



ANTARCTIC SCIENCE NEWS



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compiled by Dr. Alvarinho J. Luis

Assessing recent trends in high-latitude Southern Hemisphere surface climate

A shift in westerly winds, which has led to climate impacts in Australia and the Southern Ocean, is human-induced, new research suggests. To date, limited data on Antarctic climate has meant that it's been difficult to disentangle changes caused by human activity from natural fluctuations. Ocean fossils found in mountains are cause for concern over future sea levels, scientists say.

A shortage of data on the weather in Antarctica is hampering efforts to understand climate change in the region, according to new research.

The study, led by Dr Julie Jones from the University of Sheffield, has revealed that limited data on Antarctica's climate is making it difficult for researchers to disentangle changes caused by human activity from natural climate fluctuations.

Scientists can confidently say that Earth is warming due to greenhouse gas emissions caused by humans, but data on climate trends over the Antarctic and the surrounding Southern Ocean only go back to 1979 when regular satellite observations began. This makes it difficult for researchers to see how long-term climate trends have changed in the region.

The inhospitable nature of the continent means that it has never had permanent inhabitants to take regular weather observations unlike most other places on the planet.

The first routine observations only started in 1957 with the establishment of the network of Antarctic Research Stations. This provides important weather data, however they are mostly located around the coast, so leave vast areas of the continent and the surrounding oceans uncovered.

It is only with the advent of regular satellite observations in 1979 that measurement of surface climate over the Antarctic and the surrounding Southern Ocean became possible.

To gain a longer view of recent changes, Dr Jones and her international team of scientists used a compilation of climate records from natural archives, such as ice cores from the Antarctic ice sheet, which give indications of how the region's climate has changed over the last 200 years. They also studied how these recent changes compared to those in experiments with climate models.

They confirmed that human-induced changes have caused the belt of prevailing westerly winds over the Southern Ocean to shift towards Antarctica.

The research concludes that for other changes, such as regional warming and sea ice changes, the observations over the satellite-era since 1979 are not yet long enough for the signal of human-induced climate change to be clearly separated from the strong natural variability in the region

Understanding Antarctic climate change is important not only because of the potential sea level rise locked up in the vast Antarctic ice sheet, but also the shift in the westerly winds has moved rainfall away from southern Australia. In combination with increasing temperatures (this year is set to be the country's hottest year on record) this has had profound impacts on Australian communities and ecosystems

Dr Julie Jones said: The Antarctic climate is like a giant jigsaw puzzle with most of the pieces still missing. There are some parts of the picture which are clear, particularly the way that climate change is causing westerly winds to shift southwards, but there are still huge gaps that we need to fill in order to fully understand how much human activity is changing weather in the region.

At face-value, many of the climate trends in Antarctica seem counter-intuitive for the warming world. Scientists have good theories for why, but these are difficult to prove with the short records we are working with.

In order to better understand climate change in Antarctica, we need continued climate measurements in the Antarctic and Southern Ocean, and extension of these short observational records with past climate reconstructions and climate modelling. Scientists still had much to learn about the climate system of Antarctica and the region, and how it would affect people and the environment.

The Sheffield-led research team included scientists from 19 institutions from around the world. Their results will help to shape the way the University contributes to the global effort of understanding climate change and gives geography students at Sheffield access to the latest innovations in climate change research.

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Assessing recent trends in high-latitude Southern Hemisphere surface climate

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Understanding the causes of recent climatic trends and variability in the high-latitude Southern Hemisphere is hampered by a short instrumental record. Here, we analyse recent atmosphere, surface ocean and sea-ice observations in this region and assess their trends in the context of palaeoclimate records and climate model simulations. Over the 36-year satellite era, significant linear trends in annual mean sea-ice extent, surface temperature and sea-level pressure are superimposed on large interannual to decadal variability. Most observed trends, however, are not unusual when compared with Antarctic palaeoclimate records of the past two centuries. With the exception of the positive trend in the Southern Annular Mode, climate model simulations that include anthropogenic forcing are not compatible with the observed trends. This suggests that natural variability overwhelms the forced response in the observations, but the models may not fully represent this natural variability or may overestimate the magnitude of the forced response.

The high-latitude Southern Hemisphere (SH) is a highly complex and critically important component of the global climate system that remains poorly understood. The Antarctic Ice Sheet represents the greatest potential source of global sea-level rise¹, and its response to climate change is a key source of uncertainty for future projections^{2,3}. The Southern Ocean is important for its ability to take up heat and carbon dioxide, and thereby mitigate human-induced atmospheric temperature and CO₂ rise^{4–8}. Antarctic sea ice is important for its role in ocean–atmosphere exchange and provides an important climate feedback through its influence on albedo and atmospheric and oceanic circulation.

The leading mode of atmospheric circulation variability in the SH high latitudes is the Southern Annular Mode (SAM)⁹. It is a measure of the mid-to-high-latitude atmospheric pressure gradient and reflects the strength and position of the westerly winds that circle Antarctica. This in turn affects various aspects of Antarctic

climate and controls the timing and distribution of rainfall received by the mid-latitude SH continents¹⁰. An almost equally important aspect of large-scale circulation variability in this region is the mid-to high-latitude response to tropical variability, particularly the El Niño/Southern Oscillation (ENSO)¹¹.

Over recent decades, multiple changes have been observed in high-latitude SH climate. But the brevity and sparse distribution of observational records pose considerable challenges to understanding whether observed changes are anthropogenically forced or remain within the range of natural climate variability. We can improve our understanding of SH high-latitude climate by combining information from instrumental, satellite, palaeoclimate and reanalysis data, along with climate model simulations. Here, we provide an assessment of recent changes in the atmosphere, ocean and sea-ice systems of the southern high latitudes (south of 50° S), on timescales from decades to centuries. We describe SH climate trends using

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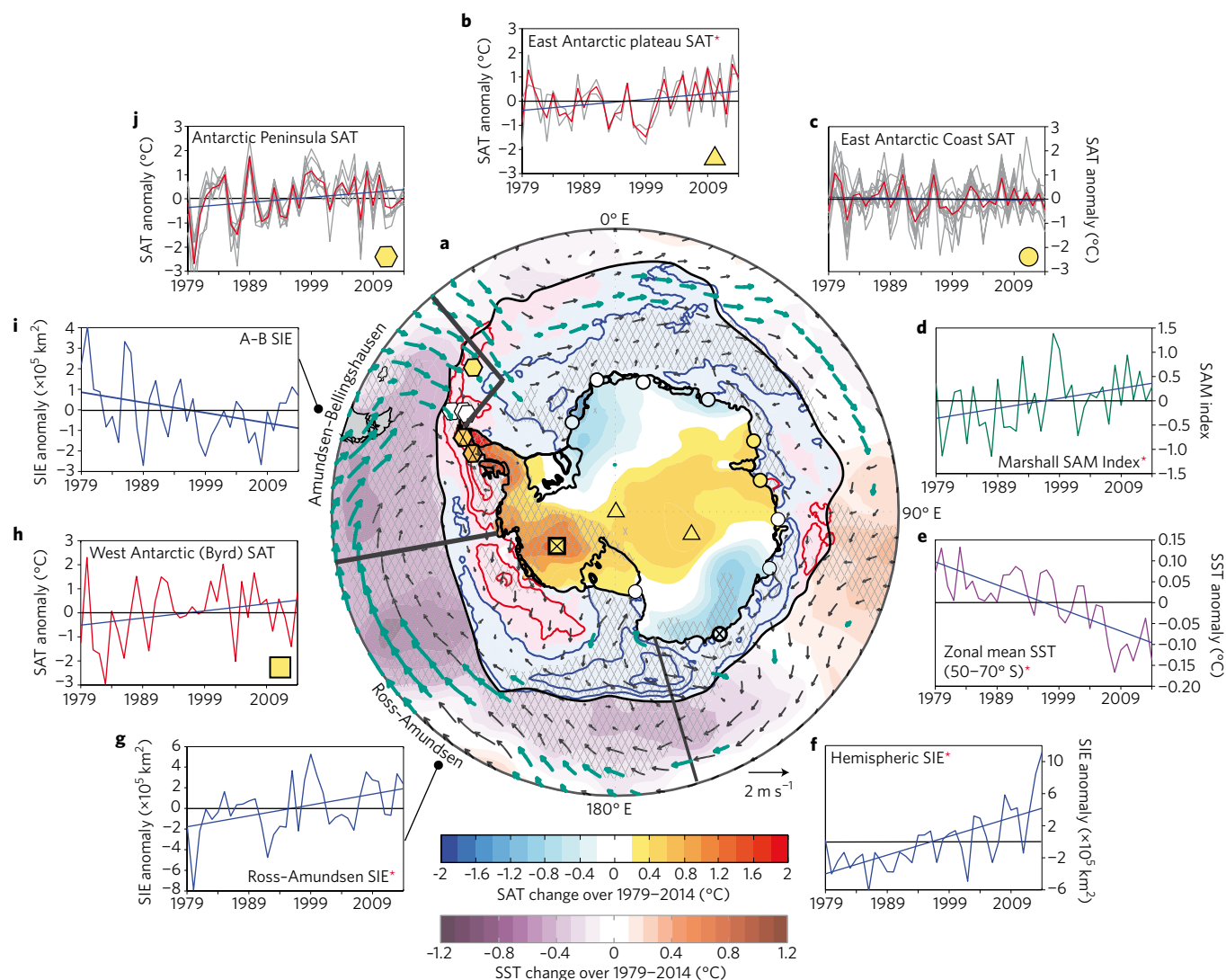


Figure 1 | Antarctic atmosphere-ocean-ice changes over the satellite-observing era. **a**, Total changes over 1979–2014 in annual mean surface air temperature (blue-red shading), station-based surface air temperature (SAT, blue-red shaded shapes), sea-ice concentration (contours, 10% intervals; red and blue contours, alongside light pink and blue shading beneath, denote negative and positive trends, respectively), sea surface temperature (SST, purple-red shading), and 10-m winds (vectors). Only SST trends equatorward of the climatological September sea-ice extent (SIE, black contour) are shown. Hatching and teal vectors highlight trends significant at the 95% level according to two-tailed Student's *t*-tests. Note that SAT trends are calculated over 1979–2012 but scaled to represent trends over the 36-year period 1979–2014. **b–j**, Surrounding figures show time-series: East Antarctic plateau SAT (**b**; triangles; red line denotes multi-station mean, grey lines those of individual East Antarctic plateau stations); East Antarctic coast SAT (**c**; circles; red line denotes multi-station mean, grey lines those of individual East Antarctic coast stations); the Marshall Southern Annular Mode index (**d**; difference in station sea-level pressure between 40° and 65° S); Southern Ocean zonal mean SST (**e**; averaged over 50–70° S); Southern Hemisphere SIE (**f**); Ross-Amundsen SIE (**g**); West Antarctic SAT (**h**; square; Byrd Station); Amundsen-Bellinghousen SIE (**i**); and Antarctic Peninsula SAT (**j**; hexagons; red line denotes multi-station mean, grey lines those of individual Antarctic Peninsula stations). For all time series, blue lines highlight the linear trend, and red asterisks where the trend is significant at the 95% level according to a two-tailed Student's *t*-test. See Supplementary Methods for details on datasets and trend significance calculation.

satellite information (1979–2014) and Antarctic station observations. These are compared with trends and multi-decadal variability from palaeoclimate data spanning the past 200 years, as well as control and forced climate simulations from the Fifth Climate Model Intercomparison Project (CMIP5)¹², to assess whether recent trends are unusual compared with natural variability. We conclude by identifying key knowledge gaps where strategically focused research will improve understanding of the contribution of SH high latitudes to global climate variability and change.

Antarctic climate monitoring

Coordinated international efforts to monitor Antarctic climate

began in the International Geophysical Year of 1957/58. Few climate measurements are available, however, over vast areas of the continent and the adjacent ice-shelves, sea ice and oceans. The advent of routine satellite sounder observations in 1979 revolutionized knowledge of climate over Antarctica and the surrounding oceans, although uncertainties remain, owing to satellite sensor changes¹³. More uncertain early satellite estimates of sea ice extend back to 1972 (ref. 14), with ongoing recovery of ice edge information for the 1964–1972 period^{15,16}. Knowledge of recent subsurface ocean trends remains more limited. The Argo profiling float programme and conductivity–temperature–depth tags mounted on elephant seals have provided substantial numbers of subsurface

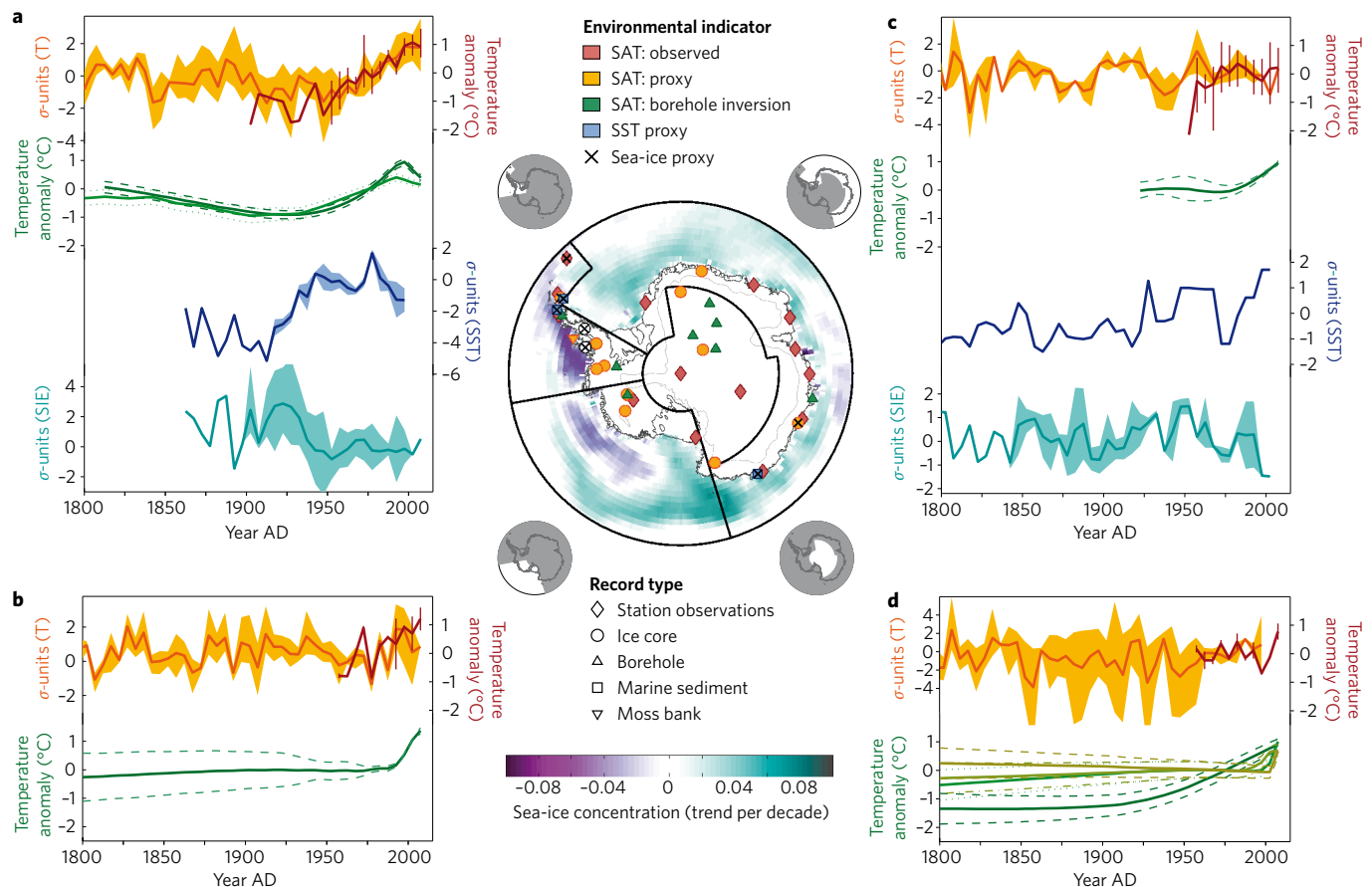


Figure 2 | Antarctic climate variability and trends over the past 200 years from long observational and proxy-derived indicators. **a–d**, Records were regionally compiled for the Antarctic Peninsula (**a**), West Antarctica (**b**), coastal East Antarctica (**c**) and the Antarctic Plateau (**d**) (see Methods). Central map shows the location of records according to environmental indicator (colours) and record type (symbols), as well as the boundaries of the four geographic regions (black lines), the 2,000-m elevation contour (grey curve), and the trend in sea-ice concentration over the 1979–2014 interval (shading). Within each region (**a–d**), records were compiled as 5-year averages (dark lines) according to the environmental parameter that they represent: observed surface air temperature (SAT) (red); proxy for SAT (orange); borehole inversion reconstruction of surface temperatures (greens); proxy for sea surface temperature (blue); and proxy for sea-ice conditions (cyan). Shadings (and thin vertical lines) denote ranges of estimates across records within each 5-year bin. The borehole temperature records are shown individually with uncertainty bounds (see Supplementary Fig. 4 for additional details). All records are expressed as temperature anomalies (°C units) or normalized data (σ -units) relative to 1960–1990. Details of datasets used in this figure are provided in Supplementary Table 1.

ocean profiles only since 2004 (ref. 7), and even now, few ocean profiles are obtained within the sea-ice zone.

Antarctic annual mean climate trends over the 1979–2014 interval covered by satellite observations (Fig. 1; see Supplementary Fig. 1 for location map) are dominated by statistically significant ($p < 0.05$) linear trends indicating: (1) an intensification of the mid-latitude westerly winds related to an increasing SAM index; (2) an overall sea surface temperature (SST) cooling, except in the southeast Indian Ocean sector, and in the Weddell, Bellingshausen and Amundsen Seas¹⁷ (not visible in Fig. 1 owing to sea-ice shading); (3) an overall expansion of sea ice, underpinned by a large increase in the Ross Sea sector, but partly offset by large decreases in the Amundsen–Bellingshausen sector, around the Antarctic Peninsula, and in the southeast Indian Ocean; (4) a strong surface air warming over the West Antarctic Ice Sheet (WAIS) and Antarctic Peninsula regions; and (5) surface air cooling above Adélie Land in East Antarctica. The surface air temperature (SAT) records from individual stations (inset panels in Fig. 1) demonstrate how considerable interannual to decadal variability underlies these long-term trends. In many cases, the annual-mean trends arise from strong trends in specific seasons (Supplementary Fig. 2).

Time series of summer anomalies in hemispherically averaged SST, zonal wind and sea-ice extent exhibit consistent multi-decadal variability since 1950 (ref. 17), suggesting that recent changes in multiple variables are strongly coupled. Many of the observed changes in SH high-latitude climate can be related to changes in atmospheric circulation. Strengthening of the westerly winds associated with the positive SAM trend causes spatially coherent changes in SAT over Antarctica¹⁸, and in particular can account for the summer warming over the eastern Antarctic Peninsula^{19,20}. Cooling of the surface ocean and warming of the subsurface ocean^{21–25} throughout the Southern Ocean can also be partly attributed to a westerly wind-forced increase in northward Ekman transport of cold sub-Antarctic surface waters. Summer trends in the SAM are distinct from natural variations²⁶, and are attributed to stratospheric ozone depletion, and the associated stratospheric cooling over Antarctica^{10,27}. In addition, regional atmospheric circulation changes led to warming trends in winter and spring, distinct from the summertime warming associated with the SAM, particularly over the WAIS and the western Antarctic Peninsula during the second half of the twentieth century^{11,28–32}. In the past 10–15 years, however, the rate of warming over the Peninsula has slowed markedly, in all seasons, but most strongly in summer (time series in Supplementary Fig. 2).

Table 1 | Summary of trend emergence analysis.

	50% of models exceeding control trends		90% of models exceeding control trends		Direction
	End year	Trend length (years)	End year	Trend length (years)	
SIE	2031	53	2098	120	Below
SST	2021	43	2056	78	Above
SAT	<2014	<36	2050	72	Above
SAM	2015	37	2044	66	Above

Indicated are the end year (20YY) and trend length (in years) of 1979–20YY linear trends for which (left) 50% and (right) 90% of Historical-RCP8.5 simulated trends in CMIP5 models fall outside the 5–95% distribution (either above 95%, or below 5%) of pre-industrial trends of the same length in the same model.

Regional atmospheric circulation changes are also a potential driver of the recent trends in Antarctic sea ice³³, in particular through the strengthening of the Amundsen Sea Low (ASL)³⁴. Deepening of the ASL is linked to both changes in the SAM³⁵ and to atmospheric teleconnections with the tropical Pacific^{11,29,34,36,37}. The ASL has intensified onshore warm air flow over the Amundsen–Bellingshausen sector, and colder air flow offshore in the Ross Sea sector³⁸. This has contributed to the characteristic dipole of contrasting SAT and sea-ice concentration changes between the Ross Sea and the Amundsen–Bellingshausen/Antarctic Peninsula regions^{11,36,39,40}. An additional mechanism that may partly explain the overall increasing trend in Antarctic sea-ice extent (SIE) involves the increased meltwater input, which has contributed to freshening of the Southern Ocean (for example ref. 41), stabilization of the water column⁴² and thus potentially a reduction of the vertical ocean heat flux, enabling more prevalent sea ice formation^{43,44}.

Changes in SAT, atmospheric and ocean circulation have also affected the ice sheet itself, through surface melting of ice shelves around the Antarctic Peninsula⁴⁵, and melting of ice shelves from below owing to the intrusion of warm circumpolar deep water onto the continental shelf⁴⁶. The importance of the latter process is particularly evident along the margin of the WAIS^{47–49} and is associated with regional atmospheric circulation changes forced by teleconnections from the tropics^{48,50}.

The numerous interconnections between changes in the SH high-latitude atmosphere, ocean and sea-ice systems provide strong feedbacks that can amplify initial perturbations related, for instance, to winds or modifications in the hydrological cycle^{42,51,52}. These connections also demonstrate the need to assess the significance and impacts of SH high-latitude climate changes in a holistic way, using multiple variables.

Historical records and natural archives

To place these recent observed trends into a longer-term context, we compiled observational records of SAT longer than 55 years as well as proxy records for SAT, SST and sea ice, extracted from annually to multi-annually resolved ice and marine sediment cores, spanning the past 200 years (see Supplementary Table 1 for details of the datasets used, and Supplementary Methods for data compilation). Datasets were grouped into four different sectors, which were designed to group observational and proxy records with similar patterns of variability while also working within the constraints of data availability. Our regions comprised three near-coastal zones: (1) the Antarctic Peninsula region including the Bellingshausen and Scotia Seas, (2) the WAIS and the Ross Sea region, and (3) a broad region spanning coastal East Antarctica and incorporating the adjacent oceans and the Weddell Sea. The final region (4) is defined over the inland East Antarctic Plateau above 2,000 m elevation. The separation of coastal from inland regions reflects known differences in atmospheric transport dynamics pathways for weather events that impact inland versus coastal sites in Antarctica⁵³. Figure 2 shows these sectors and the data available for this synthesis, and highlights the paucity of climate information currently available for many parts of Antarctica.

Antarctic Peninsula sector. Of the four sectors, the Antarctic Peninsula has the longest observed SAT record (1903 to present); prior to the late 1940s, SAT is only available from the single Orcadas station, located northeast of the Peninsula itself. Instrumental data, proxy palaeotemperature records (ice cores and a moss bank core) and borehole temperature inversions show that the Antarctic Peninsula warming trend (Fig. 1) is part of a longer-term regional warming trend (Fig. 2a). The correspondence between instrumental and proxy data and between multiple proxy data sources may be stronger here than for any other region, suggesting that this is a robust context for the late twentieth-century temperature trend. The James Ross Island (JRI) ice core suggests that local warming began in the 1920s and has been statistically significant ($p < 0.1$) since the 1940s⁵⁴. Ice cores from the Gomez and Ferrigno sites and a moss bank core demonstrate that the twentieth-century rise in SAT on the northern Peninsula also extends south to the southwest Antarctic Peninsula^{55,56} and was accompanied by increases in snow accumulation^{57,58} and increased biological productivity, suggesting that temperature changes were likely to be year-round. Antarctic Peninsula warming has been related to intensification of the circumpolar westerlies in austral summer and autumn¹⁹, to associated deepening of the ASL, and to central tropical Pacific warming in austral autumn, winter and spring¹¹.

None of the most recent 36-year trends in the proxy SAT records is unprecedented relative to trends of the same length from earlier portions of the palaeoclimate archives (Supplementary Methods; Supplementary Fig. 3a). The most recent 100-year trends do exceed the upper 95% level of all earlier 100-year trends in three of the Antarctic Peninsula ice-core isotope records (JRI, Gomez and Ferrigno; Supplementary Fig. 3c); for the JRI core the most recent 100-year warming trend falls within the upper 0.3% of the distribution of all 100-year trends over the past 2,000 years^{54,59}.

Two marine SST proxy records from the northern Antarctic Peninsula show a warming trend over the twentieth century that was most prominent over roughly the 1920s to 1950s (Fig. 2a). A cooling trend in the most recent decades of the proxy stack appears to be of similar magnitude to earlier episodes of decadal-scale variability. In this sector, sea-ice information is derived from one historical record, three ice-core chemical records⁶⁰ and two marine diatom records spanning the Bellingshausen Sea and Scotia Sea/northern Weddell Sea. They depict a regionally coherent sea-ice decrease from the 1920s to the 1950s, coincident with proxy evidence for SST increases. The proxy composite does not clearly capture the Bellingshausen sea-ice decline observed by satellites since 1979, although individual studies have demonstrated that this recent observed decline is embedded within a longer-term decreasing trend that persisted through the twentieth century and was strongest at mid-century^{61,62}.

West Antarctica. In West Antarctica, SAT observations^{28,30}, a borehole temperature profile^{63,64} and ice-core water stable isotope records⁶⁵ all depict a consistent, statistically significant warming trend beginning in the 1950s. These trends are greatest in winter

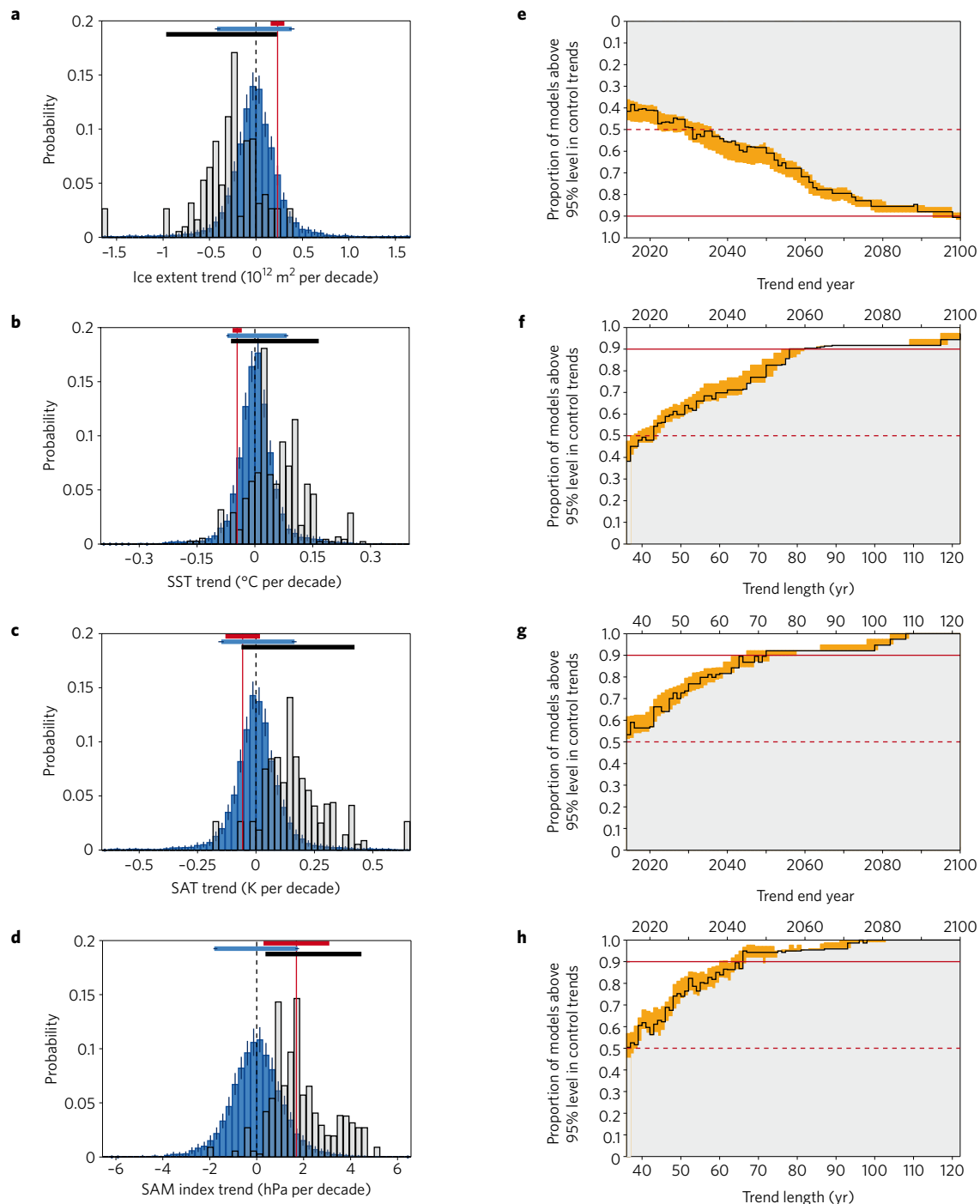


Figure 3 | Antarctic climate trends in CMIP5 simulations. a–d, Distributions of (blue) 36-year linear trends in an ensemble of CMIP5 pre-industrial simulations and (black/grey) 1979–2014 trends in an ensemble of CMIP5 historical (1979–2005)–RCP8.5 (2006–2014) simulations (see Supplementary Methods). Red vertical lines correspond to observed 36-year linear trends (1979–2014). Horizontal bars depict (red) the 90% confidence interval of the observed trend, (blue) the 5–95% range of the simulated pre-industrial distribution and (black) the 5–95% range of the simulated 1979–2014 trend distribution. The dark blue error bars on the pre-industrial histograms and horizontal ranges are 5–95% uncertainty intervals based on Monte Carlo analysis (see Methods). **e–h,** Proportion of CMIP5 model experiments whose linear trends starting in 1979 are above the 95% level (below the 5% level for panel **e**) of the distribution of trends of the same length in their matching control simulation. Simulations follow the RCP8.5 scenario after year 2005. Dashed and solid red lines highlight the 50% and 90% levels of the cumulative distributions (Table 1). The orange bars are 5–95% uncertainty ranges based on Monte Carlo analysis of equal length segments from the pre-industrial simulations (see Methods). Chosen climate variables are Southern Hemisphere sea-ice extent (**a,e**), mean SST south of 50° S (**b,f**), mean SAT south of 50° S (**c,g**) and SAM index (**d,h**). Model details are given in Supplementary Table 2. Observations used to compute observed sea-ice extent and SST trends over the 1979–2014 period are referenced in Fig. 1. The observed 1979–2014 SAT trend is derived from ERA-Interim 2-m air temperature fields. Modelled and observed SAM indices were calculated from annual mean time series using empirical orthogonal function analysis applied on 500-hPa geopotential height fields over the 90° S to 20° S region, with observation-based geopotential height fields taken from the ERA-Interim reanalysis.

and spring, and closely associated with the rapid decline in sea ice observed in the Amundsen–Bellingshausen Seas^{40,65,66}. The annual mean SAT trend over West Antarctica may be among the most rapid warming trends of the past few decades anywhere on Earth (2.2 ± 1.3 °C increase during 1958–2010 at Byrd Station, mostly owing to changes in austral winter and spring)^{30,67}. Nevertheless, the natural decadal variability in this region is also large, owing to the strong variability of the ASL⁶⁸, amplified by teleconnections with the tropical Pacific also during winter and spring^{11,29,69}. This differs markedly from the situation on the Antarctic Peninsula, where the summertime trends occur against a background of relatively small interannual variability³¹. As a consequence, the large recent trends cannot yet be demonstrated to be outside the range of natural variability (see, for example, 100-year trend analysis in Supplementary Fig. 3c). An analysis of more than 20 ice-core records from West Antarctica⁶⁵ concluded that the most recent decades were probably the warmest in the past 200 years, but with low confidence because of a similar-magnitude warming event during the 1940s associated with the major 1939–1942 El Niño event⁷⁰.

At present, no high-resolution reconstructions of SST or SIE are available for the Amundsen–Ross Sea sector to give context to the observed satellite-era trends there.

Coastal East Antarctica. No recent multi-decadal trend emerges from the compilation of SAT observations and proxy records in coastal East Antarctica. Recent fluctuations lie within the decadal variability documented from ice-core water isotope records, and recent 36-year and 100-year trends remain within the 5–95% range of earlier trends within each record (Supplementary Fig. 3a,c). The only available long-term borehole temperature reconstruction suggests a recent warming trend. This apparent contradiction may arise from spatial gradients and differences in recent temperature trends (for example Fig. 1) across this geographically extensive but data-sparse sector. Indeed, only seven meteorological stations, two ice-core water isotope records of sufficient resolution (see Supplementary Methods) and one 100-year borehole profile occupy a longitudinal region spanning 150° E to 40° W (Fig. 2a). Networks of isotope records from shallow ice cores (not compiled in this study owing to their limited temporal coverage) do provide evidence for a statistically significant increasing SAT trend in the past 30–60 years over the Fimbul Ice Shelf, East Antarctica⁷¹ and over Dronning Maud Land⁷², despite no observed warming at the nearby Neumayer station^{71,72}.

The single SST proxy record available from off the coast of Adélie Land⁷³ (Fig. 2) shows a strong increase post-1975, and, despite considerable decadal variability, the final 36-year trend exceeds the 95% range of trends in the full record (Supplementary Fig. 3a,c). Satellite observations, showing a regional SIE increase across this sector since 1979, are not mirrored by proxy records, which suggest an overall sea-ice decline since the 1950s⁷⁴, overlaid by strong decadal variability (Fig. 2). This also highlights the challenges in interpretation of sea-ice proxies, which can be sensitive to variations in sea-ice thickness, duration or local dynamics. For example, near the Mertz glacier, sea-ice proxy records spanning the past 250 years depict large multi-decadal variations that are attributed to iceberg calving events and are comparable to, or larger than, the most recent 36-year or 100-year trends⁷³ (Supplementary Fig. 3b,c).

East Antarctic Plateau. The stable isotope records for the East Antarctic Plateau do not show statistically significant trends in the final 36 years of their record (Supplementary Fig. 3a), unlike the observed SAT for the region (Fig. 1 inset b). Comparison of Figs 1 and 2 indicates that the stable water isotope records for the East Antarctic Plateau come from locations spanning differing temperature trends in Fig. 1. The Plateau Remote core on the central plateau is characterized by large decadal variability, and the most

recent 100-year trend remains well within the 5–95% range of earlier trends. Towards the margins of the East Antarctic Plateau, the EDML and Talos Dome ice cores display recent 100-year warming and cooling trends, respectively, that are significant with respect to earlier 100-year trends in these cores (Supplementary Fig. 3c). Temperature records from borehole inversions⁷⁵, which cannot resolve decadal variability, also show evidence for modest temperature increases on the Dronning Maud Land side of the East Antarctic Plateau during the late twentieth century, with warming apparently beginning earlier closer to the coast. The differing characteristics of long-term temperature variability and trends at sites across the Antarctic Plateau again highlight the importance of increasing the spatial coverage of proxy records from this data-sparse region.

The Southern Annular Mode. The history of the SAM over the past 200 years has been assessed in a number of previous reconstructions using syntheses of station observations^{26,76,77} and palaeoclimate networks^{18,78,79} (not shown). Reconstructions from station data display strong decadal variability and season-specific trends. The summer SAM exhibits the strongest post-1960s trend, which is assessed as unusual compared with trends in the earlier part of the century²⁶. A summer SAM index reconstructed from mid-latitude tree rings also indicates that the recent positive phase of the SAM is unprecedented in the context of at least the past 600 years⁷⁹. Similarly, an annual average SAM index reconstruction based on a network of temperature-sensitive palaeoclimate records spanning Antarctica and southern South America indicates that the SAM is currently in its most positive state over at least the past 1,000 years¹⁸. SAM index reconstructions display a steady⁷⁹ or declining¹⁸ SAM index since the early 1800s, reaching a minimum in the early to mid-twentieth century^{18,79}, before commencement of the positive SAM trend that is seen in observations (Fig. 1).

Simulated Antarctic climate trends and variability

The satellite observations and longer historical and proxy-based climate records reviewed in preceding sections reveal significant regional and seasonal climatic trends of both positive and negative signs and with a range of amplitudes, together with substantial decadal to centennial variability in the high-latitude SH. To further assess whether recent climate variations may be attributed to externally forced changes, or can be explained by unforced multi-decadal variability, we now examine statistics of 36-year trends in model simulations from CMIP5¹² and compare these to observed trends over the 1979–2014 period.

Trend distributions from pre-industrial control simulations provide an estimate of internally generated variability under fixed external forcing. The CMIP5 climate models display large internal multi-decadal variability in the high southern latitudes (Fig. 3), with satellite-era observational trends remaining within the 5–95% range of simulated internal variability for the annual means of all four examined variables — SIE, SST, SAT and the SAM index (Fig. 3a–d). Based on this comparison, the null hypothesis stating that the observed 1979–2014 trends are explained by internal climate system variability alone cannot be rejected at the 90% confidence level, with the underlying assumption that the simulated multi-decadal variability is of the correct magnitude. But a seasonal breakdown of observed and simulated trends reveals that observed SAM trends in summer and autumn exceed the 95% level of control variability (Supplementary Fig. 5), consistent with a dominant role of stratospheric ozone depletion in the recent shift toward positive SAM^{10,27}. The summer SAT trend also stands out as anomalously negative against the modelled pre-industrial variability (Supplementary Fig. 5).

In order to estimate the combined influence of the intrinsic variability of the SH climate system and the response to known historical (natural and anthropogenic) forcings, we next compare

statistics of modelled 1979–2014 trends in externally forced simulations against observations (see Supplementary Methods). With this measure of multi-model variability, the observed trends in SIE, SST and SAT appear only marginally consistent with the CMIP5 ensemble of simulated trajectories (Fig. 3a–c), in agreement with previous analyses^{44,80,81}. For instance, only 15% of model simulations exhibit sea-ice expansion over 1979–2014, and only 3% a larger SIE increase than that observed by satellites. Similarly, only 8% of models predict a negative trend in average SAT south of 50° S. In contrast, the likelihood of positive trends in the SAM index is increased in the externally forced simulations relative to unforced simulations, resulting in an improved agreement with the observed SAM trend (Fig. 3d).

Thus the statistics of 36-year trends are consistent with the hypothesis that anthropogenic forcing contributes to the recent positive SAM trend. Our comparisons also highlight the mismatch between CMIP5 historical simulations and observed recent trends in SIE and surface temperatures. We suggest that internal variability alone is unlikely to be sufficient to explain this mismatch. Indeed, the recent observed expansion of Antarctic sea ice and average surface cooling south of 50° S stand out as rare events when benchmarked against the ensemble of simulated trends for the 1979–2014 period (Fig. 3a–c).

Deficiencies in the model representation of SH climate are likely contributors to the disagreement between observations and forced climate simulations^{82,83}. Inaccurate or missing Earth system feedbacks in the CMIP5 simulations, such as the absence of the freshwater input due to ice-sheet mass loss, and unresolved physical processes, related to sea-ice rheology, thin ice properties, stratospheric processes, katabatic winds, ocean–ice shelf interactions and sub-grid-scale ocean processes, can bias both the simulated internal variability and the model response to external forcing. For example, subsurface ocean warming around Antarctica in response to strengthening of the SH westerly winds has been found to occur at twice the magnitude in a high-resolution ocean model compared with coarser CMIP5 simulations²². Comparisons of CMIP5 last-millennium simulations against palaeoclimate data have also shown deficiencies in the SH, indicating that CMIP5 models may underestimate the magnitude of unforced variability in the SH or overestimate the SH climate response to external forcing⁸⁴. Understanding the missing processes and the relationships between these processes and model skill will be crucial for future model developments in order to improve the model ability to simulate variability of the SH high-latitude climate and its response to forcing.

Within these limitations in the representation of SH high-latitude climate in the current generation of climate models, the available CMIP5 model output suggests that the observed and simulated 36-year (1979–2014) trends are not large enough to determine whether they are externally forced or merely a reflection of internal variability (Fig. 3a–d). Similarly, the most recent 36-year trends in the palaeoclimate records reviewed here are also too short to be considered unusual relative to the range of earlier 36-year trends in the past 200 years (Supplementary Fig. 3).

We further explore this by calculating the required duration of anthropogenically driven trends under the RCP8.5 scenario for SH high-latitude climate variables to emerge as statistically distinct from pre-industrial control variability. In a perfect model framework, this could be understood as estimating how long SH observations may need to be sustained before ongoing trends can be definitively attributed to anthropogenic climate change (Fig. 3e–h and Table 1).

For each model and variable, we assess whether the simulated trend starting in 1979 falls outside the matching 5–95% range of pre-industrial variability, and we calculate trends with lengths between 36 years (1979–2014) and 122 years (1979–2100). Our analysis reveals that, in 2015, over half of the models already simulate ‘unusual’ post-1979 trends in SAT and the SAM. For SST, 50%

of models have linear trends that emerge above unforced variability by 2021 (43-year trends), and for SIE the majority of CMIP5 models do not display trends emerging above the 95% significance level (relative to the pre-industrial distribution) until 2031 (that is, 53-year trends). For a trend emergence threshold of more than 90% of all CMIP5 models, trends do not emerge until between 2044 (66-year trends for SAM) and 2098 (120-year trends for SIE). Our results for the time of emergence of linear trends are in agreement with an earlier assessment using a different methodology⁸⁵, suggesting that the mid to high SH latitudes are among the last regions where the signal of anthropogenic forcing will be large enough to differentiate it from the range of natural variability. These CMIP5-based estimates may in fact underestimate the true length of time required for statistically distinct trends to emerge, if CMIP5 models underestimate the magnitude of internal variability or overestimate the forced climate response. Hence, notwithstanding known limitations in CMIP5 models, our analysis suggests that 36 years of observations are simply insufficient to interrogate and attribute trends in SH high-latitude surface climate.

Discussion

Climate change and variability over the high latitudes of the SH are characterized by strong regional and seasonal contrasts for all the variables investigated here. This is valid at interannual to decadal timescales, as illustrated in instrumental observations, as well as on longer timescales, as indicated in proxy-based reconstructions. The most unequivocal large-scale change over recent decades is the increase of the SAM index¹⁹ and the freshening and subsurface warming of the ocean^{23,24,41}. Regionally, a large warming has been observed over the Antarctic Peninsula and West Antarctic regions across the past 50 years. SIE has decreased in the Amundsen–Bellingshausen Seas while it has increased in the Ross Sea sector since 1979.

The large multi-decadal variations seen in high-resolution proxy-based reconstructions of temperature and SIE also have clear regional contrasts. Some estimates suggest common signals over the whole Southern Ocean, such as the decrease of the ice extent between the 1950s and the late 1970s deduced from whaling records (for example refs 86–88), but this remains to be confirmed by the analysis of additional observations. The longer records independently support the conclusion that most of the recent changes for any single variable largely result from natural variability and are not unprecedented over the past two centuries. This is consistent with results from state-of-the-art climate models showing that, except for the SAM index, most recent changes remain in the range of large-scale simulated internal variability. When analysing specifically the 1979–2014 period, including forced changes and internal variability, models struggle to track the observed trends in SST, SAT and sea-ice cover. This suggests either that a singular event associated with internal variability has been able to overwhelm the forced response in observations, or that CMIP5 models overestimate the forced response (potentially partly because of key processes missing in the models), or a combination of both.

Recent observations and process understanding of the atmosphere, sea ice, ocean and ice sheets suggest strong coupling, which means that investigations need to encompass and understand the dynamics of the whole climate system. Statistics independently applied to a few large-scale metrics may not allow a robust comparison between observed and simulated trends. Regional and seasonal complexity⁸⁹ as well as physical relationships between different climate variables must be taken into account to evaluate the overall consistency of observed and modelled time-evolving climate states, and to identify caveats. We advocate process-oriented studies in which the primary mechanisms behind modelled behaviour are identified and their plausibility evaluated against available observations and theory.

In particular, the accelerating melting and calving of Antarctic ice shelves^{46,90,91} could have a pronounced influence on the recent and future evolution of the high-latitude Southern Ocean^{41,43,92–94}. Understanding and quantifying the role of changing glacial discharge in past and ongoing climatic trends is an important unresolved question requiring attention.

To improve the sampling of forced and natural variability for the recent period, we also emphasize the importance of considering multiple models, as well as multiple realizations of different models. In this sense, large ensembles, such as those recently released by some modelling groups⁹⁵, are particularly useful for improving estimates of internal variability compared with forced signals.

Atmospheric reanalyses are strongly dependent on the prescribed surface boundary conditions that are particularly uncertain before the 1970s in the Southern Ocean⁹⁶ and therefore have limited skills prior to the satellite era. Alternative approaches involve assimilation methods using proxy records and climate simulations in order to best reconstruct the past state of the Antarctic atmospheric circulation. Coupled ocean–sea-ice–atmosphere reanalysis⁹⁷, with specific attention to the high latitudes of the Southern Ocean, should thus be a target for the future. Preliminary studies have demonstrated the feasibility of this approach for ensuring the consistency between the various components of the system and the study of their interactions⁹⁸.

Our synthesis has emphasized that less than 40 years of instrumental climate data is insufficient to characterize the variability of the high southern latitudes or to robustly identify an anthropogenic contribution, except for the changes in the SAM. Although temperature changes over 1950–2008 from the average of individual stations have been attributed to anthropogenic causes⁹⁹, only low confidence can be assigned, owing to observational uncertainties¹⁰⁰ and large-scale decadal and multi-decadal variability. Detection and attribution studies depend on the validity of estimates of natural variability from climate model simulations. This is particularly the case for variables such as Antarctic sea ice, which have problematic representation in climate models³⁶ and short observational time series from which to estimate real multi-decadal variability. The strong regional variability on all timescales implies that the sparsity of observations and proxy data is a clear limitation, especially in the ocean, and that averaging climate properties over the entire Antarctic or Southern Ocean potentially aliases the regional differences.

The Antarctic climate system is strongly coupled, and future investigations need to combine information from different climate variables to identify the causes and mechanisms driving SH high-latitude climate variations. Process studies are essential to this task, along with a continued effort to maintain current observations from stations and satellites, and to expand the observational network in undocumented areas. The rescue of historical data is also critical to obtain a longer perspective. New high-resolution proxy data should be collected, both by expanding existing data types (for example lake sediments and deep-sea sediments) and by investing in new records such as moss banks. Improved spatial coverage of ice-core records and a requirement for a minimum suite of information from these archives (for example accumulation, water isotopes, borehole temperatures) are desirable, together with multiple records allowing improvement of the signal-to-noise ratio. Improved calibration of these proxy records (for example, water stable isotopes against temperature) is critical for the uncertainties associated with past temperature reconstructions. Progress is expected from the use of historical data, but also through improved proxy modelling, for example by incorporating water stable isotopes in high-resolution atmospheric models and quantifying post-deposition effects. Not least important is the use of nonlinear statistical analysis tools to improve the statistical analysis of observations and proxy data as well as model output evaluation. Gathering, utilizing, combining and improving the interpretation of data from all available sources

are imperative to understand recent climate changes in this data-sparse, but climatically important, region.

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Author contributions

All authors conceived the paper. J.M.J., H.G. and S.T.G. organized the contributions to the manuscript, and contributed to writing and editing the manuscript. Observational data: G.R.S. undertook data analysis and figure preparation (Fig. 1 and Supplementary Fig. 2), which included contributions from M.H.E., E.J.S. and G.J.M.; M.H.E., G.R.S., J.A.R., R.L.F., M.N.R., G.J.M., D.P.S., I.E., P.O.C. and K.R.C. all contributed to discussions of analysis design, and to writing and revising the Antarctic climate monitoring section, and associated methods. Palaeoclimate and historical data: N.J.A. undertook the data compilation, with data contributions from B.S., A.J.O., X.C., P.O.C. and D.J.C. N.J.A. and T.R.V. prepared the figures (Fig. 2 and Supplementary Figs 3 and 4). T.R.V., N.J.A., P.O.C., D.J.C., X.C., V.M.D., A.J.O., E.J.S. and B.S. all contributed to discussions of analysis design, and to writing and revising the section on historical records and natural archives, and associated methods. Climate simulations: D.S. undertook coordination, D.S., C.d.L., N.J.A., A.K.M. and L.M.F. undertook data analysis, and C.d.L. and N.J.A. prepared the figures (Fig. 3 and Supplementary Fig. 5). D.S., N.J.A., M.H.E., L.M.F., C.d.L. and A.K.M. all contributed to discussions of analysis design, and to writing and revising the section on simulated Antarctic climate trends and variability, and associated methods. All authors reviewed the full manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.