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Original Article

Assessment of future Antarctic amplification of surface temperature change under different Scenarios from CMIP6

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Abstract: Global warming may result in increased polar amplification, but future temperature changes under different climate change scenarios have not been systematically investigated over Antarctica. An index of Antarctic amplification (AnA) is defined, and the annual and seasonal variations of Antarctic mean temperature are examined from projections of the Coupled Model Intercomparison Project Phase 6 (CMIP6) under scenarios SSP119, SSP126, SSP245, SSP370 and SSP585. AnA occurs under all scenarios, and is strongest in the austral summer and autumn, with an AnA index greater than 1.40. Although the warming over Antarctica accelerates with increased anthropogenic forcing, the magnitude of AnA is greatest in SSP126 instead of in SSP585, which may be affected by strong ocean heat uptake in high forcing scenario. Moreover, future AnA shows seasonal difference and regional difference. AnA is most conspicuous in the East Antarctic sector, with the amplification occurring under all scenarios and in all seasons, especially in austral summer when the AnA index is greater than 1.50, and the weakest signal appears in austral winter. Differently, the AnA over West Antarctica is strongest in austral autumn. Under SSP585, the temperature increase over the Antarctic Peninsula exceeds 0.5°C when the global average warming increases from 1.5°C to 2.0°C above pre-industrial levels, except in the austral summer, and the AnA index in this region is strong in the austral autumn and winter. The projections suggest that the warming rate under different scenarios might make a large difference to the future AnA.

Keywords: Antarctic Amplification; Amplification index; CMIP6; ScenarioMIP; Near-surface temperature; Climate change

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1 Introduction

Antarctica, as the largest ice sheet (Roussel et al. 2020) and the most remote region on earth (Rintoul et al. 2018), is intimately coupled to the rest of the climate system (Convey et al. 2009; Rintoul et al. 2018). Observational data show an accelerated loss of Antarctic ice shelf mass, which contributes to sea level sea rise, and warming in the near-surface air temperature is considered to be one of the factors responsible for this phenomenon (Paolo et al. 2015; Truser et al. 2015; Bronselaer et al. 2018).

Anthropogenic greenhouse gas emissions are rapidly altering Earth's climate, pushing it toward a warmer state for which there is no historical precedent (Tierney et al. 2020). As the other pole of the earth, surface air temperature over Arctic has increased more than double the global average over the past decades, whereas less warming has occurred over Antarctica because of ocean heat uptake in the Southern Ocean and deep ocean mixing (Collins et al. 2013; Notz and Stroeve 2016; Richter-Menge et al. 2017).

The near-surface temperature change in Antarctica has been enigmatic over recent years. The Antarctic Peninsula was one of the most rapidly warming regions for the second half of the twentieth century (Turner et al. 2005), which relates to the strengthening of circumpolar westerlies (Thompson and Solomon 2002). Warming on the western side of the Antarctic Peninsula is strongest in austral spring and winter, with the winter temperature increased over 5°C since 1950 and the annual mean having increased by about 3°C (Steig et al. 2009; Turner et al. 2013). However, there was a cooling of 0.47°C per decade in this region from 1990 to 2014, which is mainly a result of the high natural internal variability of the regional atmospheric circulation, rather than of global temperature change (Turner et al. 2016). The temperature change over Antarctica in recent decades is mainly attributable to the internal variability, however, external forcing also plays a role. The analysis of Community Earth System Model (CESM) large ensemble simulations during the period 1979-2005 show that the influence of externally forced factors on the temperature change over Antarctica can be divided into the forced thermodynamic response and the forced dynamic response, and the latter contributes much more to the temperature change over West Antarctica than the former, which indicates that the externally-forced warming in West Antarctica is mainly mediated by changes in atmospheric circulation (Wang et al. 2020).

West Antarctica has warmed since the 1950s: the temperature increased 2.44°C during 1958-2010, and the warming in the late 1980s is coincidental with the westward shift and deepening of the Amundsen Sea low (Bromwich et al. 2013). East Antarctica, however, shows a small, but statistically non-significant, cooling trend (Schneider et al. 2012). This East Antarctic cooling is associated with a positive trend in the Southern Annular Mode (SAM) and a strengthening of the westerlies, and the cooling in austral autumn is also tied to an increase of La Niña events (Clem et al. 2018).

Previous research has found that a positive SAM can weaken turbulent sensible heat exchanges between the surface and the atmosphere in East Antarctica, which associates with temperature cooling over much of the Antarctic continent (van den Broeke and van Lipzig 2003; van den Broeke and van Lipzig 2004). The SAM trends contribute to the rapid change of Antarctic near-surface temperature in austral autumn relative to the period 1957-2004 (Marshall 2007). In addition, positive SAM also contributes to the warming on the eastern side of the Antarctic Peninsula in austral summer, and the western side in winter (Marshall 2007; Roscoe et al. 2007; Schneider et al. 2012).

The tropical sea surface temperature (SST) also has an important impact on the temperature change over West Antarctica, and warmer SST can drive Rossby waves into Amundsen Sea, which can induce enhanced warm advection transport (Ding et al. 2011; Clem and Fogt 2015; Fogt and Wovrash 2015; Smith and Polvani 2017). This influence has become stronger since 2000 (Li et al. 2014; Schneider et al. 2015; Clem et al. 2017).

In austral summer, Antarctic temperature showed a positive trend from the late 1970s to the late 1990s, which was mainly derived from the increase in Antarctic ozone depletion during this period (Schneider et al. 2015; Waugh et al. 2015). It has been confirmed that the Antarctic ozone hole can attribute to not only more ultraviolet radiation reaching the surface, but also to tropospheric circulation in the Southern Hemisphere and surface climate, as well as the incidence of high-index polarity of the SAM (Thompson et al. 2011). In austral summer, the high-index polarity is associated with lower temperature than normal over most of East Antarctica, which is influenced by the weaker katabatic flow by anomalous rising motion (Thompson and Wallace 2000; Thompson and Solomon 2002). Meanwhile, higher temperature on the northern side of the Antarctic Peninsula is consistent with increased warm air advection from over the Southern Ocean due to the stronger eastward surface flow (van den Broeke and van Lipzig 2004; Marshall et al. 2006). In addition, sea ice modifies heat exchange between the ocean and atmosphere, and influences climate change over the Antarctica (Bukatov et al. 2016).

The polar amplification is asymmetry in recent years. Arctic Amplification occurs in all seasons and is strongest in autumn and winter (Cohen et al. 2014), and will continue with future warming (Holland and Bitz 2003). In contrast, Antarctic amplification (AnA) has not been clearly demonstrated to date (Smith et al. 2019), but is expected with further future warming.

The Coupled Model Intercomparison Project (CMIP) aims to better understand past, present and future climate change caused by natural, unforced variability in a multi-model context (Meehl et al. 2005; Eyring et al. 2016). Research addressing Antarctic climate with the fifth phase of CMIP (CMIP5) included the trends of future precipitation and temperature (Tang et al. 2018), sea ice (Mahlstein et al. 2013), surface mass balance (Agosta et al. 2015), and projections of Antarctic Ice Shelf melt (Naughten et al. 2018). So far, one-third of the latest-generation climate models from the CMIP phase 6 (CMIP6) exhibit a higher equilibrium climate sensitivity (ECS) than did the previous generation (CMIP5) (Forster et al. 2020). To integrate future changes in climate and society, CMIP6 models are forced by new scenarios, named shared socioeconomic pathways (SSPs), which describes the alternative changes in society including demographic, economic, technological, social, governance and environmental factors (Eying et al. 2016), combined with forcing levels of the Representative Concentration Pathways (RCPs) (O'Neill et al. 2014). The CMIP6 models have stronger climate sensitivity than CMIP5 in general (Forster et al. 2020).

In this paper we investigate future changes in the near-surface temperature over Antarctica under different Scenarios, with outputs from CMIP6 models. We also use the model projections to identify any AnA phenomenon with future warming. We compare the changes over Antarctica and over the Southern Ocean under global average warming of 1.5°C and 2°C above pre-industrial levels. Understanding any discrepancies between the different SSPs is of critical importance for future adaptation and mitigation strategies over the region.

2 Data and Methods

The monthly near-surface temperature used here were from the CMIP6 archive, available at https://esgf-node.llnl.gov/projects/cmip6/ (variable name "tas"). The five ScenarioMIP (Scenario Model Intercomparison Project) future forcing experiments SSP119, SSP126, SSP245, SSP370, and SSP585 were used to assess changes in the 21st century. The SSP119, SSP126, SSP245, SSP370 and SSP585 combine the SSP1 and RCP1.9, SSP1 and RCP2.6, SSP2 and RCP4.5, SSP3 and RCP7.0, SSP5 and RCP8.5, respectively. The pathways SSP1, SSP2, SSP3 and SSP5 are respectively for sustainability with low challenges to mitigation and adaptation (taking a green road); a middle road with moderate challenges; regional rivalry with high challenges (a rocky road); and fossil-fueled development with high challenges to mitigation, but low to adaptation (the highway) (O'Neill et al. 2017). The RCP1.9, RCP2.6, RCP4.5, RCP7.0 and RCP8.5 respectively represent the radiative forcing from greenhouse gases limited to no more than 1.9, 2.6, 4.5, 7.0 and 8.5 W/m^2 above pre-industrial levels in 2100 (Rogelj et al. 2018). We used the data from 7 models for these five scenarios during the period 2015-2100 (Table 1), for the limitation of the outputs in SSP119. In addition, we also employed the CMIP6 outputs from "historical" experiments which are driven by observed boundary conditions for the period 1850-2014 (Roussel et al. 2020). Because the models have different resolutions, re-gridded the data to a resolution of 0.25°×0.25° using bilinear interpolation. As the model projections of temperature change differ, the multi-model ensemble mean (MMEM) is an appropriate way to weight all models equally (Taylor et al. 2012; You et al. 2020).

Table 1 List of CMIP6 models used in this study.

Model No.	Model name	Lat × Long. grid (km × km)
1	FGOALS-g3	80 × 180
2	CanESM5	64 × 128
3	EC-Earth3-Veg	256 × 512
4	IPSL-CM6A-LR	143 × 144
5	MIROC6	128 × 256
6	MRI-ESM2-0	160 × 320
7	GFDL-ESM4	180 × 288

The observational data is lack in Antarctica, and the reanalysis ERA5 has a high skill in representing the near-surface temperature over this region (Zhu et al. 2021). MMEM can capture the spatial patterns of Antarctic temperature, although the MMEM on average underestimates the temperatures over the

Antarctica (Fig. 1).

The F test was used to estimate the significance of the temperature trends in MMEM, with the significance at the 95% confidence level. To quantify AnA, we imitated the definition of Arctic Amplification (Davy et al. 2018), and defined an AnA index as the ratio of the value of the linear trend in near-surface air temperature over Antarctica to the value of the linear trend in near-surface air temperature over the entire Southern Hemisphere.

3 Results

3.1 Temperature trends over Antarctica and its sub-regions under different scenarios

Table 2 summarizes the year when mean surface temperature over the globe and over Antarctica rises by 1.5°C, 2.0°C and 3.0°C relative to pre-industrial levels under the five scenarios. The difference in time taken to reach the 1.5°C threshold for the different forcings, both globally and for Antarctica, is only 3 years; and for the 2.0°C threshold it is only 10 years. For SSP126, Antarctica leads the globe in achieving both the 1.5°C and 2.0°C warming thresholds.

For SSP119, both the globe and Antarctica maintain overall warming at about the 1.5°C level (Fig. 2). Antarctica displays steady warming in medium to highest forcings. Especially in SSP585, the rapid warming occurs in all seasons, with the warming nearly 7°C at the end of the 21st century relative to pre-industrial period. In all scenarios, the effect of different forcing on temperature appears most noticeably after 2050.

Fig. 3 shows the spatial patterns of annual mean temperature trends over Antarctica and the Southern Ocean from MMEM for the period 2015-2100 under the five scenarios. Significant (p<0.05) warming dominates the Antarctica under the SSP245, SSP370 and SSP585 scenarios, and a conspicuous warming signal exists over the ocean. But only slight warming occurs over East Antarctica under SSP119 and the Antarctic Peninsula cools. In austral summer (December-February, DJF), warming is observed in the northern region of West Antarctica, and cooling is seen in other seasons, especially in austral winter (June-August, JJA) (not shown). In SSP126, negative trend prevails over the Antarctic Peninsula in austral spring (September-November, SON), and Marie Byrd Land cools in JJA.

Fig. 4 shows the 2015-2100 average annual mean surface temperature trends for different regions of the Southern Hemisphere under different scenarios. The

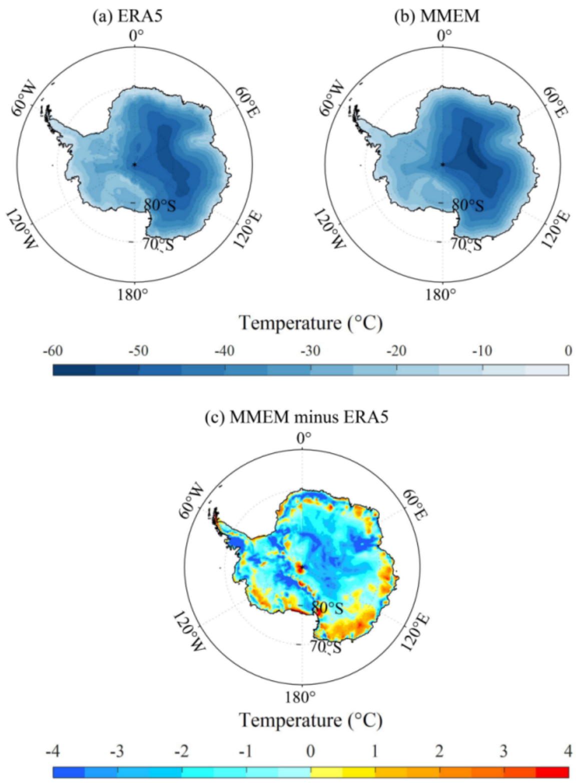

Fig. 1 Spatial patterns of annual mean temperature from the ERA5 (a), the multi-model ensemble mean (MMEM) of the CMIP6 model simulations (b), and their biases (MMEM minus observations) (c) over the Antarctica during 1979-2014.

Table 2 The corresponding year in the multi-model ensemble mean (MMEM) when mean surface temperature over the globe and Antarctica rise by 1.5°C, 2°C and 3°C relative to pre-industrial levels (1850-1900 period) for the first time under the different scenarios.

Regions	Warming threshold	SSP119	SSP126	SSP245	SSP370	SSP585
Global mean	1.5°C	2017	2018	2017	2017	2016
	2.0°C	2034	2034	2032	2032	2028
	3.0°C	NA	NA	2066	2053	2049
Antarctica	1.5°C	2015	2015	2017	2017	2016
	2.0°C	2038	2030	2034	2032	2032
	3.0°C	NA	NA	2072	2054	2050

Note: NA (not applicable) indicates that the threshold is not reached.

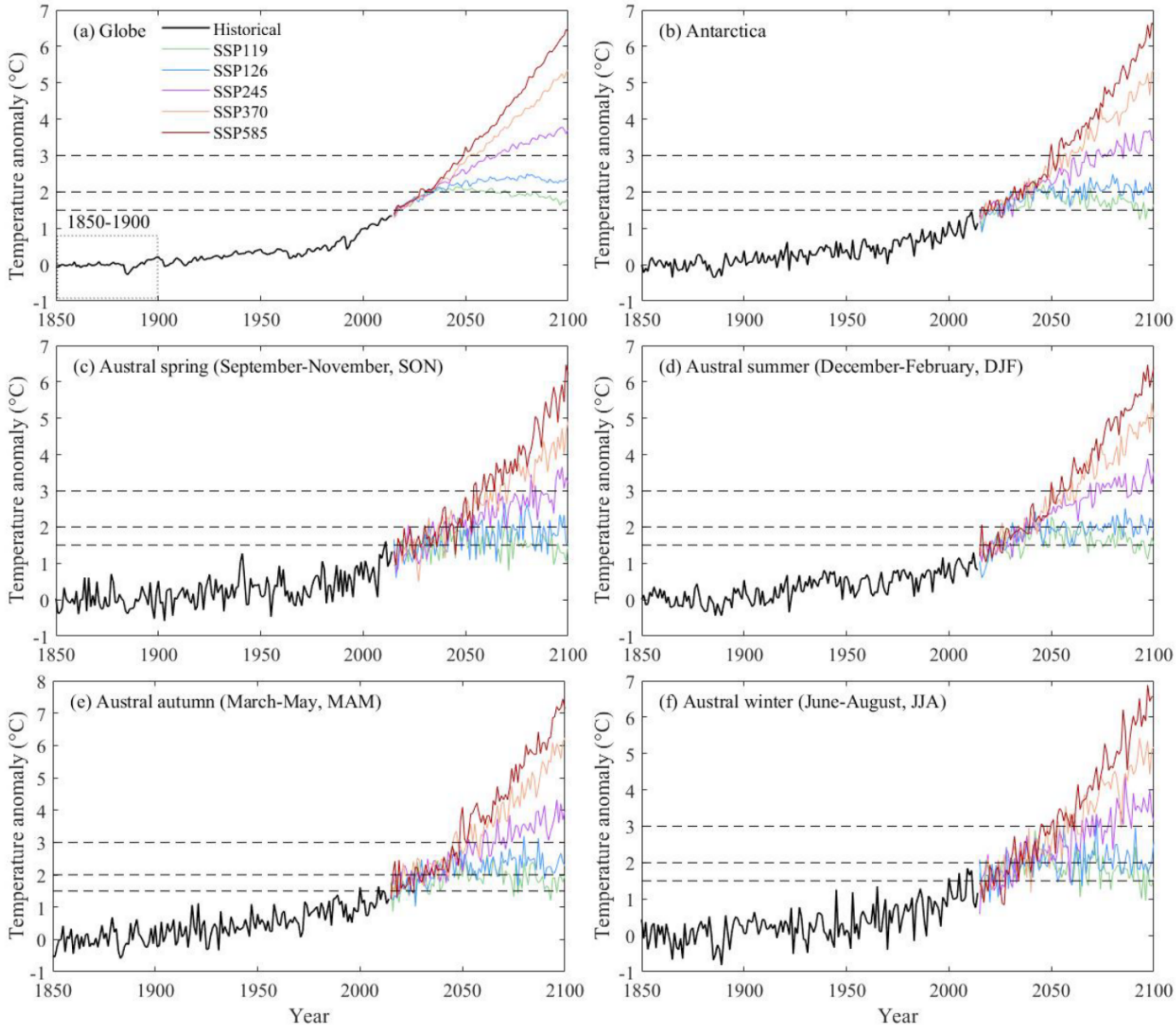

Fig. 2 Annual mean surface temperature anomaly for the Globe and Antarctica, and seasonal mean anomalies for Antarctica, for 1850-2100 from multi-model ensemble mean (MMEM) of the CMIP6 simulations. The different colors show the historical simulation and simulations for the SSP119, SSP126, SSP245, SSP370, SSP585 scenarios. Horizontal dotted lines show the surface mean temperature increase of 1.5°C, 2°C and 3°C above pre-industrial levels (1850-1900). The unit is °C.

average temperature warms significantly ($p<0.05$) in SSP245, SSP370 and SSP585 scenarios. A small, but significant warming trend of 0.02°C per decade ($p<0.05$) occurs over East Antarctica in SSP119. However, the Antarctic Peninsula shows a slight cooling trend in the annual mean and in all the seasonal means (not shown). In SSP126, a cooling trend of -0.01°C per decade also appears in the Antarctic Peninsula during SON only (not shown) a warming trend occurs in the annual mean and for other regions.

For Antarctica and its sub regions, the annual mean temperature has historically increased over the period 1850-2014, although this Antarctic warming is only significant ($p<0.05$) for the Antarctic Peninsula. Warming occurred in all seasons except DJF, with the most conspicuous warming of 0.05°C per decade in austral autumn (March-May, MAM) (not shown). The Antarctic Peninsula has had the highest mean trend of 0.12°C per decade over the historical period.

The all-Antarctic warming continues over 2015-2100 for the scenarios SSP126, SSP245, SSP370 and SSP585. But, contrary to expectations, the fastest future warming in annual temperature occurs over the continental East Antarctica in all SSPs. At higher forcings (SSP245, SSP370 and SSP585), the East Antarctic warming trend is regionally dominant, and exceeds 0.50°C per decade under SSP585. Seasonally however, the winter warming trend over the Antarctic Peninsula is as high as 0.77°C per decade under the

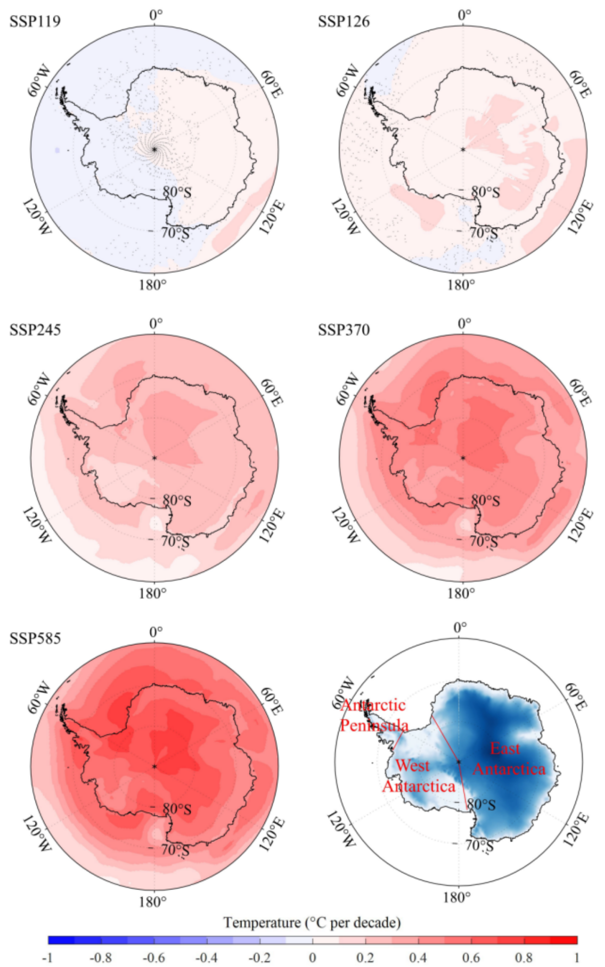

Fig. 3 Spatial patterns of the annual temperature trend from the multi-model ensemble mean (MMEM) of the CMIP6 simulations under different scenarios over the Antarctica for 2015-2100. The grey stippling shows the regions that fail to pass the 95% significant confidence test (the trends for SSP245, SSP370 and SSP585 over the Antarctica are all statistically significant at the 95% level). The unit is °C per decade. The bottom right panel shows the boundaries of the three Antarctic sub-regions presented in Fig. 4.

highest forcing (not shown).

To further explore the influence of the ocean, the regionally averaged surface annual temperature trend over the Southern Hemisphere (land and ocean), Southern Hemisphere (land only), Southern Hemisphere (ocean only), the region between 60°S and 90°S and all Antarctica are also shown in Fig. 4. The difference in annual trend between regions that include some ocean and regions with land only increases with the strength of forcing, indicating the influence of the ocean in moderating atmospheric warming. The trends in regions including ocean are also lower in all scenarios than for the Antarctic continent. For the Southern Hemisphere, the temperature warming for land only is faster than for all regions including ocean, except for SSP119, and the difference reaches almost 0.2°C per decade under the highest forcing.

3.2 Temperature changes over Antarctica with global warming of 1.5°C and 2.0°C

Many studies have examined climate changes under 1.5°C and 2.0°C global warming, but little attention has been paid to Antarctica. In this section, we use MMEM to assess changes in Antarctic temperature at 1.5°C and 2.0°C threshold. When global warming reaches 1.5°C above pre-industrial levels, the annual mean temperature over Antarctica is -35.88°C, -35.97°C, -35.77°C, -35.75°C, -35.79°C in the SSP scenarios from the lowest to the highest forcing. Since the differences between the various scenarios are not great, we only compare the change of Antarctic temperature at global warming of 1.5°C and 2.0°C for the strongest forcings. Fig. 5 shows the spatial distribution over Antarctica of the annual and seasonal mean temperature difference between the SSP370 and SSP585 scenarios when global warming reaches 1.5°C and 2.0°C (see Table 2 for the relevant dates). At a global warming of 1.5°C, East Antarctica and the Antarctic Peninsula show cooler annual temperature, and West Antarctica shows warmer annual temperature, in SSP585 than in SSP370. The phenomenon is also apparent in the austral winter (JJA), The average temperature over all of Antarctica is 0.16°C warmer in SSP370 than in SSP585. In winter, warming in Marie Byrd Land and the Ross Ice Shelf (West Antarctica) under SSP585 is as much as 0.80°C higher than under SSP370. In SON, higher temperature for SSP585 dominates West Antarctica, whereas the average temperature over the Antarctic Peninsula is 0.57°C colder than for SSP370.

At a global warming of 2.0°C in the austral spring, East Antarctica is considerably warmer under the SSP585 scenario than for SSP370 (Fig. 5b). But for the annual mean, and in winter, the Antarctic Peninsula and the region of the Oates Coast (East Antarctica) warms more under SSP585. The above phenomenon indicates that the emission pathways have a significant impact on the Antarctic temperature.

Fig. 6 shows the Antarctic distribution of the change in the annual mean and in seasonal

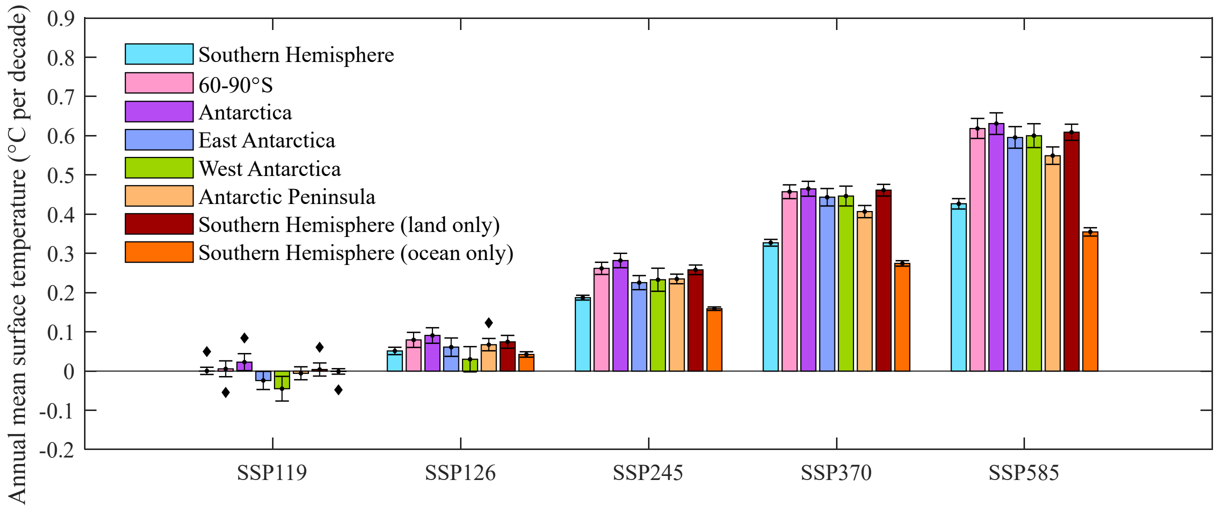

Fig. 4 Annual mean surface temperature trends for 2015-2100 over the Southern Hemisphere, the region between 60°S and 90°S, all Antarctica, East Antarctica, West Antarctica, the Antarctic Peninsula, Southern Hemisphere land regions only and Southern Hemisphere ocean regions only, from the CMIP6 model simulation under the different SSP Scenarios. Diamonds "♦" represent a trend that is not significant. All others are significant above the 95% confidence interval. The unit is °C per decade. The error bar indicates the 95% confidence intervals.

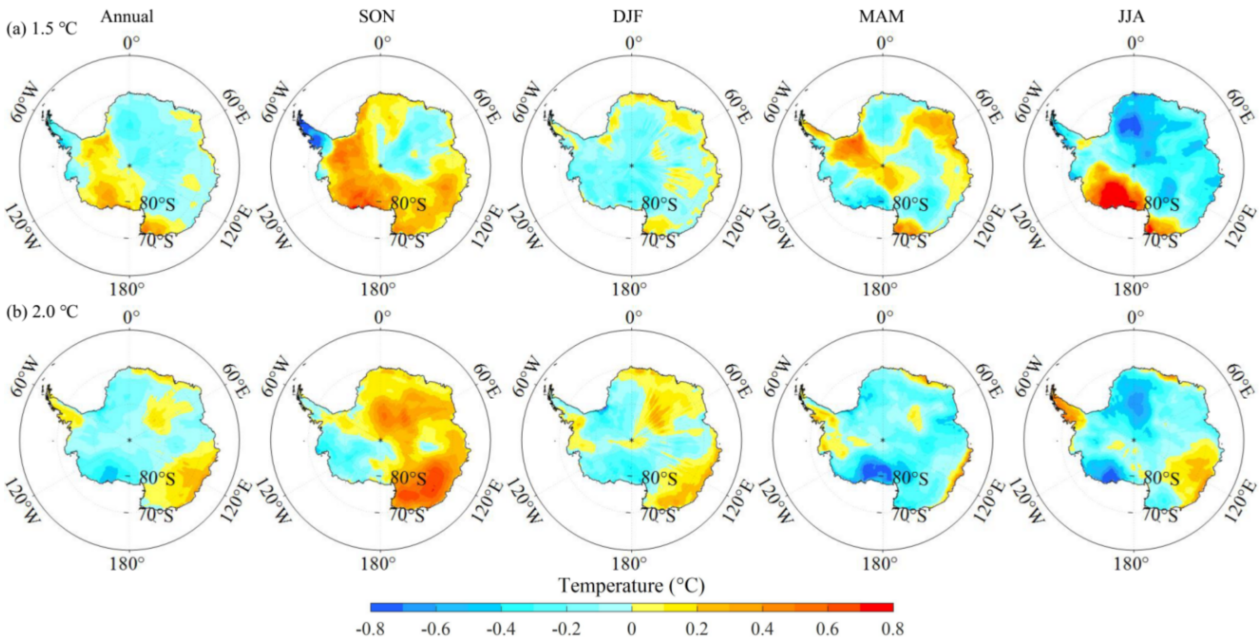

Fig. 5 Spatial patterns of the difference between SSP370 and SSP585 (SSP585-SSP370) for a 1.5°C global warming threshold (a) and for a 2.0°C threshold (b) for annual mean and seasonal mean temperature from the CMIP6 simulations MMEM. The unit is °C. SON, September to November; DJF, December to February; MAM, March to May; JJA, June to August.

temperature between when global warming reaches 2.0°C and 1.5°C for SSP370 and SSP585, respectively. In SSP370, warming dominates Antarctica, except during SON when the Antarctic Peninsula cools. However, at the higher forcing the warming is not uniform. Except during DJF, the temperature change under SSP585 in Marie Byrd Land and on the Ross Ice Shelf shows a cooling as the global mean warming increases from 1.5°C to 2.0°C. As the global mean temperature warms by 0.5°C, the annual mean Antarctic temperature increases by only 0.34°C under SSP370, and by only 0.31°C under SSP585. Under SSP585 in JJA, the Antarctic Peninsula warms by 0.83°C as global temperature warms by 0.50°C.

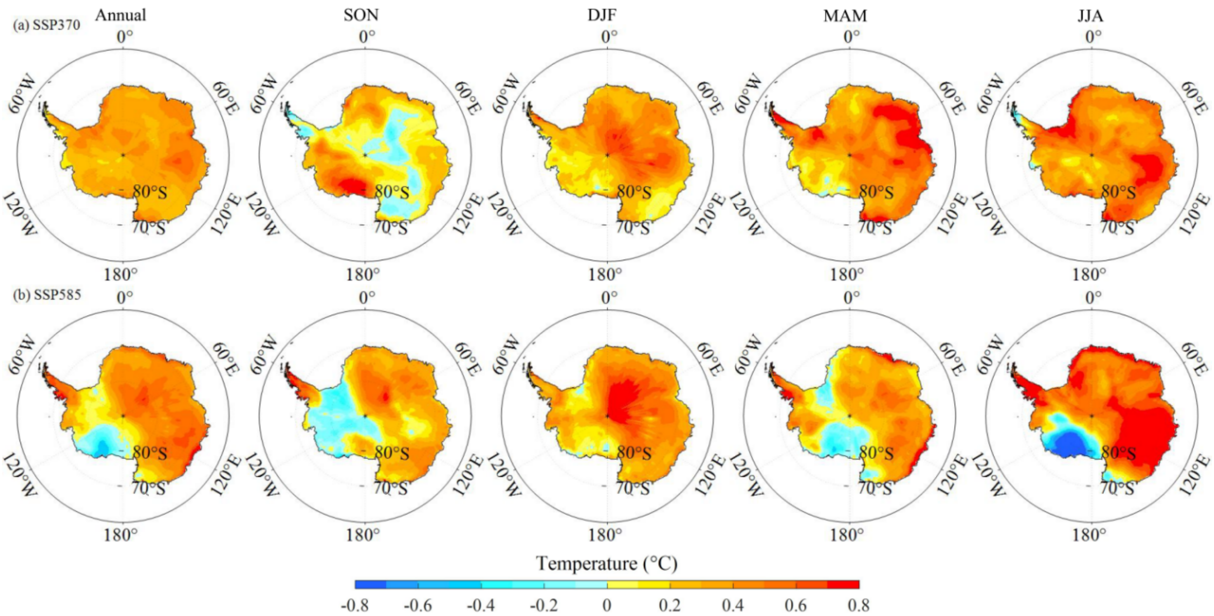

Fig. 6 Distribution of the annual and seasonal temperature variations when global warming increases from 1.5°C threshold to 2.0°C threshold for SSP370 (a) and SSP585(b).

3.3 Antarctic Amplification phenomenon under different scenarios

Fig. 7 shows the annual and seasonal zonally mean temperature trends as a function of latitude during 2015-2100 under different scenarios. AnA can be seen for latitudes greater than 70°S under SSP245, SSP370 and SSP585, most clearly at the highest forcing scenario. The AnA is however absent in SSP119. Over Antarctica, the annual, spring and summer zonally averaged temperature trends increases as a function of latitude. In autumn and winter, the warming trend is even stronger around 70°S.

Table 3 summarizes the amplification index for Antarctica and its sub-regions, both annually and seasonally, for all scenarios except SSP119. For all Antarctica and for East Antarctica, amplification generally occurs in all cases, and the amplification index is almost always greater than 1.30. The index is strongest in the austral summer and autumn. In SSP126, SSP370 and SSP585, the amplification for all of Antarctica is strongest in austral autumn, with amplification index of 1.78, 1.52 and 1.55, respectively. The annual temperature warming rate for all Antarctica is 1.55, 1.40, 1.40 and 1.45 times that of the whole Southern Hemisphere under SSP126, SSP245, SSP370 and SSP585 scenarios, respectively. It is worth noting that the intensity of AnA is not linear with the enhancement of emission scenarios. Generally, the amplification is strongest in SSP126 except austral winter. However, AnA is most conspicuous in SSP585 if the amplification in SSP126 is not considered. The ratio of the linear trends in surface air temperature over ocean to the trends over Southern Hemisphere in SSP126 are 0.82, 080, 0.80, 0.78 and 0.92 in annual, SON, DJF, MAM and JJA,

Table 3 Antarctic Amplification Index over all Antarctica and its sub-regions under different scenarios.

Scenarios	Annual	SON	DJF	MAM	JJA
Antarctica					
SSP126	1.55	1.57	1.63	1.78	1.15
SSP245	1.40	1.33	1.51	1.42	1.35
SSP370	1.40	1.30	1.47	1.52	1.30
SSP585	1.45	1.34	1.52	1.55	1.39
East Antarctica					
SSP126	1.77	1.97	1.87	1.71	1.51
SSP245	1.51	1.49	1.63	1.51	1.41
SSP370	1.42	1.34	1.57	1.52	1.27
SSP585	1.48	1.39	1.61	1.55	1.38
West Antarctica					
SSP126	1.19	0.91	1.23	1.95	0.49
SSP245	1.21	1.05	1.31	1.24	1.22
SSP370	1.35	1.24	1.30	1.52	1.34
SSP585	1.40	1.26	1.39	1.54	1.39
Antarctic Peninsula					
SSP126	0.58	0.27	0.57	1.09	0.90
SSP245	1.24	1.05	1.07	1.52	1.31
SSP370	1.36	1.00	0.99	1.66	1.74
SSP585	1.41	1.23	1.02	1.63	1.69

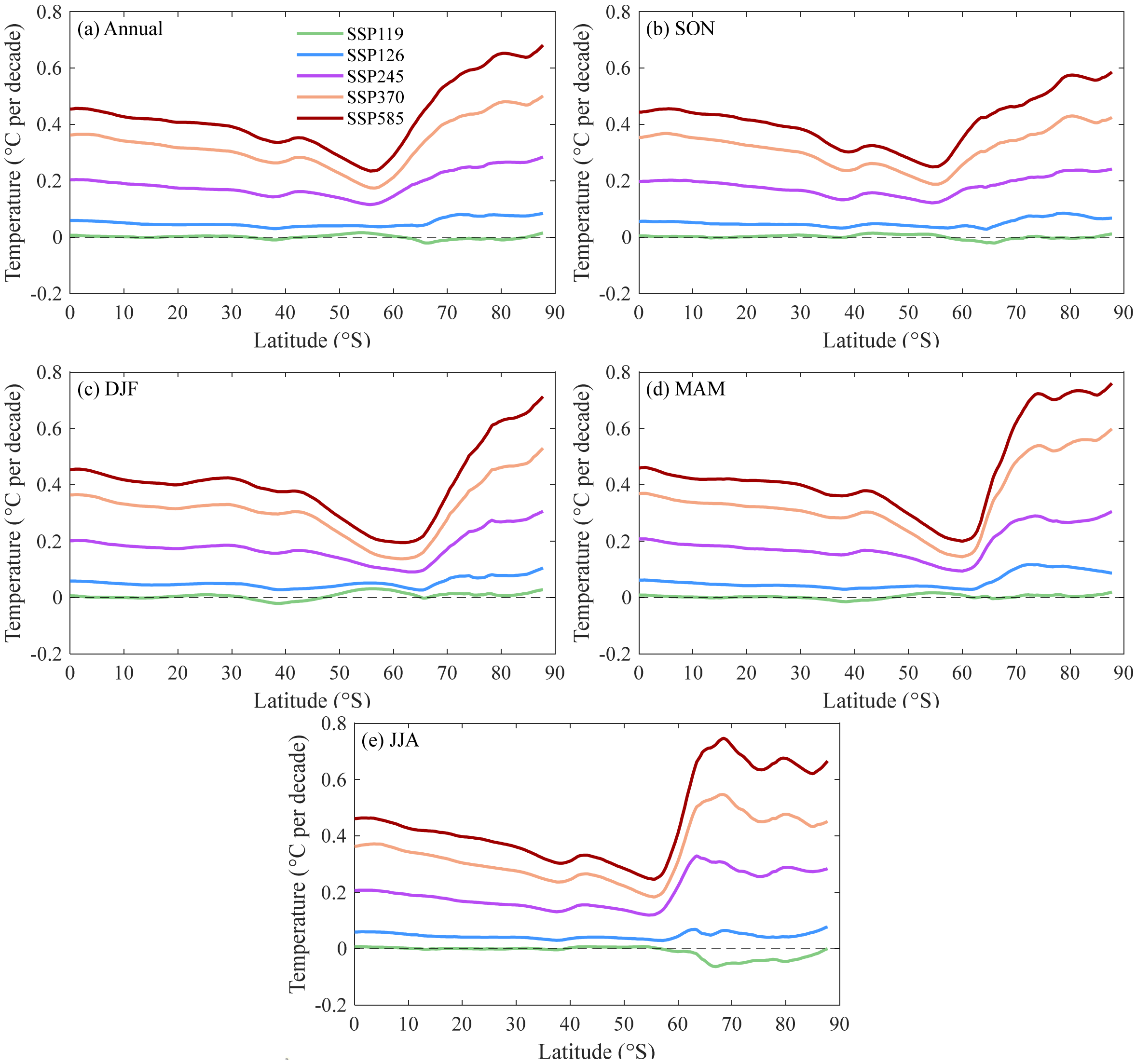

Fig. 7 Annual and seasonal, zonally average temperature trends as a function of latitude during 2015-2100 from the multi-model ensemble mean (MMEM) of the CMIP6 simulations under different scenarios. The unit is °C per decade.

and the corresponding values in SSP585 are 0.83, 0.83, 0.81, 0.82 and 0.86, respectively. This phenomenon corresponds to the greater AnA in wintertime in SSP585, rather than SSP126. The magnitude of AnA is generally stronger in SSP126 than SSP585, which may be affected by the strong ocean heat uptake associated with rapid and sustained forcing in SSP585.

Fig. 8 is similar to Fig. 7, but investigates whether amplification also occurs for each Antarctic sub-region. It is clear that the amplification occurs for the East Antarctica sector in all cases, with an amplification index almost always above 1.30 (Table 3), and the amplification of East Antarctica is most conspicuous in austral summer, except for SSP126. The amplification in West Antarctica is generally strongest in autumn, with the amplification index higher than 1.50. For all scenarios, the amplification of the West Antarctic meridional sector is weakest in the austral spring. For the Antarctic Peninsula, the amplification is weak in austral spring and summer, and absent in SSP126 except in autumn. The strongest amplification for the Antarctic Peninsula occurs in the austral autumn (SSP126, SSP245) to winter (SSP370, SSP585).

From another perspective, the regional and seasonal differences of AnA are the differences of temperature changes. In SSP585, there is a positive trend in SAM in response to increasing greenhouse gas concentration. On annual scale, significant (p<0.05) decrease in sea-level pressure (SLP) over the Antarctica can be observed (Fig. 9), especially in

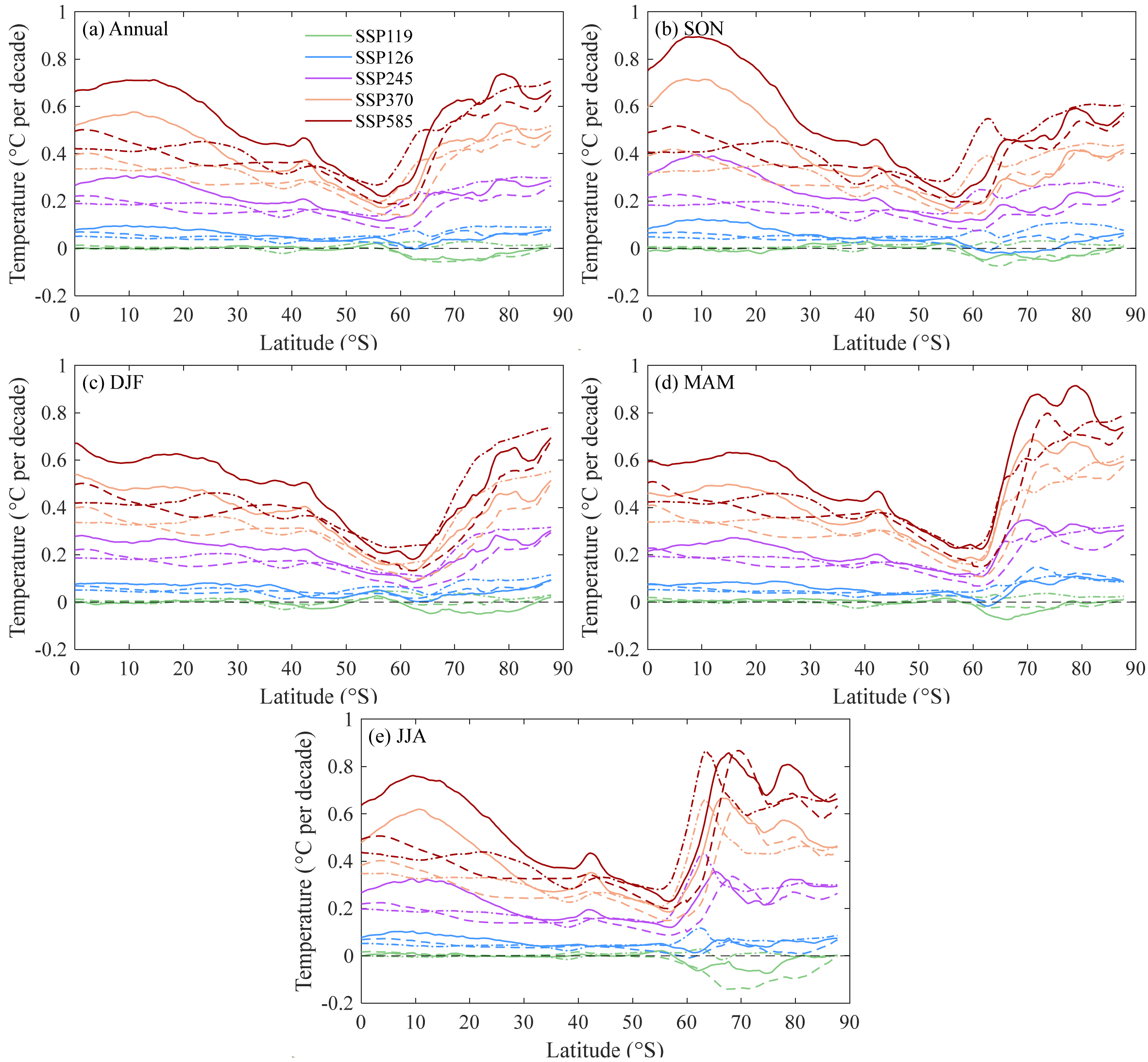

Fig. 8 Annual and seasonal, zonally average temperature trends of the meridional sectors of East Antarctica (chain line), West Antarctica (dashed line) and Antarctic Peninsula (solid line) as a function of latitude during 2015-2100 from the multi-model ensemble mean (MMEM) of the CMIP6 simulations under different scenarios. The unit is °C per decade.

Antarctic Plateau, accompanied by a decrease in sea-ice concentration (SIC) (Fig. 10) and strengthening westerly jet (Fig. 11). Similarly, seasonal mean SLP and SIC decrease in high latitude areas, and the intensity of westerly jet increases except JJA. The amplification of East Antarctica and West Antarctica are strong in austral summer and spring. In these seasons, the SIC near the West Antarctic coast decreases rapidly, and there is even an ice free period in summer, which may affect the poleward transport of atmospheric heat and moisture and induce the warming in West Antarctica (Schneider et al. 2012). In addition, the strengthening and poleward shift of westerly jet is most conspicuous in DJF and MAM, while the wind speed generally decreases over the Antarctic continent. Previous studies have found that the strengthening of mid-latitude jet is related to increase in SAM, which reduces the poleward advection of heat toward the continent, which generally leads to cooling across the Antarctic continent (van den Broeke and van Lipzig 2003; Marshall et al. 2013; Clem et al. 2018). However, the abnormal high pressure ridge over Antarctica can cause the enhancement of the warm advection transport, and this circulation situation will also destroy the surface inversion, resulting in the rise of the near surface temperature in the interior of Antarctica (Marshall et al. 2013). In addition, Tropical forcing is also an important factor affecting Antarctic temperature, and the increase of El Niño in future

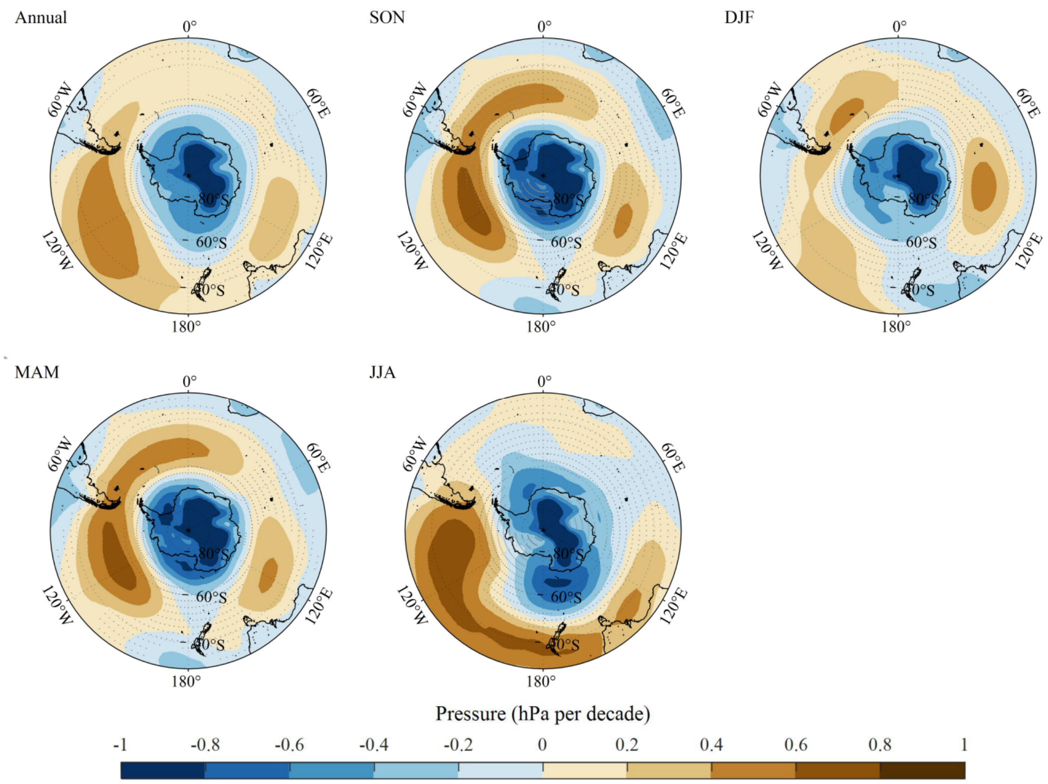

Fig. 9 Spatial patterns of the annual and seasonal sea-level pressure trend from the multi-model ensemble mean (MMEM) of the CMIP6 simulations under SSP585 for 2015-2100. The grey stippling shows the regions that fail to pass the 95% significant confidence test.

may cause the warming over East Antarctica (Ding et al. 2011; Nicolas and Bromwich 2014; Clem et al. 2018). The amplification over Antarctic Peninsula is strongest in JJA, and the SLP decrease across the Weddell Sea and increase in Bellingshausen Sea, and the circulation situation generally give a higher temperature across the Antarctic Peninsula (Turner et al. 2016). In addition, a large decrease in SIC occurs in the Bellingshausen Sea, associated with a weakening mid-latitude jet, and this atmospheric circulation can transport warm air towards the Antarctic Peninsula (Turner et al. 2005).

4 Discussion

Generally, AnA will appear in future scenarios, and the intensity of AnA is weaker than Arctic Amplification (Xie et al. 2022). The asymmetry in polar amplification of warming between the Antarctica and the Arctic is primarily due to asymmetry in local feedbacks under polar forcing, and may also be attributed to the asymmetry in ocean heat uptake and atmospheric heat transport (Stuecker et al. 2018).

Arctic Amplification has several suggested causes. One of the major ones is surface albedo feedback, especially the ice-albedo feedback. As sea ice declines with temperature increase, it decreases the albedo of the underlying surface where ice is replaced by open water, especially in summer, increasing absorption of incoming solar radiation. Multi-year Arctic pack ice has drastically reduced (mostly due to oceanic causes). With the reduction in the extent of thick ice, and the normal summer melt of thin ice, there is a far lower surface albedo in summer when incoming solar radiation is greatest. This is a strong positive feedback (You et al. 2021). In Antarctica, there is little sea ice extent in summer when the ice-albedo feedback is important, and the amplification is strongest over the high East Antarctic plateau where surface albedo changes will be zero or very small.

AnA doesn't seem to get systematically stronger at higher forcings. The AnA index over the period 2015-2100 for annual temperature is 1.55, 1.40, 1.40 and 1.45 under SSP126, SSP245, SSP370 and SSP585 scenarios, respectively. This is in agreement with the

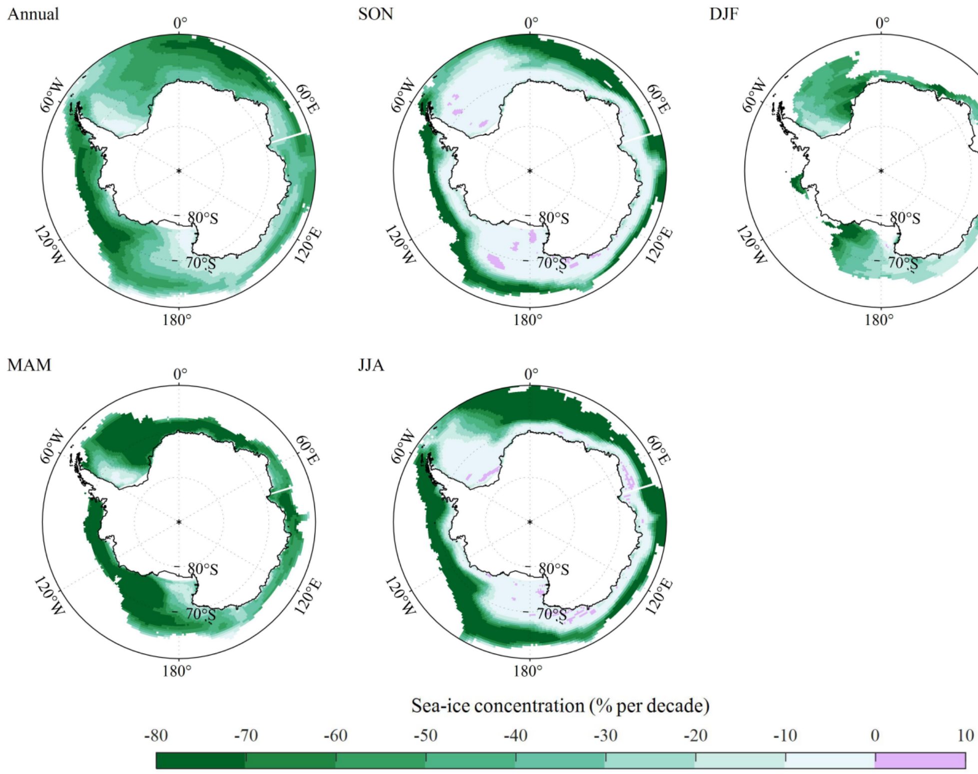

Fig. 10 Spatial patterns of the annual and seasonal sea-ice concentration trend from the multi-model ensemble mean (MMEM) of the CMIP6 simulations under SSP585 for 2015-2100. The grey stippling shows the regions that fail to pass the 95% significant confidence test.

IPCC AR6 conclusion that warming and weak polar amplification is projected as very likely over the Antarctica (IPCC 2021). In addition, previous research found that the warming over the costal Antarctica and Southern Ocean in SSP126 and SSP245 are stronger than that in SSP370 and SSP585 (Bracegirdle et al. 2020), which may connects to the nonlinear variation of AnA.

Our study illustrates that the average temperature over East Antarctica will have a strong increasing trend in future under all scenarios. The trajectory of future Antarctic warming and its consequences highlights the long-term effect of emission control decisions made today (Rintoul et al. 2018).

The models in CMIP6 have many improvements over those in CMIP5, including new and better representation of physical, chemical and biological processes, and higher resolution, and better performance on resolving the actual mean state of climate (IPCC 2021). However, the feedback mechanisms are often still poorly reproduced and this limits the simulation of ocean warming close to Antarctica and its influence on sea ice and ice shelves (IPCC 2021). Compared to the Arctic, weaker lapse-rate and surface-albedo feedbacks and more-negative cloud feedbacks occur in Antarctica, CMIP6 decreases the uncertainty range for the cloud feedback by about 50% compared to the previous generation (Hyder et al. 2018; IPCC 2021). In CMIP6, some models have less-negative cloud feedbacks at high latitude, which leads to a stronger polar amplification (Zelinka et al. 2020). In addition, while the ice-albedo feedback, is well recognized as a key driver of polar amplification (Pithan and Mauritsen 2014). There is low confidence in model simulations of past and future Antarctic sea ice evolution due to deficiencies of process representation, in particular at the regional level (Roach et al. 2020). In CMIP6, there are some really large biases and inter-model differences in Antarctic sea ice, in particular, models do not capture the observed stability of Antarctic sea ice area during the historical period (IPCC 2021).

New models will be released progressively, and will help further improve the accuracy. Therefore, further investigation is needed of temperature changes with more models under each scenario. In this study, the MMEM based on 7 models is limited by the small ensemble of SSP119, which may affect the

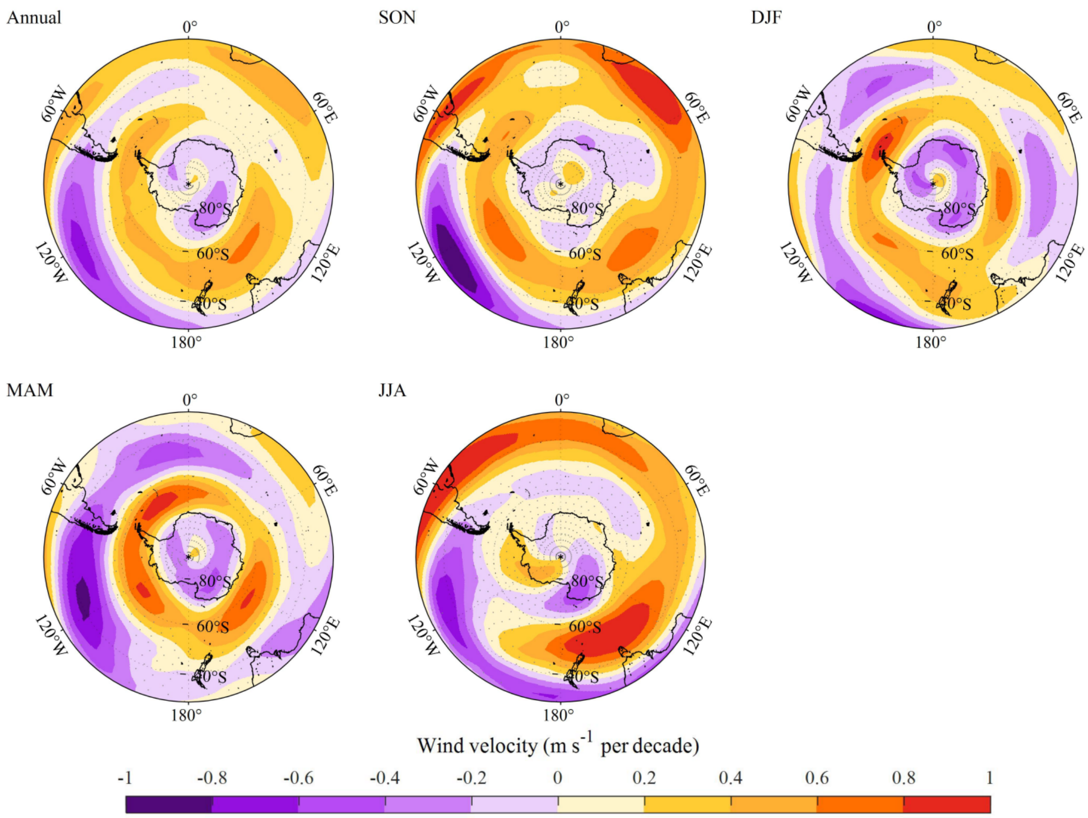

Fig. 11 Spatial patterns of the annual and seasonal 300 hPa zonal wind component trend from the multi-model ensemble mean (MMEM) of the CMIP6 simulations under SSP585 for 2015-2100. The grey stippling shows the regions that fail to pass the 95% significant confidence test.

credibility of results. To explore whether there is a obvious difference between the results based on 7 models and those based on the more models, the amplification index on annual and seasonal scale based on MMEM from 14 models (Table 4) under SSP126, SSP245, SSP370 and SSP585 are calculated, and the results are shown in Table 5. Clearly, the AnA can be observed in all scenarios, and is strong in austral summer and autumn, with the amplification index higher than 1.39. Among the sub-regions, the amplification is the strongest in East Antarctica in general. In addition, the amplification in West Antarctica and Antarctic Peninsula is weak in austral spring. Although the results of amplification index based on MMEM from 7 models and 14 models are slightly different (Table 3 and Table 5), the characteristics of AnA reflected by them are consistent, which indicates that the current results are reliable.

The temperature change over Antarctica caused by greenhouse gases in recent decades is mainly masked by the strong internal variability, although the positive trend of SAM is mainly affected by the increase of greenhouse gas concentration and stratospheric ozone depletion (Arblaster and Meehl 2006; Thompson et al. 2011; Wang et al. 2020). In future scenarios, the temperature over Antarctica is begin to clearly diverge around 2045. After this point, the effects of continued stratospheric ozone recovery dominate the temperature change in Antarctica under SSP126 and SSP245, while westerly jet responses to increased greenhouse gases dominate in SSP370 and SSP585 (Bracegirdle et al. 2020). In future, it is necessary to explore the impact of external forcing and natural internal variability on Antarctic temperature in future scenarios. Moreover, the mechanisms of Antarctic temperature changes remain ambiguous due to the complex climatology including atmospheric circulation changes, and air-sea ice feedback, more high-quality observations are also necessary to support our findings (Hakim et al. 2020). Understanding AnA primarily requires a better insight into local forcing and feedbacks as well as extra-polar processes (Stuecker et al. 2018). Further research is also required to investigate the combined impacts of atmospheric circulation and regional feedbacks with longer time series and more high-quality observations over Antarctica.

Table 4 List of CMIP6 models under SSP126, SSP245, SSP370 and SSP585.

Model number	Model name	Lat × Lon grid (km × km)
1	AWI-CM-1-1-MR	192×384
2	BCC-CSM2-MR	160×320
3	CanESM5	64×128
4	EC-Earth3	256×512
5	EC-Earth3-Veg	256×512
6	FGOALS-g3	80×180
7	INM-CM4-8	120×180
8	INM-CM5-0	120×180
9	IPSL-CM6A-LR	143×144
10	MIROC6	128×256
11	MPI-ESM1-2-HR	192×384
12	MPI-ESM1-2-LR	96×192
13	MRI-ESM2-0	160×320
14	NorESM2-MM	192×288

Table 5 Antarctic Amplification Index over all Antarctica and its sub-regions under different scenarios based on the multi-model ensemble mean (MMEM) from 14 CMIP6 models in Table 4.

Scenarios	Annual	SON	DJF	MAM	JJA
Antarctica					
SSP126	1.44	1.29	1.52	1.64	1.30
SSP245	1.41	1.36	1.51	1.39	1.41
SSP370	1.44	1.34	1.50	1.56	1.36
SSP585	1.44	1.34	1.51	1.54	1.39
East Antarctica					
SSP126	1.61	1.60	1.68	1.64	1.51
SSP245	1.50	1.47	1.61	1.46	1.46
SSP370	1.47	1.37	1.60	1.57	1.35
SSP585	1.48	1.38	1.59	1.56	1.39
West Antarctica					
SSP126	1.17	0.75	1.27	1.69	0.91
SSP245	1.26	1.16	1.32	1.24	1.30
SSP370	1.39	1.27	1.35	1.54	1.38
SSP585	1.38	1.26	1.38	1.50	1.37
Antarctic Peninsula					
SSP126	0.68	0.25	0.63	0.76	1.05
SSP245	1.28	0.90	1.10	1.64	1.45
SSP370	1.35	1.08	1.08	1.60	1.59
SSP585	1.45	1.25	1.10	1.74	1.66

5 Conclusions

In this study, we provide an initial evaluation of Antarctic temperature changes from 1850 to 2100 based on the five CMIP6 scenarios of SSP119, SSP126, SSP245, SSP370 and SSP585. As expected, results show that the warming will be strengthened with the increase of forcing. However, there is no obvious difference in the time that global mean temperature achieves 1.5°C warming above pre-industrial under different scenarios. The warming of Antarctica displays a seasonal variation, with a rapid warming trend in austral autumn, except under SSP119. In addition, the Antarctic Peninsula exhibits a slight cooling tendency in SSP119, and conspicuous warming in austral autumn and winter in other scenarios, with the warming rate higher than 0.5°C per decade under SSP370 and SSP585 scenarios.

On the other hand, Antarctic warming shows regional variation, with strong annual warming in East Antarctic in all scenarios. When global warming rises from 1.5°C to 2.0°C threshold, the Antarctic Peninsula experiences faster warming under SSP585, with temperature rising more than 0.5°C except in austral summer, and this also occurs in East Antarctica in summer and winter.

Our analysis also shows that AnA of climate change will occur, particularly in the later part of this century. For the whole Antarctic, amplification is projected to appear in SSP126 to SSP585 scenarios, and will be strongest in DJF and MAM. Similarly, East Antarctic amplification occurs and is strongest in austral summer, with an amplification index over 2015-2100 of more than 1.57. For West Antarctica, the amplification sign is strongest in austral autumn. For the Antarctic Peninsula sector, the amplification is more obvious in austral autumn and winter, with an amplification index higher than 1.30 except under SSP126.

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