± 0.52	0.04 ± 0.51	**0.35 ± 0.27**	−0.02 ± 0.39	0.05 ± 0.22
	M10	1979–2005	−0.25 ± 0.52	0.07 ± 0.66	**0.37 ± 0.35**	−0.01 ± 0.73	0.06 ± 0.33
	Steigv1	1979–2005	−0.09 ± 0.36	0.13 ± 0.55	0.40 ± 0.55	0.13 ± 0.77	0.15 ± 0.34
	Steigv2	1979–2005	−0.25 ± 0.34	−0.04 ± 0.52	0.23 ± 0.48	−0.05 ± 0.76	−0.02 ± 0.31
	OBS	1979–2005	**−0.25 ± 0.15**	0.06 ± 0.08	**0.30 ± 0.12**	−0.02 ± 0.12	0.03 ± 0.11
East	CHAPMAN	1979–2002	*−0.53 ± 0.63*	0.11 ± 0.75	0.08 ± 0.37	−0.22 ± 0.35	−0.15 ± 0.34
	GISTEMP	1979–2005	−0.34 ± 0.67	−0.02 ± 0.60	0.21 ± 0.28	−0.09 ± 0.86	−0.03 ± 0.29
	M10	1979–2005	−0.35 ± 0.85	0.01 ± 0.85	0.19 ± 0.48	−0.09 ± 0.86	−0.04 ± 0.49
	Steigv1	1979–2005	−0.15 ± 0.43	0.10 ± 0.64	0.38 ± 0.71	0.15 ± 0.93	0.13 ± 0.45
	Steigv2	1979–2005	*−0.31 ± 0.42*	−0.06 ± 0.63	0.21 ± 0.66	−0.02 ± 0.93	−0.03 ± 0.40
	OBS	1979–2005	**−0.34 ± 0.17**	0.03 ± 0.09	**0.21 ± 0.13**	−0.05 ± 0.17	−0.02 ± 0.12
West	CHAPMAN	1979–2002	−0.19 ± 0.40	0.06 ± 0.54	**0.38 ± 0.31**	0.04 ± 0.23	0.06 ± 0.20
	GISTEMP	1979–2005	0.01 ± 0.34	0.16 ± 0.53	**0.63 ± 0.36**	0.08 ± 0.22	**0.22 ± 0.20**
	M10	1979–2005	−0.04 ± 0.55	0.18 ± 0.60	**0.75 ± 0.36**	0.14 ± 0.30	**0.26 ± 0.19**
	Steigv1	1979–2005	0.06 ± 0.24	0.18 ± 0.46	**0.45 ± 0.24**	0.07 ± 0.44	*0.19 ± 0.23*
	Steigv2	1979–2005	−0.12 ± 0.23	0.00 ± 0.43	**0.27 ± 0.20**	−0.12 ± 0.44	0.01 ± 0.20
	OBS	1979–2005	−0.06 ± 0.12	**0.11 ± 0.10**	**0.49 ± 0.24**	0.04 ± 0.12	**0.15 ± 0.13**

For each reconstruction we determine statistical significance following the first method outlined in Sect. 2. For OBS, we determine statistical significance following the second method outlined in Sect. 2 (denoted below with asterisks). Italicized and bolded trends are significant at the 90 and 95 % levels, respectively. See Sect. 2 for further information on the temperature reconstructions used

temperature trends, throughout the remainder of the paper we will refer primarily to the OBS trends in order to simplify our comparison between the observations and CMIP5 models.

Before comparing these observed trends with those simulated by the CMIP5 models, it is illuminating to consider how the observed trends over the period 1979–2005, which we have just discussed, differ from those of the longer time period 1960–2005. The latter are shown in the left column of Fig. 6, for the mean of the five reconstructions (again denoted OBS). Note that the range of the colorbar is narrower in Fig. 6 relative to Fig. 5: hence the interesting point that the spatial and seasonal asymmetry in SAT trends between East and West Antarctica is considerably larger for the shorter, more recent period. In the annual mean, the spatial asymmetry is substantially smaller for the 1960–2005 time period. This is primarily due to a weakening of the seasonal asymmetry between the MAM and SON trends, but there are also contributions from differences in trends in JJA between the two time periods depending on which reconstruction is considered (see Tables 2 and 3 of Schneider et al. (2012) and Figure 6 of Nicolas and Bromwich (2014)). The warming trend in the West in SON in Fig. 5g is amplified relative to Fig. 6e, and while there is a cooling trend in the East in MAM in 1979–2005 (Fig. 5d), there is essentially no trend in East Antarctica for the 1960–2005 time period (Fig. 6c). And, note that although we are comparing the unweighted means of the five reconstructions here, the difference in SAT trends between the two time periods is a robust characteristic across all five reconstructions (see Table 2; Schneider et al. 2012). We note that the Nicolas and Bromwich (2014) reconstruction shows little difference in the magnitude of the West Antarctic SON trends for the two different time periods.

The key point is this: the fact that the East–West asymmetry in SAT trends is quite different between the two time periods is, we submit, clear evidence for the key role of natural climate variability in such trends. Greenhouse gases have been *monotonically* increasing over the entire 1960–2005 span. From a purely thermodynamic perspective, why would East Antarctica show any cooling in the more recent period? Such trends appear to be difficult to attribute to the direct radiative effect of increasing greenhouse gases, which ought to generate surface warming. Also, if the asymmetry were forced by greenhouse gases, the magnitude of the asymmetry over the longer and shorter time periods should be roughly the same, yet the asymmetry has increased in recent decades.

As for ozone depletion: it has been argued that the cooling of East Antarctica is linked to the positive trend in the SAM, which likely has a strong anthropogenic component in DJF associated with ozone depletion (Thompson and

Table 3 Total, East and West multi-model mean Antarctic surface air temperature (SAT) trends (in K dec^{-1}) for the satellite era (1979–2005) for the CMIP5 and AMIP5 models

Region	Multi-Model Ensemble	Time Period	MAM	JJA	SON	DJF	ANN
Total	CMIP5	1979–2005	**0.22 ± 0.09**	**0.23 ± 0.09**	**0.25 ± 0.08**	**0.23 ± 0.17**	**0.22 ± 0.06**
	AMIP5	1979–2005	0.04 ± 0.07	**0.160 ± 0.09**	**0.22 ± 0.08**	**0.10 ± 0.08**	**0.13 ± 0.05**
East	CMIP5	1979–2005	**0.21 ± 0.11**	**0.26 ± 0.11**	**0.29 ± 0.11**	**0.22 ± 0.20**	**0.24 ± 0.07**
	AMIP5	1979–2005	−0.03 ± 0.08	**0.14 ± 0.11**	**0.21 ± 0.10**	**0.11 ± 0.10**	**0.11 ± 0.06**
West	CMIP5	1979–2005	**0.22 ± 0.08**	**0.19 ± 0.09**	**0.16 ± 0.08**	**0.23 ± 0.11**	**0.19 ± 0.05**
	AMIP5	1979–2005	**0.18 ± 0.10**	**0.21 ± 0.10**	**0.24 ± 0.08**	**0.07 ± 0.05**	**0.18 ± 0.05**

We determine statistical significance following the second method outlined in Sect. 2. Bolded trends are significant at the 95 % level

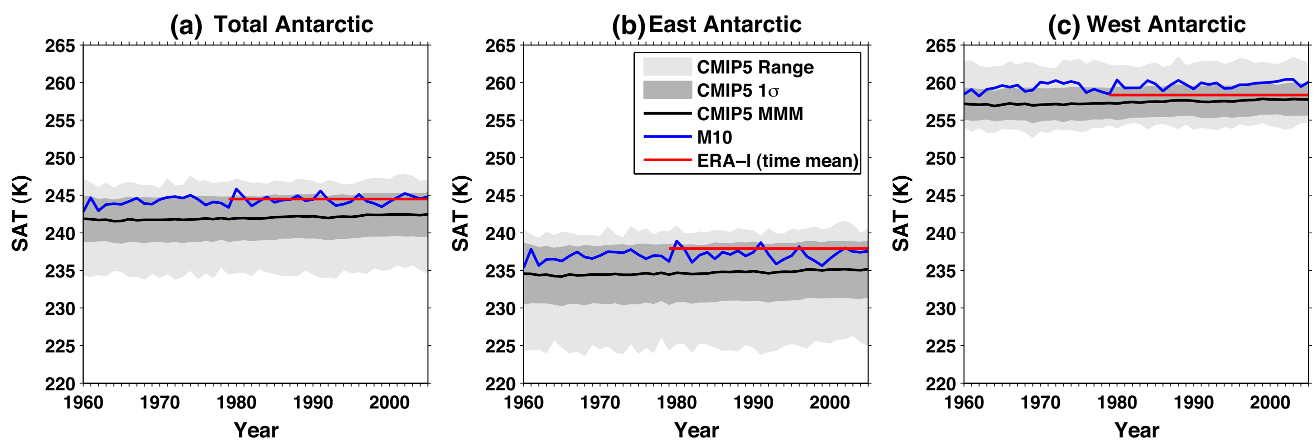


Fig. 1 Annual mean SAT Time series: **a** total, **b** East and **c** West Antarctica, from 1960 to 2005. *Solid black lines* the CMIP5 multi-model-mean (MMM). *Dark gray shading* standard deviation (1σ) spread in the CMIP5 integrations; *light gray shading* the full range of the CMIP5 integrations. *Solid blue line* the M10 reconstruction. *Solid red line* the 1960–2005 mean from ERA-Interim Reanalysis. Units are in K

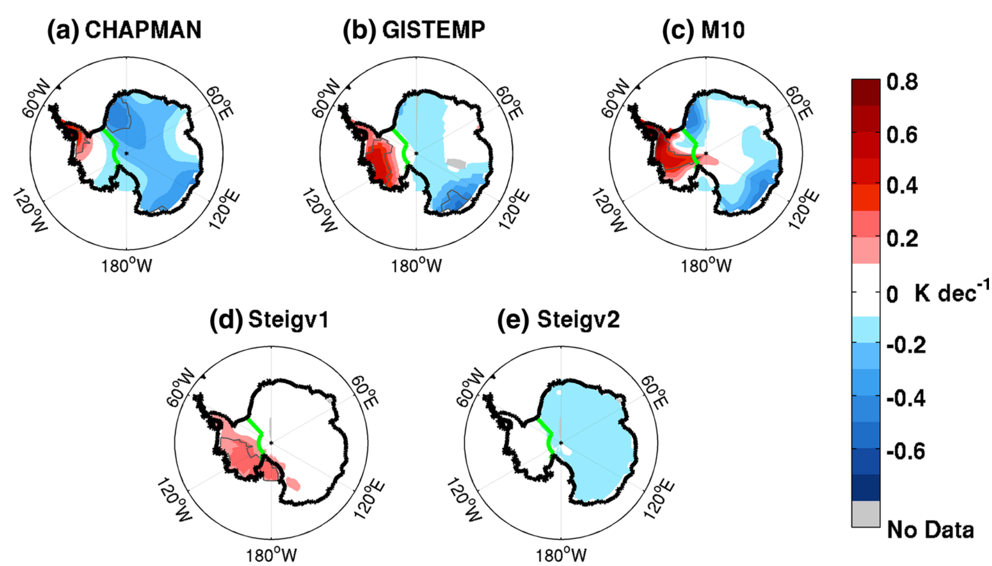


Fig. 2 Annual mean Antarctic SAT trends for 1979–2005 for five observationally-based reconstructions: **a** CHAPMAN, **b** GISTEMP, **c** M10, **d**, Steigv1, and **e** Steigv2. Units are inK dec^{-1}. *Green line* in each panel shows the division between East and West Antarctica. *Gray lines* in each panel enclose the regions in which the trends are statistically significant at the 90 % level. Projection: polar stereographic

Solomon 2002; Marshall 2007; Nicolas and Bromwich 2014); however, there is observational evidence that the link between SAM trends and East Antarctic temperature trends may not be stationary in time (Marshall et al. 2013). More importantly, the cooling of the East—which is strongest in austral autumn—does not match the seasonality of

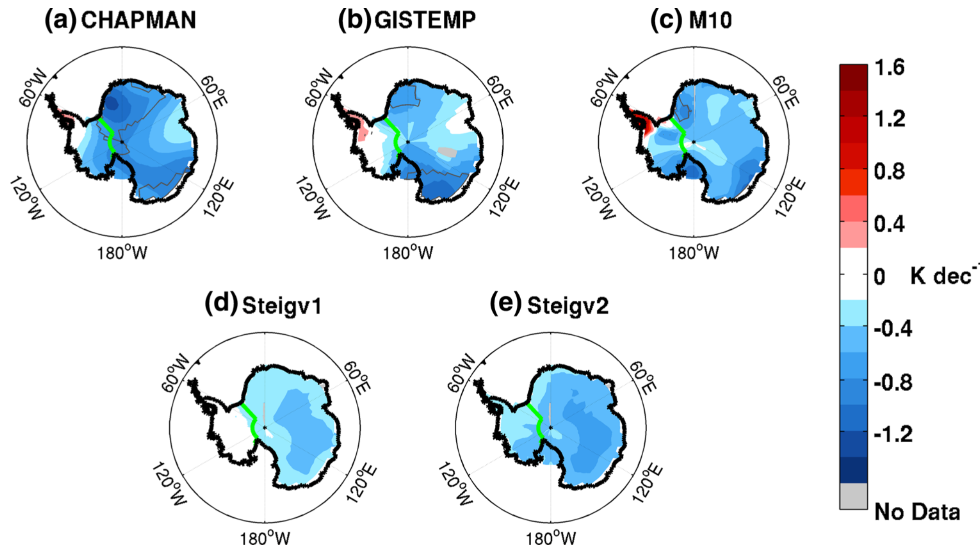


Fig. 3 As in Fig. 2, but for March–April–May (MAM)

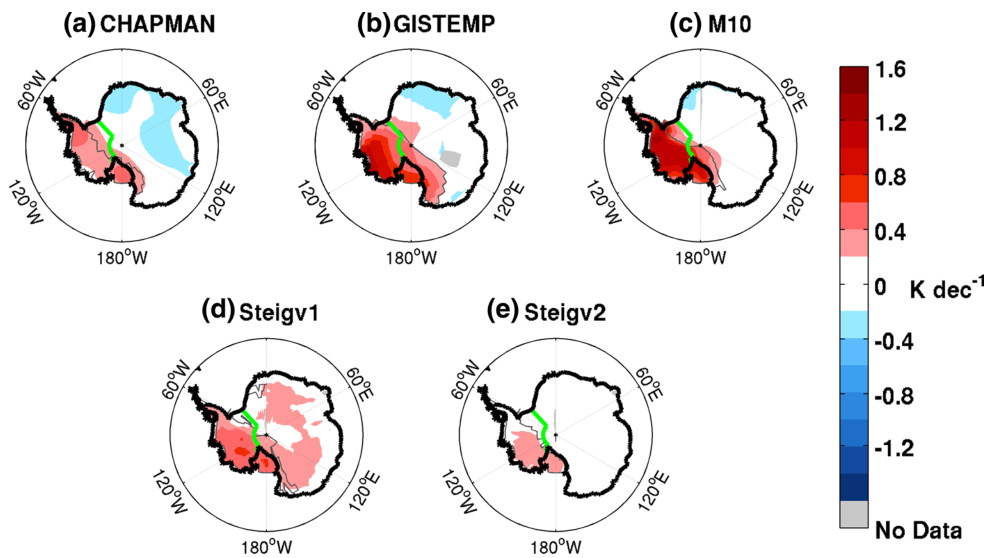


Fig. 4 As in Fig. 2, but for September–October–November (SON)

the SAM response to ozone forcing—which is strongest in austral summer (Thompson et al. 2011; Previdi and Polvani 2014). Hence, it seems difficult to argue that ozone depletion is causing the East–West SAT asymmetry. We stress that the above considerations, which highlight the role of natural variability, are based entirely on observations, and do not rely on the output of any climate model.

4 Antarctic SAT trends in CMIP5 models

State-of-art climate models, however, add considerable additional evidence pointing to the important role of natural variability. Let us start by comparing the modeled and observed SAT climatologies. In Fig. 1, superimposed on the observational data, we show the CMIP5 multi-model mean (MMM) temperature for each Antarctic region (black curves). The MMM shows a persistent cold bias of a couple of degrees relative to the M10 reconstruction, but note that this bias is nearly identical in all regions. Dark and light gray shading indicate 1-σ and full ranges, respectively, across the 40 integrations. From this figure we conclude that the MMM of the CMIP5 models is able to capture the mean climatological temperatures reasonably well in each region over the latter half of twentieth century and, notably, the large climatological differences between East and West Antarctica.

Given this, we are now ready to carefully analyze the modeled SAT trends. Recall that the CMIP5 integrations analyzed here include all historical forcings, notably ozone depletion, the forcing that is largely responsible for the positive trend in the summertime SAM in recent decades (Eyring et al. 2013; Polvani et al. 2011). With this in mind, consider the MMM of the SAT trends as simulated by the

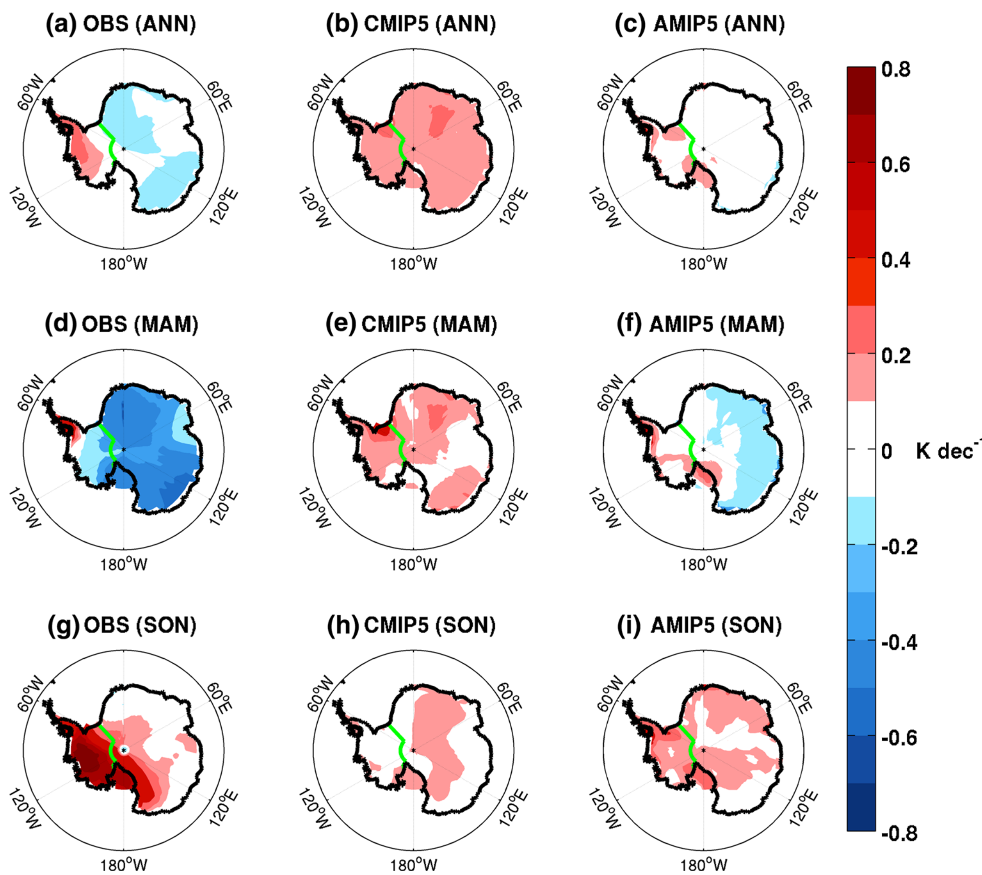


Fig. 5 Annual mean (*top*), MAM (*middle*) and SON (*bottom*) Antarctic SAT trends, over the period 1979–2005, for the unweighted mean of the five reconstructions (OBS, *left*), the CMIP5 MMM (*middle*) and the AMIP5 MMM (*right*). Units are inK dec^{-1}. *Green line* in each panel shows the division between East and West Antarctica. Projection: polar stereographic

CMIP5 models: these are shown in the middle column of Fig. 5 and right-hand column of Fig. 6, respectively, and are also listed in Table 3. The first thing to keep in mind, as one compares these CMIP5 panels with those on their left, the OBS trends, is that the CMIP5 MMM plots are an average of 40 integrations. By construction, therefore, the natural variability and some of the structural biases (i.e., model biases associated with physics schemes, parameterizations and numerics) present in each single model integration is absent from the MMM (as it has been "averaged out"): in other words, the MMM represents the forced response alone, as computed using the CMIP5 models. The observations, in contrast, show a single realization of the climate system. The two, therefore, will only be similar to the degree that the observed evolution is mostly a forced one, rather than one dominated by processes with multi-decadal variability (Deser et al. 2010, 2012).

The key point here is that, in the CMIP5 forced response, SAT trends over West Antarctica are small in both the annual mean and in SON (that area is mostly white in panels b and h of Fig. 5), the Peninsula does not distinguish itself with any particularly strong warming trends in MAM and, in fact, East Antarctica, if anything, is warming in MAM (Fig. 5e). Given the observed links between the ASL and West Antarctic climate, we note here that Hosking et al. (2013) has demonstrated that the multi-model mean of a subset of CMIP5 models shows no significant bias in the climatological ASL longitude or central pressure in austral spring over the 1979–2005 time period. It is, of course, possible that the CMIP5 models are fundamentally flawed in some other crucial respect (e.g. they might be missing or misrepresenting one or more key physical processes). Barring that possibility, however, there is an interesting lesson to be learned from the CMIP5 MMM trends: since, in response to increasing greenhouse gases and ozone depletion over the late 20th Century, the state-of-the art climate models show little East–West asymmetry in SAT trends over the Antarctic continent, we conclude the observed asymmetry is likely due to the natural variability of the climate system, which possesses internal, multi-decadal fluctuations that are able to exceed the externally forced anthropogenic signal.

Since such multi-decadal variability arises primarily from the ocean and sea ice components of the climate system, it is informative to compare the CMIP5 simulations to the AMIP5 simulations to assess the degree to which discrepancies in the SST and sea ice boundary conditions influence the CMIP5 MMM response to historical forcing. In the AMIP5 simulations, monthly mean observed SSTs and sea ice for the 1979–2005 time period are prescribed.

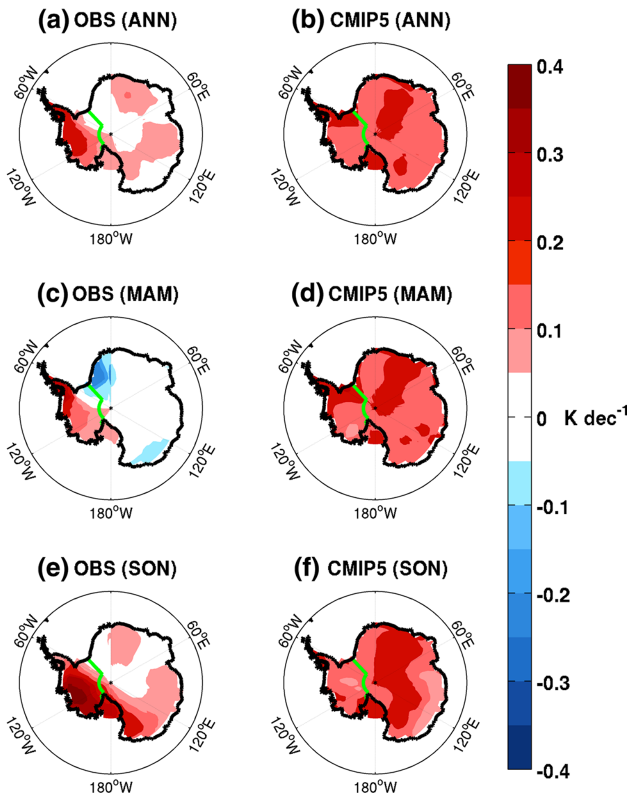


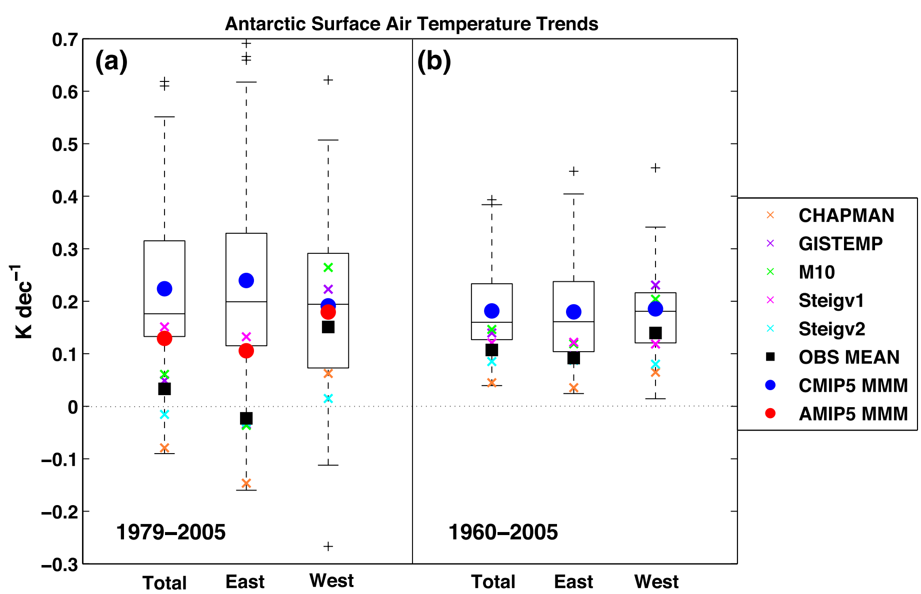
Fig. 6 As in Fig. 5, but for the period 1960–2005. *Left* OBS; *right* CMIP5 MMM. No AMIP5 data is available for this period

We find that when the models are forced with the historical evolution of SSTs and sea ice in addition to external forcings, the SAT trends are closer to those of the reconstructions. In particular, we see that East Antarctica shows weak cooling in MAM (Fig. 5f) and that the largest positive trends in West Antarctica occur in SON (Fig. 5i, see also Table 3). Given the chaotic nature of the climate system, we do not expect these AMIP5 trends to be a perfect match to the reconstructions but the fact that they are in better agreement with the reconstructions suggests that natural variability associated with SSTs and sea ice may be playing an important role in driving the observed trends. In addition, the greater correspondence between the AMIP5 SAT trends and the reconstructions, demonstrates that the models likely have a reasonable representation of climate processes in the high-latitude Southern Hemisphere region.

To strengthen these qualitative statements, we now offer a more quantitative assessment: in Fig. 7 we present boxplots of the annual mean SAT trends for the CMIP5 models, for both time periods, together with the observed trends from the reconstructions. The horizontal bar at the center of each box is the median across the CMIP5 models, while the blue dots indicate the MMM. The black squares indicate the SAT trends for the OBS and the red dots indicate the AMIP5 MMM (shown only for the 1979–2005 time period).

For the shorter and more recent 1979–2005 time period (see also Tables 2 and 3), the CMIP5 MMM trends in the East and West are both positive (East: 0.24 K dec^{-1}; West: 0.19 K dec^{-1}), while the observations show a very substantial asymmetry, with warming in the West (OBS: 0.15 K dec^{-1}) and weak cooling in the East (OBS: −0.02 K dec^{-1}). Consequently, for the entire Antarctic continent, the CMIP5 MMM exhibits a warming trend that is almost an order of magnitude larger the observed one (CMIP5 MMM: 0.22 K dec^{-1}; OBS: 0.03 K dec^{-1}) over this time period. The AMIP5 MMM, instead, exhibits SAT trends showing more spatial asymmetry, i.e. weaker trends in the East relative to the West (East: 0.11 K dec^{-1}; West: 0.18 K dec^{-1}). Although this asymmetry is not statistically

Fig. 7 Boxplots of Total, East and West annual mean Antarctic SAT trends in CMIP5 historical integrations for (*left*) 1979–2005 and (*right*) 1960–2005. *Black squares* the unweighted mean trend of the five reconstructions, OBS. *Blue* and *red circles* CMIP5 and AMIP5 multi-model mean (MMM) trends. *Crosses* individual trends for each reconstruction, as indicated in the legend. Units are in K dec^{-1}. The boxes are bounded by the 25th and 75th percentiles and the whisker lengths extend to ±2.7 standard deviations or to the nearest value. Values beyond the whiskers are plotted as black plus signs



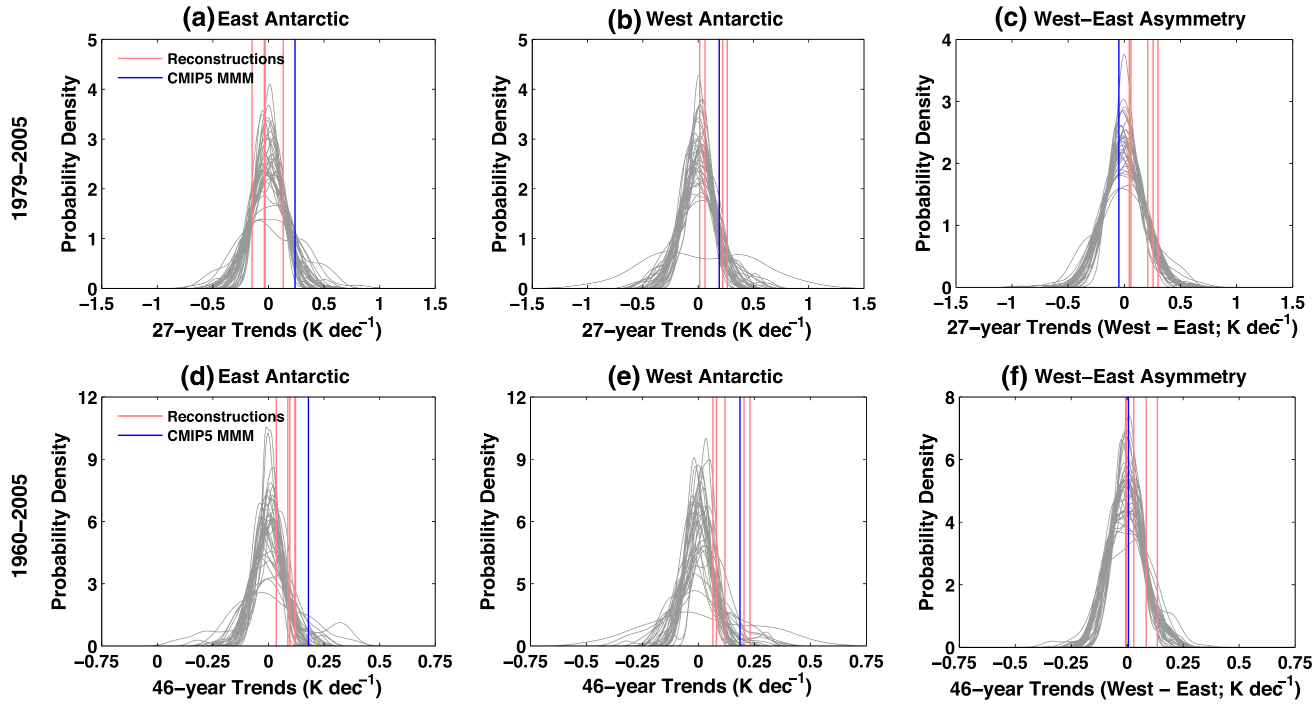


Fig. 8 Probability density distributions of annual mean SAT trends for periods of 27 years (*top*) and 46 years (*bottom*), as computed from the CMIP5 preindustrial integrations for East Antarctica (*left*), West Antarctica (*middle*) and the difference between West and East Antarctica (*right*). Individual models are shown in *gray curves*. *Vertical pink lines* individual trends for the 5 reconstructions, over the period 1979–2005 (*top*) and 1960–2005 (*bottom*). *Vertical blue line* the multi-model-mean trend for 1979–2005 (*top*) and 1960–2005 (*bottom*) from the CMIP5 historical integrations. Units are in K dec^{-1}

significant in the annual mean, comparing the AMIP5 MMM trend in the East for MAM (–0.03 K dec^{-1}) and the West for SON (0.24 K dec^{-1}), reveals a statistically significant difference not evident in the CMIP5 MMM. The closer correspondence of the AMIP5 MMM to the observations points to natural variability as a key driver of the observed trends.

For the 1960–2005 time period on the right, we see at first glance that the CMIP5 MMM trend is quantitatively very similar in both the East (0.18 K dec^{-1} $\pm$ 0.03) and West (0.19 K dec^{-1} $\pm$ 0.03), whereas the observations show more warming in the West (0.14 K dec^{-1} $\pm$ 0.09) than in the East (0.09 K dec^{-1} $\pm$ 0.04), by roughly fifty percent. For the Antarctic continent as a whole, the CMIP5 MMM overestimates the warming trend over this time period by approximately 60 % (CMIP5 MMM: 0.18 K dec^{-1} $\pm$ 0.03; OBS: 0.11 K dec^{-1} $\pm$ 0.05).

Again, we stress that the discrepancy between the CMIP5 MMM and the observations need not be interpreted as evidence that the models are "wrong". As one can see in Fig. 7, there is considerable spread in the SAT trends across the models (associated with both natural and structural variability), suggesting that some models are in fact able to capture the observed values (note that the observations lie within the range of the CMIP5 models). Hence, an equally plausible interpretation of the discrepancy between the CMIP5 MMM and observations is that natural variability of the climate system over Antarctica is large, and comparable to the forced response, so as to be able to either enhance or reverse the sign of anthropogenic trends over multi-decadal periods.

At this point, one is led to ask: how can one estimate the amplitude of the natural variability? To answer this question, at least in the context of the CMIP5 models, we simply examine the probability distributions of multi-decadal Antarctic SAT trends in the 35 CMIP5 models for which the preindustrial integrations are available (see Table 1). These distributions of trends are shown in (Fig. 8). Recall that the preindustrial integrations are unforced, so any trends occurring therein can be unambiguously attributed to the natural climate variability in each model.

In the top row (Fig. 8a–c), we show probability density distributions (gray curves, one curve per model) of 27-year annual mean SAT trends for the East and West Antarctic regions as well as for the difference in 27-year trends between the West and the East. The 27-year length was selected to compare these naturally occurring trends with the observed ones over a period of comparable length, in this case the 1979–2005 time period. For each model, the distributions are obtained by computing all consecutive and overlapping 27-year trends, starting from the first year, for each model time series. The probability density distributions shown in Fig. 8 are then computed from these using a kernel density estimator, which performs a non-parametric, smoothed fit to the data. The area under each curve is one, by construction. The vertical lines show the SAT trends for the historical CMIP5 MMM (blue) and all five reconstructions (pink).

The widths of the distributions highlight the large multidecadal variability in each region arising spontaneously from coupled climate dynamics, in the absence of any anthropogenic forcing. If we consider the vertical lines for the 1979–2005 time period, we find that the observed trends for East Antarctica are remarkably small relative to the natural variability. Even the significant warming trends in West Antarctica and the West-East trend asymmetry, when taken in the context of the natural variability of the models (Fig. 8b, c), fall well within the natural preindustrial distributions: it appears difficult, therefore, to attribute them primarily to anthropogenic causes, at least in as far as the models are able to accurately simulate the natural climate variability.

Performing a paired t-test on the ensemble of 1979–2005 CMIP5 trends and the ensemble of preindustrial 27-year trends, we find that the CMIP5 ensemble is significantly different from the preindustrial ensemble for the East and West Antarctica and the West-East difference. Now performing a complementary paired t-test on the unweighted mean reconstruction trend, OBS, we find that OBS is not significantly different from the preindustrial ensemble for East and West Antarctica and also for the West-East difference. Although, a more rigorous detection-attribution analysis is required, we have included this simple statistical test here to demonstrate that distinguishing the observed SAT trends from natural variability is very challenging in this region.

The bottom row of Fig. 8 is identical to the top row, except that trends are calculated over 46-year segments, and the vertical lines show the corresponding trends for the reconstructions and CMIP5 MMM for the longer 1960–2005 period. Again we see that the observed trends fall well within the natural variability. We note, however, they are all found within the right tail of the distribution, particularly for West Antarctica. This suggests that over the longer time period, a forced anthropogenic signal – a warming trend, in fact – in both the observations and CMIP5 may be emerging from the climate noise. Nonetheless, again assuming we can trust the CMIP5 models in correctly representing the Antarctic climate system, that signal appears small compared to the natural variability.

As was done above, we perform paired t-tests between the 1960–2005 CMIP5 ensemble of SAT trends, OBS and the ensemble of 46-year preindustrial trends. Again, we find that the CMIP5 ensemble is significantly different from the preindustrial ensemble and that OBS is not significantly different.

Figure 8 also highlights the spread in the representation of natural variability across the models. The shapes and widths of the distributions of preindustrial SAT trends (the individual gray curves) vary from model to model, reflecting structural differences in model physics and numerics. Despite these differences across models, the important role of natural variability in the Antarctic region remains clear, regardless of which gray curve is considered.

5 Antarctic SAT and the SAM

Although, in a globally averaged sense, increases in greenhouse gases predominantly affect surface temperatures via simple energy balance principles, changes in atmospheric circulation due to climate change can also affect surface temperatures regionally. In the Southern Hemisphere extratropics, increasing greenhouse gases and stratospheric ozone depletion have contributed to a positive trend in the SAM, the leading mode of atmospheric circulation variability (Thompson and Wallace 2000). The relationship between the SAM and Antarctic SAT anomalies has been discussed widely in the literature (Thompson and Solomon 2002; Shindell 2004; Schneider et al. 2004; Gillett et al. 2006; Marshall 2007; Fogt et al. 2012; Nicolas and Bromwich 2014; Previdi and Polvani 2014) with suggestions that the SAM trend may have contributed to the observed trends in Antarctic SAT, particularly in East Antarctica in autumn and along the Peninsula in summer (Marshall 2007). Here we revisit the SAM-SAT relationship in the observations and contrast it with the one in the CMIP5 models in order to better understand the extent to which SAM trends can explain the seasonal asymmetry in Antarctic SAT trends.

First, we compare the interannual relationship between the SAM and Antarctic SAT in the CMIP5 and AMIP5 models to an observationally-based estimate. In Fig. 9a we regress detrended, annual mean Antarctic SAT from ERA-Interim onto the detrended, non-normalized, annual mean SAM index using sea level pressure (SLP) data from Marshall (2003) for the years 1979–2005. We find the characteristic pattern of negative SAT anomalies over most of the continent and positive SAT anomalies over the Peninsula (note: the positive anomalies over the Peninsula are somewhat weak and difficult to discern in Fig. 9; Schneider et al. 2004). Given the biases in the ERA-Interim reanalysis SAT, we have also performed the SAM-SAT regression using the M10 reconstruction and find that the results are qualitatively similar (see Supplementary Figure 1).

We repeat this regression analysis using detrended SLP and SAT for each of the CMIP5 and AMIP5 integrations

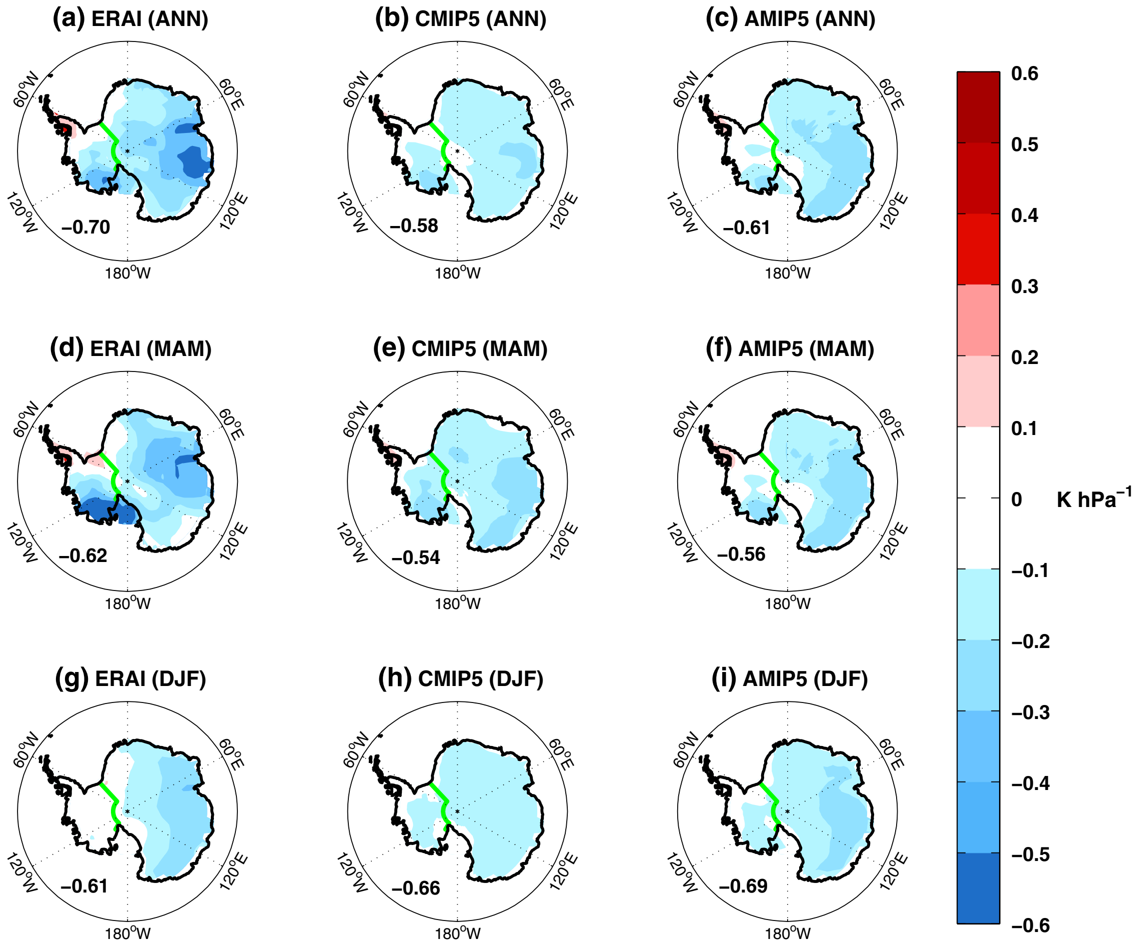


Fig. 9 Annual (*top*), MAM (*middle*) and DJF (*bottom*) interannual SAM-Antarctic SAT regressions, over the period 1979–2005, for the detrended, non-normalized Marshall (2003) SAM index/ERA-Interim reanalysis SAT (*left*), the CMIP5 MMM (*middle*) and the AMIP5 MMM (*right*). Units are in K hPa^{-1}. *Green line* in each panel shows the division between East and West Antarctica. The corresponding area-averaged SAM-SAT correlations are displayed in the bottom left quadrant of each panel. Projection: polar stereographic

and then compute the MMM of the regression coefficients for each ensemble. These are shown in Fig. 9b, c, respectively. We find that although the magnitude of the Antarctic SAM-SAT regression is slightly weaker in the models (Marshall and Bracegirdle 2014), the sign and overall spatial pattern agrees with the observationally-based estimate. We find a similar result for each season (e.g. MAM is shown in Fig. 9d–f and DJF is shown in Fig. 9g–i).

There are two key conclusions to be drawn from Fig. 9. First, the ability of the models to capture the interannual Antarctic SAM-SAT relationship reasonably well is evidence that the models are not fundamentally flawed in this respect. Second, despite the slightly weaker magnitude of the regression patterns, the correlations associated with these regression patterns for the CMIP5 and AMIP5 models are large, greater than 0.5 (area-averaged correlations are shown in the lower left quadrant of each panel in Fig. 9). Therefore, to the extent that the observed SAM trends are externally forced, the models should be able to simulate Antarctic SAT trends that are congruent with the SAM trends if, indeed, the SAM is the dominant factor driving the SAT trends and that the interannual SAM-SAT relationship holds on multi-decadal timescales.

Second, we now ask whether the interannual SAM-SAT relationship shown in Fig. 9 can be used to link 1979–2005 SAM and SAT trends in both the observations and models. Beginning with the observations, Fig. 10a shows the SAM trends for the Marshall (2003) time series (gray bars) by season. The observations show a statistically significant positive trend in the annual mean SAM arising from large, significant positive trends in austral summer (DJF) and autumn (MAM). The positive trend in DJF has been primarily attributed to stratospheric ozone depletion (Arblaster and Meehl 2006; Polvani et al. 2011; Lee and Feldstein 2013), while the trend in MAM appears to be

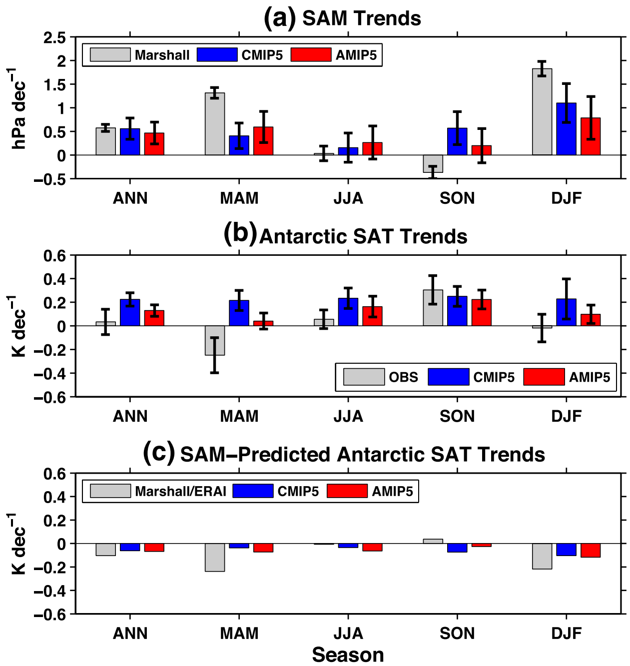


Fig. 10 1979–2005 annual mean, March–April–May (MAM), June–July–August (JJA), September–October–November (SON) and December–January–February (DJF). **a** Southern Annular Mode (SAM) trends (hPa dec^{-1}), **b** Antarctic average SAT trends (K dec^{-1}) and **c** SAM-predicted Antarctic average SAT trends (K dec^{-1}) using the detrended, interannual Antarctic average SAM-SAT regression coefficients. In (**a**) the observed SAM trend is computed using the Marshall (2003) data set (*gray bars*) and the 95 % confidence intervals (CIs) are determined using the first method discussed in Sect. 2. In (**b**) the observed Antarctic SAT trend is computed using the unweighted mean of the five reconstructions, OBS (*gray bars*), and the 95 % CIs are determined using the second method discussed in Sect. 2. The 95 % CIs of the historical CMIP5 trends (*blue bars*) and the AMIP5 trends (*red bars*) in (**a**) and (**b**) are determined using the second method discussed in Sect. 2. In (**c**) we use the Marshall (2003) SAM trend and the Antarctic average SAM-SAT regression coefficients from ERA-Interim to calculate the predicted Antarctic SAT trend for the observations (and no CIs are displayed)

dominated by natural variability (see below and Fogt et al. 2009).

Comparing these SAM trends with the total Antarctic SAT trends (Fig. 10b, gray bars), we are confronted with conflicting relationships between the SAM and SAT trends. On the one hand, we confirm the work of Marshall (2007) and others, that, by extending the interannual relationship between the SAM and Antarctic SAT to the historical trends, the negative SAT trend in MAM in the observations appears to be consistent with the positive trend in the SAM in MAM (see Fig. 9d). On the other hand, we find that the even larger SAM trend in DJF does not appear to explain the observed SAT trend in this season.

We can be more quantitative in our estimate of the role of the observed SAM trends in driving SAT trends by computing the Antarctic SAT trend that would arise assuming that the SAM trend were the sole influencing factor (Fig. 10c, gray bars) using the detrended SAM-SAT regression coefficients displayed in Fig. 9. We denote these SAT trends as the "SAM-predicted" SAT trends (for comparison, we have repeated this analysis using the M10 reconstruction, Supplementary Figure 2).

When attributing observed Antarctic SAT trends to the SAM via the SAM-predicted trend, several assumptions are made in the process: (1) that the interannual SAM-SAT relationship carries over to multi-decadal timescales, (2) that the SAM is an actual driver of the observed SAT change, and (3) that the factors influencing Antarctic SAT (including the SAM) are linearly additive. Keeping these assumptions in mind, we now compare the SAM-predicted SAT trends to the observed SAT trends.

In DJF, we find that the observed positive trend in the SAM yields a negative SAM-predicted Antarctic SAT trend. This disagrees with the actual observed SAT trend (which is not significantly different from zero for both the total continent and for East Antarctica only, see Table 2) indicating that, despite the large SAM trend in DJF, the SAM does not play a dominant role in influencing the SAT trend in this season. As suggested by Nicolas and Bromwich (2014) and Marshall (2007), the fact that there is little observed warming in DJF may indicate that a negative SAT trend induced by the SAM is offset by a positive SAT trend due to anthropogenic radiative forcing. However, it may also indicate that the assumptions that were made regarding the attribution of the observed trends to the SAM-predicted trends may be invalid.

On the contrary, in MAM, it appears that the observed SAM trend may contribute to the SAT trend (contrast the gray bars in MAM in Fig. 10b, c). Although the SAM-predicted SAT trends are similar in magnitude to the observed SAT trends in MAM, the SAM is not likely the only factor driving the observed SAT trends. For example, the argument by Nicolas and Bromwich (2014) and others that anthropogenic warming is offsetting the SAM-predicted cooling trends in DJF may also apply to MAM. At this point, we can only speculate about what other factors may act in tandem with the SAM-predicted SAT trends and whether they act in a linear or nonlinear way; however, examining the forced response in the CMIP5 and AMIP5 model integrations may provide some insight.

Let us now consider the SAM-SAT trend relationship in the models. Both the CMIP5 and AMIP5 MMMs show statistically significant SAM trends in DJF and MAM, in agreement with the observations (Fig. 10a, blue and red bars are for the CMIP5 and AMIP5 MMMs, respectively); however, the magnitudes of the trends in the models are somewhat weaker. Again, this does not necessarily imply that the models are "wrong". The observational record is one possible realization of the climate

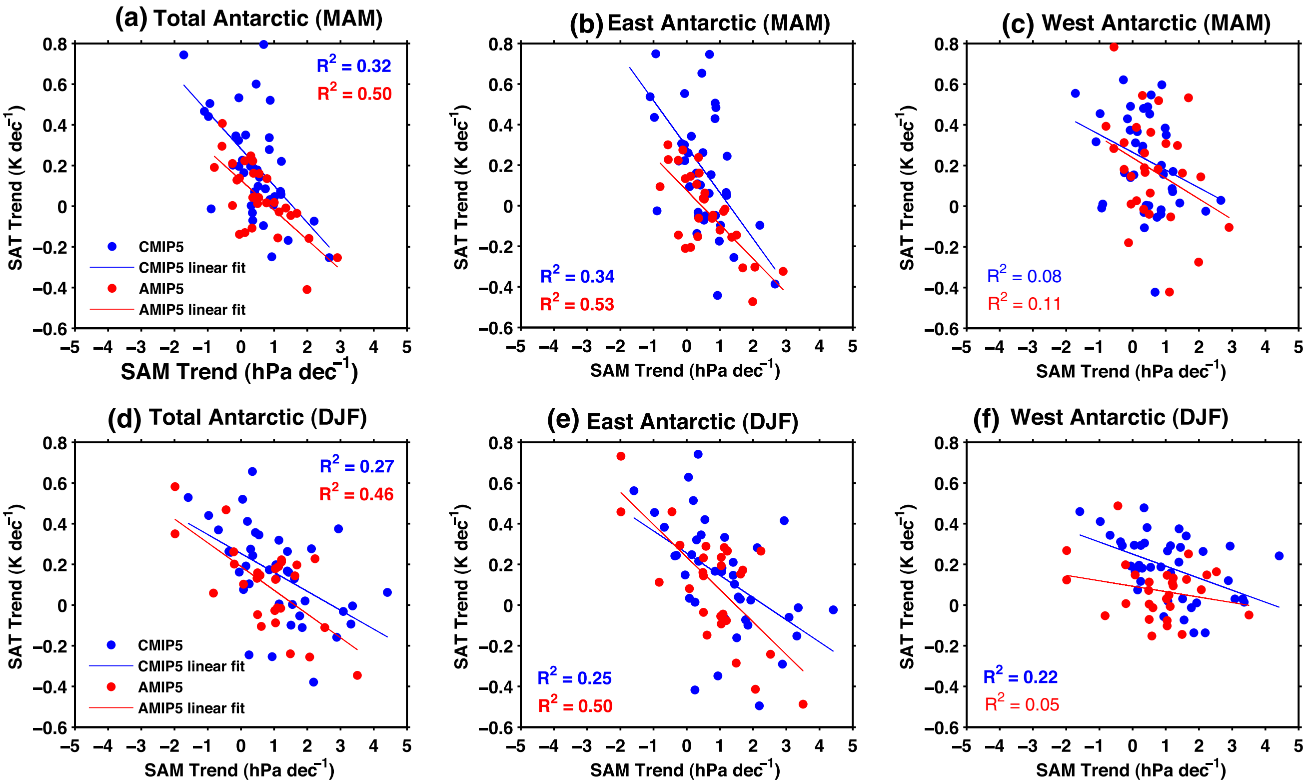


Fig. 11 Scatter plots of the 1979–2005 MAM (*top*) and DJF (*bottom*) SAT trend (K dec^{-1}) versus the SAM trend (hPa dec^{-1}) for total (*left*), East (*middle*) and West (*right*) Antarctica for the historical CMIP5 integrations (*blue*) and the AMIP5 integrations (*red*). R-squared values that are statistically significant at the 95 % level are shown in bold font

system, which includes both externally forced and internally variable components. Thomas et al. (2015) demonstrate that, despite the clear externally forced SAM trend in DJF, a large fraction of the observed trend may be due to natural variability. In MAM, the discrepancy in magnitude between the observed and CMIP5 MMM SAM trend, i.e., the externally forced SAM trend, supports the work of Fogt et al. (2009), which argues that the observed SAM trend is largely due to natural variability in that season.

Next, we compare the CMIP5 and AMIP5 MMM SAM trends to the corresponding total Antarctic SAT trends (Fig. 10b). We find little evidence that the interannual SAM-SAT relationship in the models carries over to the multi-decadal trends (Monaghan et al. 2008, find a similar result for the CMIP3 models). In particular, for the CMIP5 models, in DJF and MAM, the SAT trends are positive, despite significantly positive SAM trends.

As was done for the observations, we also compute the SAM-predicted SAT trends for the CMIP5 and AMIP5 models (Fig. 10c). In DJF, the SAM-predicted SAT trends for the models are large and negative, in agreement with the observations, and like the observations, the SAM-predicted trends are very different from the actual SAT trends, both in sign and magnitude. In MAM, the CMIP5 and AMIP5 MMM SAM-predicted SAT trends are also negative, as expected from the interannual relationship, yet the actual SAT trends are not. Thus, on a continental scale, while forced trends in the SAM can be seen in the models, these forced trends are not the dominant drivers of the modeled Antarctic SAT trends.

Furthermore, the models give some insight into factors that may potentially act to offset the negative SAM-predicted SAT trends shown in Fig. 10c. The CMIP5 MMM SAT trends represent the *total* forced response, including both dynamically-driven components, such as trends in SAT due to anthropogenic trends in the SAM, and thermodynamically-driven components, such as the direct radiative warming due to greenhouse gases. The results summarized in Fig. 10 suggest that the CMIP5 forced SAT trend is dominated by the thermodynamically-driven component, which more than offsets any dynamically-driven component due to the SAM (the blue bars in Fig. 10b are all positive). In the observations, we also have these two distinct forced components acting on the SAT trends, as well as a third component, natural variability, which, we argue, accounts for much of the disagreement between the CMIP5 MMM and the reconstructions.

We also contrast the CMIP5 and AMIP5 models. The AMIP5 model integrations capture some of the natural variability of the 1979–2005 time period by prescribing observed SSTs and sea ice. Consequently, as discussed in Sect. 3, there is better agreement between the SAT trends for the observations and the AMIP5 models, particularly in MAM. Upon inspection, we see that the CMIP5 and AMIP5 MMM SAM trends in autumn are not significantly different, yet the SAT trends are significantly different (see Table 3 and Fig. 5e, f). This points to the importance of multi-decadal variability, arising from the historical evolution of SSTs and sea ice, in influencing Antarctic SAT trends, which may be linked to a more realistic representation of tropical-Antarctic teleconnections during the 1979–2005 time period, and the consequent, zonally asymmetric features of the SAM, rather than the magnitude of the SAM itself (Fogt et al. 2012).

Finally, although the evidence presented here clearly indicates that the SAM is not the dominant driver of multi-model mean Antarctic SAT trends in the CMIP5 and AMIP5 models, we do find that the SAM trend explains some of the spread across the simulated SAT trends in the models. Figure 11 shows scatter plots of the MAM and DJF Antarctic SAT trends for the total continent, East Antarctica and West Antarctica. In East Antarctica, the SAM trend is negatively correlated with the SAT trend and explains 34 % of the spread across the CMIP5 models in MAM and 25 % in DJF. In the AMIP5 models, the SAM trends explains approximately 53 % of the spread in SAT trends in MAM and 50 % in DJF. We find similar results in SON but much weaker correlations in June–July–August (JJA).

Bottome line: in the annual mean (not shown), the SAM trend explains only 33 % of the variance in the total Antarctic SAT trend across the CMIP5 models and 29 % across the AMIP5 models, indicating that the SAM is a contributing factor but that ∼70 % of the variance is determined by other processes.

6 Summary and discussion

Analyzing 40 CMIP5 model integrations, we have shown that the CMIP5 multi-model mean (MMM) historical climatology of Antarctic surface air temperatures (SAT) are reasonably well simulated, albeit with a slight cold bias relative to observations and a large model spread. The MMM, in particular, is able to capture the large climatological East–West difference between the colder surface temperatures over East Antarctica compared to warmer West Antarctica. We have also shown that the CMIP5 and AMIP5 integrations are able to qualitatively capture the continental-scale negative interannual relationship between Antarctic SAT and the SAM.

However, in spite of this realistic climatology and interannual variability, we have shown that the MMM Antarctic temperature trends of the CMIP5 models differ considerably from those observed over the past several decades. The key discrepancy rests in the models showing a uniform warming over the entire continent in all seasons, whereas the observed trends show much greater warming over the West of the Antarctic continent in spring and a widespread cooling over the East in autumn, resulting in a distinct spatially asymmetric pattern of SAT trends in the annual mean. Because of this lack of spatial asymmetry, the CMIP5 MMM exhibits a total Antarctic SAT trend, over the satellite era, that is almost an order of magnitude larger than the one seen in the observations.

The large qualitative and quantitative discrepancy between observed and model-simulated MMM trends can be interpreted in two ways: either the models are crucially flawed or the observed trends are dominated by natural climate fluctuations. The possibility that the models are seriously flawed cannot be discounted at this time, but is difficult to reconcile with (1) their reasonably accurate simulation of the climatological asymmetry in SAT between East and West Antarctica (Fig. 1), (2) the reduced discrepancy between MMM and OBS SAT trends when observed SSTs and sea ice are prescribed in the AMIP5 integrations (Fig. 5), and (3) the models' qualitative ability to simulate the interannual SAM-Antarctic SAT relationship (Fig. 9). That said, continued research to quantify biases will further our understanding of the relative contributions of anthropogenic forcing and multi-decadal variability to the simulated and observed trends.

The second possibility, that large natural climate fluctuations are overwhelming a relatively smaller forced signal in Antarctic SAT is, we here suggest, the more likely explanation for the discrepancy. This explanation finds additional support in the width of the distribution functions of multi-decadal trends, as computed from the CMIP5 preindustrial integrations. We have shown that the observed trends, as well as the simulated forced trends, lie well within the natural variability of the models. This is particularly true for the shorter 1979–2005 satellite period.

We have also examined the role of the SAM in driving the trends in Antarctic SAT in both the observations and the models. Although the SAM likely contributes to the observed SAT trend in MAM, we find that there is little evidence that this is a response to external forcings. Rather, our analysis of the observed SAM and SAT trends in autumn supports the hypothesis that multi-decadal variability is the dominant factor influencing Antarctic SAT in the satellite era. This confirms and extends earlier work on historical SAM trends (Fogt et al. 2009).

The key role of natural variability that emerges from our analysis is also supported by the findings Ding et al.

(2011); Schneider et al. (2012); Fogt and Wovrosh (2015); Clem and Fogt (2015) and Clem and Renwick (2015), who have argued that tropical Pacific SSTs play a key role in controlling the warming observed over West Antarctica. While not emphasized by the authors, a similar result can also be seen in the study of Steig et al. (2009), who where able to simulate the warming of West Antarctica, including the Peninsula, with a single atmospheric model integration by prescribing the observed SSTs and sea ice concentrations as part of the model input. As one can see in their Fig. 4, the role of anthropogenic forcings in their model is remarkably small in comparison.

Further evidence for the large role played by natural variability is adduced by noting that MMM trends analyzed here for the CMIP5 models appear to be quite different from those produced by the CMIP3 models. Notably, the CMIP3 MMM trends show a clear warming of the Peninsula in the annual mean (see Fig. 17 of Chapman and Walsh 2007). Careful examination of that figure, however, reveals that the amplitude of the CMIP3 MMM trends are almost an order of magnitude smaller than the observed ones. Furthermore, the CMIP3 MMM also shows warming signals over the Ross sea and a large fraction of the Southern Ocean (Indian sector) where no trends exist in the observations. Finally, we also note that only 11 simulations were used to construct the CMIP3 MMM, whereas we have used 40 in this study. Beyond such details, we believe the very fact that the CMIP3 and CMIP5 MMM show quite different patterns of annual Antarctic SAT trends can be taken as additional evidence for the importance of natural climate variability in controlling temperature trends over the Antarctic continent.

Lastly, setting aside all modeling evidence, we argue that the observations themselves appear to suggest that natural variability may be a big player in the Antarctic climate system (Simpkins et al. 2013; Thomas et al. 2013; Fan et al. 2014). For instance, Fan et al. (2014) have recently demonstrated that, over the Southern Ocean (50−70°S) in summer, atmospheric, oceanic and sea-ice trends have all changed sign in the decades before and after 1978, providing strong evidence for multi-decadal climate variability in this region. And, as we have shown in Sect. 3 above, the spatial and seasonal asymmetry in Antarctic SAT trends are much weaker over the longer 1960–2005 period than over the shorter 1979–2005 period. This is exactly what one would expect from unforced, natural climate variations: regional trends become smaller as the averaging period is made longer, as short-term positive and negative trends tend to cancel out. Of course, longer observations and improved models are needed to determine the precise causes for the observed trends: what the results of this paper indicate is that natural variability is likely to be a key player.

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References

Arblaster JM, Meehl GA (2006) Contributions of external forcings to southern annular mode trends. J Clim 19(12):2896–2905. doi:10.1175/JCLI3774.1

Bracegirdle TJ, Marshall GJ (2012) The reliability of antarctic tropospheric pressure and temperature in the latest global reanalyses. J Clim 25:7138–7146. doi:10.1175/JCLI-D-11-00685.1

Bracegirdle TJ, Stephenson DB, Turner J, Phillips T (2015) The importance of sea ice area bias in 21st century multimodel projections of Antarctic temperature and precipitation. Geophys Res Lett. doi:10.1002/2015GL067055

Bromwich DH, Nicolas JP, Monaghan AJ, Lazzara MA, Keller LM, Weidner DA, Wilson AB (2013) Central West Antarctica among the most rapidly warming regions on Earth. Nat Geosci 6(2):139–145. doi:10.1038/ngeo1671

Chapman WL, Walsh JE (2007) A synthesis of Antarctic temperatures. J Clim 20(16):4096–4117. doi:10.1175/JCLI4236.1

Clem KR, Fogt RL (2015) South Pacific circulation changes and their connection to the tropics and regional Antarctic warming in austral spring, 1979–2012. J Geophys Res 120(7):2773–2792. doi:10.1002/2014JD022940

Clem KR, Renwick JA (2015) Austral spring Southern Hemisphere circulation and temperature changes and links to the SPCZ. J Clim 28:7371–7384. doi:10.1175/JCLI-D-15-0125.1

Clement A, Seager R, Cane M, Zebiak S (1996) An ocean dynamical thermostat. J Clim 9:2190–2196

Dai A, Fyfe JC, Xie SP, Dai X (2015) Decadal modulation of global surface temperature by internal climate variability. Nat Clim Change 5(6):555–559. doi:10.1038/nclimate2605

Dee DP, Uppala SM, Simmons aJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda Ma, Balsamo G, Bauer P, Bechtold P, Beljaars aCM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer aJ, Haimberger L, Healy SB, Hersbach H, Hólm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally aP, Monge-Sanz BM, Morcrette JJ, Park BK, Peubey C, de Rosnay P, Tavolato C, Thépaut JN, Vitart F (2011) The ERA-interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc 137(656):553–597. doi:10.1002/qj.828

Deser C, Phillips A, Bourdette V, Teng H (2010) Uncertainty in climate change projections: the role of internal variability. Clim Dyn 38(3–4):527–546. doi:10.1007/s00382-010-0977-x

Deser C, Knutti R, Solomon S, Phillips AS (2012) Communication of the role of natural variability in future North American climate. Nat Clim Change 2(11):775–779. doi:10.1038/nclimate1562

Ding Q, Steig EJ, Battisti DS, Küttel M (2011) Winter warming in West Antarctica caused by central tropical Pacific warming. Nat Geosci 4(6):398–403. doi:10.1038/ngeo1129

Eyring V, Arblaster JM, Cionni I, Sedláček J, Perlwitz J, Young PJ, Bekki S, Bergmann D, Cameron-Smith P, Collins WJ, Faluvegi G, Gottschaldt KD, Horowitz LW, Kinnison DE, Lamarque JF, Marsh DR, Saint-Martin D, Shindell DT, Sudo K, Szopa S, Watanabe S (2013) Long-term ozone changes and associated climate impacts in CMIP5 simulations. J Geophys Res Atmos 118(10):5029–5060. doi:10.1002/jgrd.50316

Fan T, Deser C, Schneider D (2014) Recent Antarctic sea ice trends in the context of Southern Ocean surface climate variations since 1950. Geophys Res Lett. doi:10.1002/2014GL059239

Ferreira D, Marshall J, Bitz CM, Solomon S, Plumb A (2015) Antarctic ocean and sea ice response to ozone depletion: a two-time-scale problem. J Clim 28(3):1206–1226. doi:10.1175/JCLI-D-14-00313.1

Fogt RL, Wovrosh AJ (2015) The relative influence of tropical sea surface temperatures and radiative forcing on the Amundsen Sea Low. J Clim 28(21):8540–8555. doi:10.1175/JCLI-D-15-0091.1

Fogt RL, Zbacnik EA (2014) Sensitivity of the Amundsen Sea low to stratospheric ozone depletion. J Clim 27(24):9383–9401. doi:10.1175/JCLI-D-13-00657.1

Fogt RL, Perlwitz J, Monaghan AJ, Bromwich DH, Jones JM, Marshall GJ (2009) Historical SAM variability. Part II: twentieth-century variability and trends from reconstructions, observations, and the IPCC AR4 models*. J Clim 22(20):5346–5365. doi:10.1175/2009JCLI2786.1

Fogt RL, Jones JM, Renwick J (2012) Seasonal zonal asymmetries in the Southern Annular Mode and their impact on regional temperature anomalies. J Clim 25(18):6253–6270. doi:10.1175/JCLI-D-11-00474.1

Gagne ME, Gillett NP, Fyfe JC (2015) Observed and simulated changes in Antarctic sea ice extent over the past 50 years. Geophys Res Lett 42(1):90–95. doi:10.1002/2014GL062231

Gillett NP, Kell TD, Jones PD (2006) Regional climate impacts of the Southern Annular Mode. Geophys Res Lett 33(23):L23,704. doi:10.1029/2006GL027721

Hansen J, Ruedy R, Sato M, Lo K (2010) Global surface temperature change. Rev Geophys 48:1–29. doi:10.1029/2010RG000345.1.INTRODUCTION

Hawkins E, Sutton R (2012) Time of emergence of climate signals. Geophys Res Lett. doi:10.1029/2011GL050087

Hosking JS, Orr A, Marshall GJ, Turner J, Phillips T (2013) The Influence of the AmundsenBellingshausen seas low on the climate of West Antarctica and its representation in coupled climate model simulations. J Clim. doi:10.1175/JCLI-D-12-00813.1

Hosking JS, Orr A, Bracegirdle TJ, Turner J (2016) Future circulation changes off West Antarctica: sensitivity of the Amundsen Sea low to projected anthropogenic forcing. Geophys Res Lett. doi:10.1002/2015GL067143

Jones PD, Lister DH (2015) Antarctic near-surface air temperatures compared with ERA-Interim values since 1979. Int J Climatol 35:1354–1366. doi:10.1002/joc.4061

Joughin I, Smith BE, Medley B (2014) Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. Science 344(6185):735–738. doi:10.1126/science.1249055

Kosaka Y, Xie SP (2013) Recent global-warming hiatus tied to equatorial Pacific surface cooling. Nature 501(7467):403–7. doi:10.1038/nature12534

Lee S, Feldstein SB (2013) Detecting ozone- and greenhouse gas-driven wind trends with observational data. Science 339(6119):563–567. doi:10.1126/science.1225154

Li X, Gerber EP, Holland DM, Yoo C (2015) A Rossby wave bridge from the tropical Atlantic to West Antarctica. J Clim 28(6):2256–2273. doi:10.1175/JCLI-D-14-00450.1

Marshall G (2003) Trends in the Southern Annular Mode from observations and reanalyses. J Clim 16(1999):4134–4143

Marshall GJ (2007) Short communication half-century seasonal relationships between the Southern Annular Mode and Antarctic temperatures. Int J Climatol 383:373–383. doi:10.1002/joc

Marshall GJ, Bracegirdle TJ (2014) An examination of the relationship between the Southern Annular Mode and Antarctic surface air temperatures in the CMIP5 historical runs. Clim Dyn. doi:10.1007/s00382-014-2406-z

Marshall GJ, Orr A, Turner J (2013) A predominant reversal in the relationship between the SAM and East Antarctic temperatures during the twenty-first century. J Clim 26(14):5196–5204. doi:10.1175/JCLI-D-12-00671.1

McLandress C, Shepherd TG, Scinocca JF, Da Plummer, Sigmond M, Jonsson AI, Reader MC (2011) Separating the dynamical effects of climate change and ozone depletion. Part II: Southern Hemisphere troposphere. J Clim 24(6):1850–1868. doi:10.1175/2010JCLI3958.1

Meehl GA, Arblaster JM, Fasullo JT, Hu A, Trenberth KE (2011) Model-based evidence of deep-ocean heat uptake during surface-temperature hiatus periods. Nat Clim Change 1(7):360–364. doi:10.1038/nclimate1229

Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque JF, Matsumoto K, Sa Montzka, Raper SCB, Riahi K, Thomson a, Velders GJM, Vuuren DPP (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim Change 109(1–2):213–241. doi:10.1007/s10584-011-0156-z

Monaghan AJ, Bromwich DH (2008) Advances in describing recent Antarctic climate variability. Bull Am Meteorol Soc 1295–1306

Monaghan AJ, Bromwich DH, Schneider DP (2008) Twentieth century Antarctic air temperature and snowfall simulations by IPCC climate models. Geophys Res Lett. 89:9. doi:10.1029/2007GL032630

Nicolas JP, Bromwich DH (2014) New reconstruction of Antarctic near-surface temperatures: multidecadal trends and reliability of global reanalyses. J Clim 27(21):8070–8093. doi:10.1175/JCLI-D-13-00733.1

ODonnell R, Lewis N, McIntyre S, Condon J (2011) Improved methods for PCA-based reconstructions: case study using the Steig et al. (2009) Antarctic temperature reconstruction. J Clim 24(8):2099–2115. doi:10.1175/2010JCLI3656.1

Polvani LM, Smith KL (2013) Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5. Geophys Res Lett 40(12):3195–3199. doi:10.1002/grl.50578

Polvani LM, Waugh DW, Correa GJP, Son SW (2011) Stratospheric ozone depletion: the main driver of twentieth-century atmospheric circulation changes in the Southern Hemisphere. J Clim 24(3):795–812. doi:10.1175/2010JCLI3772.1

Previdi M, Polvani LM (2014) Climate system response to stratospheric ozone depletion and recovery. Q J R Meteorol Soc 140(685):2401–2419. doi:10.1002/qj.2330

Previdi M, Smith KL, Polvani LM (2015) How well do the CMIP5 models simulate the antarctic atmospheric energy budget? J Clim 28(20):7933–7942. doi:10.1175/JCLI-D-15-0027.1

Raphael MN, Marshall GJ, Turner J, Fogt R, Schneider D, Dixon DA, Hosking JS, Jones JM, Hobbs WR (2015) The Amundsen Sea low: variability, change and impact on antarctic climate. Bull Am Meteorol Soc. doi:10.1175/BAMS-D-14-00018.1

Rignot E, Mouginot J, Morlighem M, Seroussi H, Scheuchl B (2014) Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica. Geophys Res Lett. doi:10.1002/2014GL060140

Santer BD, Wigley TML, Boyle JS, Gaffen DJ, Hnilo JJ, Nychka D, Parker DE, Taylor KE (2000) Statistical significance of trends and trend differences in layer-average atmospheric temperature time series. J Geophys Res 105(D6):7337. doi:10.1029/1999JD901105

Schneider D, Steig E, Comiso J (2004) Recent climate variability in Antarctica from satellite-derived temperature data. J Clim 17:1569–1583

Schneider DP, Reusch DB (2015) Antarctic and Southern Ocean surface temperatures in CMIP5 models in the context of the surface energy budget. J Clim 29:1689–1716. doi:10.1175/JCLI-D-15-0429.1

Schneider DP, Deser C, Okumura Y (2012) An assessment and interpretation of the observed warming of West Antarctica in the austral spring. Clim Dyn 38(1–2):323–347. doi:10.1007/s00382-010-0985-x

Schneider DP, Deser C, Fan T (2015) Comparing the impacts of tropical SST variability and polar stratospheric ozone loss on the Southern Ocean westerly winds. J Clim 28(23):9350–9372. doi:10.1175/JCLI-D-15-0090.1

Shindell DT (2004) Southern Hemisphere climate response to ozone changes and greenhouse gas increases. Geophys Res Lett 31(18):L18,209. doi:10.1029/2004GL020724

Simpkins GR, Ciasto LM, England MH (2013) Observed variations in multidecadal Antarctic sea ice trends during 1979–2012. Geophys Res Lett 40(14):3643–3648. doi:10.1002/grl.50715

Simpkins GR, McGregor S, Taschetto AS, Ciasto LM, England MH (2014) Tropical connections to climatic change in the extratropical Southern Hemisphere: the role of Atlantic SST trends. J Clim 27(13):4923–4936. doi:10.1175/JCLI-D-13-00615.1

Steig EJ, Schneider DP, Rutherford SD, Mann ME, Comiso JC, Shindell DT (2009) Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. Nature 457(7228):459–462. doi:10.1038/nature07669

Swart NC, Fyfe JC (2012) Observed and simulated changes in the Southern Hemisphere surface westerly wind-stress. Geophys Res Lett 39(16):6–11. doi:10.1029/2012GL052810

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93(4):485–498. doi:10.1175/BAMS-D-11-00094.1

Thomas ER, Bracegirdle TJ, Turner J, Wolff EW (2013) A 308 year record of climate variability in West Antarctica. Geophys Res Lett 40(20):5492–5496. doi:10.1002/2013GL057782

Thomas JL, Waugh D, Gnanadesikan A (2015) Decadal variability in the Southern Hemisphere extratopical circulation: recent trends and natural variability. Geophyis Res Lett 42(13):5508–5515. doi:10.1002/2015GL064521.Changes

Thompson D, Wallace J (2000) Annular modes in the extratropical circulation. Part I: month-to-month variability. J Clim 13:1000–1016

Thompson DWJ, Solomon S (2002) Interpretation of recent Southern Hemisphere climate change. Science 296(5569):895–899. doi:10.1126/science.1069270

Thompson DWJ, Solomon S, Kushner PJ, England MH, Grise KM, Karoly DJ (2011) Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. Nat Geosci 4(11):741–749. doi:10.1038/ngeo1296

Turner J, Colwell SR, Marshall GJ, Lachlan-Cope TA, Carleton AM, Jones PD, Lagun V, Reid PA, Iagovkina S (2005) Antarctic climate change during the last 50 years. Int J Climatol 25(3):279–294. doi:10.1002/joc.1130

Turner J, Phillips T, Hosking JS, Marshall GJ, Orr A (2013) The Amundsen Sea low. Int J Climatol 33:1818–1829. doi:10.1002/joc.3558

Turner J, Hosking JS, Marshall GJ, Phillips T, Bracegirdle TJ (2015) Antarctic sea ice increase consistent with intrinsic variability of the Amundsen Sea low. Clim Dyn. doi:10.1007/s00382-015-2708-9

Zunz V, Goosse H, Massonnet F (2012) How does internal variability influence the ability of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? Cryosphere Discuss 6(5):3539–3573. doi:10.5194/tcd-6-3539-2012