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Assessing recent trends in high-latitude Southern Hemisphere surface climate

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Preface

In southern high latitudes, satellite records document regional climate changes during the last few decades (since 1979). For many variables, the satellite-derived trends are not consistent with output from the suite of current climate models over the same period (1979-2015). The recent climate variations are compared with a synthesis of instrumental and palaeoclimate records spanning the last 200 years, which document large pre-satellite Antarctic climate fluctuations. We conclude that the available 36-years of satellite-derived observations are generally not yet long enough to distinguish forced trends from natural variability in the high-latitude Southern Hemisphere.

Abstract

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. However, most observed trends are not unusual when compared with Antarctic paleoclimate 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 likely 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.

1. Introduction

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 rise[1], and its response to climate change is a major source of uncertainty for future projections[2,3]. The Southern Ocean is important for its ability to uptake heat and carbon dioxide, and thereby mitigate human-induced atmospheric temperature and CO_2 rise[4,5,6,7,8]. 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 impacts various aspects of Antarctic climate and controls the timing and distribution of rainfall received by the mid-latitude SH continents[10]. 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. However, the brevity and sparse distribution of observational records pose major 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 satellite information (1979-2014) and Antarctic station observations. These are compared with trends and multi-decadal variability from palaeoclimate data spanning the last 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 focussed research will improve understanding of the contribution of SH high latitudes to global climate variability and change.

2. Antarctic climate monitoring

Coordinated international efforts to monitor Antarctic climate began in the International Geophysical Year of 1957/58. However, few climate measurements are available over vast areas of the continent and the adjacent ice-shelves, sea ice and oceans. The advent of routine satellite sounder observations in 1979 revolutionised knowledge of climate over Antarctica and the surrounding oceans, although uncertainties remain due to satellite sensor changes[13]. More uncertain early satellite sea ice estimates extend back to 1972[14], with ongoing recovery of ice edge information for the 1964-1972 period[15,16]. Knowledge of recent sub-surface ocean trends remains more limited. The Argo profiling float program and conductivity-temperature-depth tags mounted on elephant seals have provided substantial numbers of subsurface ocean profiles only since 2004[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 Seas[17] (not visible in Fig. 1 due 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 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[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 surface air temperature over Antarctica[18], 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[21,22,23,24,25] throughout the Southern Ocean can also be partly attributed to a westerly wind-forced increase in northward Ekman transport of cold subantarctic surface waters. Summer trends in the SAM are distinct from natural variations[26], 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 West Antarctic Ice Sheet (WAIS) and the western Antarctic Peninsula during the second half of the Twentieth Century[11,28,29,30,31,32]. However, in the last 10-15 years the rate of warming over the Peninsula has slowed markedly, in all seasons, but most strongly in summer (time series in Supplementary Fig. 2).

Regional atmospheric circulation changes are also a potential driver of the recent trends in Antarctic sea ice[33], in particular through the strengthening of the Amundsen Sea Low (ASL)[34]. Deepening of the ASL is linked to both changes in the SAM[35] 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 sector[38]. 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 (e.g.[41]), stabilization of the water column[42] 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 Peninsula[45], and melting of ice shelves from below owing to the intrusion of warm circumpolar deep water onto the continental shelf[46]. The importance of the latter process is particularly evident along the margin of the WAIS[47,48,49] 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-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.

3. 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 last 200 years (see Supplementary Table 1 for details of the datasets used, and 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 are comprised of three near-coastal zones spanning: (1) the Antarctic Peninsula region including the Bellingshausen and Scotia Seas, (2) the West Antarctic Ice Sheet 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 is defined over the inland East Antarctic Plateau above 2000 m elevation (4). 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 Antarctica[53]. Fig. 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.

3.1. Antarctic Peninsula sector

Of the four sectors, the Antarctic Peninsula has the longest observed SAT record (1903-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 this is a robust context for the late 20th 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 1940s[54]. Ice cores from the Gomez and Ferrigno sites and a moss bank core demonstrate that the 20th 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 temperature changes were likely year-round. Antarctic Peninsula warming has been related to intensification of the circumpolar westerlies in austral summer and autumn[19], associated deepening of the Amundsen Sea Low, and to central tropical Pacific warming in austral autumn, winter and spring[11].

None of the most recent 36-year trends in the proxy SAT records are unprecedented relative to trends of the same length from earlier portions of the palaeoclimate archives (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 last 2000 years[54,59].

Two marine SST proxy records from the northern Antarctic Peninsula show a warming trend over the 20th century that was most prominent over 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 records[60] 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 sea-ice decline is embedded within a longer-term decreasing trend that persisted through the 20th century and was strongest at mid-century[61,62].

3.2. West Antarctica

In West Antarctica, SAT observations[28,30], a borehole temperature profile[63,64], and ice core water stable isotope records[65] all depict a consistent, statistically significant warming trend beginning in the 1950s. These trends are greatest in winter 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 last few decades anywhere on Earth (2.2±1.3°C increase during 1958-2010 at Byrd Station, mostly due 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 ASL[68], 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 inter-annual variability[31]. As a consequence, the large recent trends cannot yet be demonstrated to be outside the range of natural variability (e.g. 100-year trend analysis in Supplementary Fig. 3c). An analysis of more than twenty ice core records from West Antarctica[65] concluded that the most recent decades were likely the warmest in the last 200 years, but with low confidence because of a similar-magnitude warming event during the 1940s associated with the major 1939-1942 El Niño event[70].

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.

3.3. 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 (e.g. 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 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 due 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 Antarctica[71] and over Dronning Maud Land[72], despite no observed warming at the nearby Neumayer station[71,72].

The single SST proxy record available from off the coast of Adélie Land[73] (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 1950s[74], 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 trends[73] (Supplementary Fig. 3b-c).

3.4. 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 Figure 3a), unlike the observed SAT for the region (Fig. 1 inset b). Comparison of Figs. 1 and 2 indicates that the East Antarctic Plateau stable water isotope records come from locations spanning differing temperature trends in Fig. 1. The Plateau Remote core on the central Plateau is characterised 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 inversions[75], 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 20th 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.

3.5. The Southern Annular Mode

The history of the SAM over the last 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 to trends in the earlier part of the century[26]. 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 years[79]. 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 last 1000 years[18]. SAM index reconstructions display a steady[79] or declining[18] SAM index since the early 1800s, reaching a minimum in the early to mid-20th century[18,79], before commencement of the positive SAM trend that is seen in observations (Fig. 1).

4. 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 multidecadal variability, we now examine statistics of 36-year trends in model simulations from CMIP5[12] 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. However, 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 preindustrial 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 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 compared 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^{o}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 simulations[22]. Comparisons of CMIP5 last millennium simulations against palaeoclimate data have also shown deficiencies in the SH, suggesting that CMIP5 models may underestimate the magnitude of unforced variability in the SH or overestimate the SH climate response to external forcing[84]. 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 last 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 on-going 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 of the matching 5-95% range of preindustrial 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 preindustrial distribution) until 2031 (i.e. 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 methodology[85], suggesting that the mid to high SH latitudes are among the last regions where the signal of anthropogenic forcing will be sufficiently large 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.

5. 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 time scales, as indicated in proxy-based reconstructions. The most unequivocal large-scale change over recent decades is the increase of the SAM index[19] 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 last 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 (e.g.[86,87,88]), 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 that either 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 due to 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 complexity[89] 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 on-going 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 groups[95], 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 Ocean[96] 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 reanalysis[97], 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 interactions[98].

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 causes[99], only low confidence can be assigned due to observational uncertainties[100] and large-scale decadal and multidecadal 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 models[36] and short observational time series from which to estimate real multi-decadal variability. The strong regional variability on all time scales 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 (e.g. 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 (e.g. 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 (e.g. 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 non-linear statistical analysis tools to improve the statistical analysis of observations and proxy data as well as model output evaluation. Gathering, utilising, 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. JMJ, HG and STG organised the contributions to the manuscript,and contributed to writing and editing the manuscript.

Observational data: GRS undertook data analysis and figure preparation (Fig.1 and Supplementary Fig. 2), which included contributions from MHE, EJS and GJM. MHE, GRS, JAR, RLF, MNR, GJM, DPS, IE, POC, and KRC all contributed to discussions of analysis design, and to writing and revising Section 2 and associated methods.

Paleoclimate and historical data: NJA undertook the data compilation, with data contributions from BS, AJO, XC, POC, and DJC. NJA and TRV prepared the figures (Fig. 2 and Supplementary Figures 3 and 4). TRV, NJA, POC, DJC, XC, VMD, AJO, EJS, and BS all contributed to discussions of analysis design, and to writing and revising Section 3 and associated methods.

Climate simulations: DS undertook coordination, DS, CdL, NJA, AKM and LMF undertook data analysis, and CdL and NJA prepared the figures (Fig. 3 and Supplementary Fig. 5). DS, NJA, MHE, LMF, CdL and AKM all contributed to discussions of analysis design, and to writing and revising Section 4 and associated methods.

All authors reviewed the full manuscript.

Competing financial interests

The authors declare no competing financial interests.

Materials and Correpondence

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Tables

	50% of models exceeding control trends		**90% of models exceeding control trends**		
	end year	**trend length (y)**	**end year**	**trend length (y)**	**direction**
SIE	2031	53	2098	120	below
SST	2021	43	2056	78	above
SAT	<2014	<36	2050	72	above
SAM	2015	37	2044	66	above

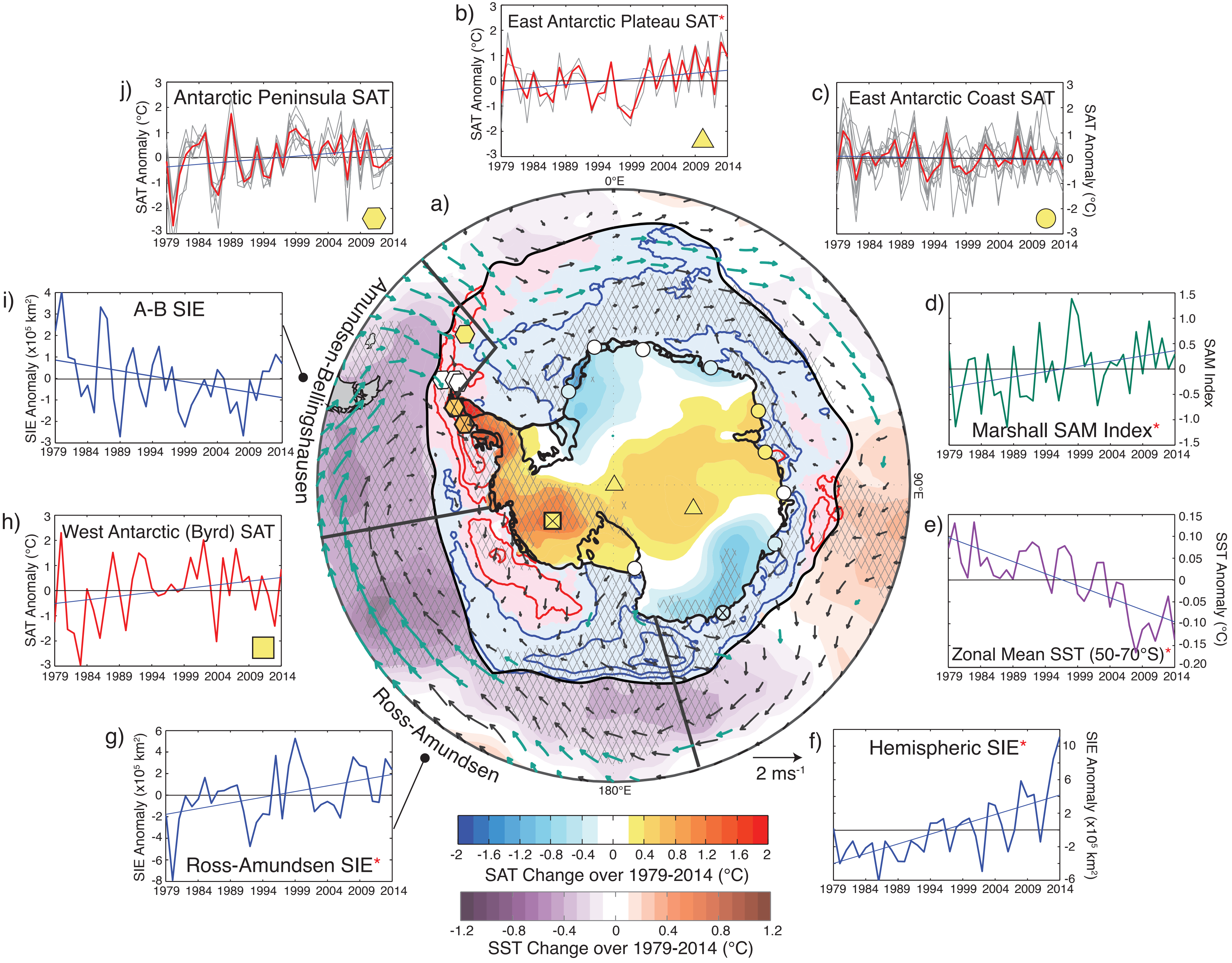
Table 1: Summary of trend emergence analysis. Indicated are the end year (20YY) and trend length (in years) of 1979-20YY linear trends for which (left) 50% and (right) 90% of Historical-RCP8.5 simulated trends in CMIP5 models fall outside the 5-95% distribution (either above 95%, or below 5%) of pre-industrial trends of the same length in the same model.

Figure Legends

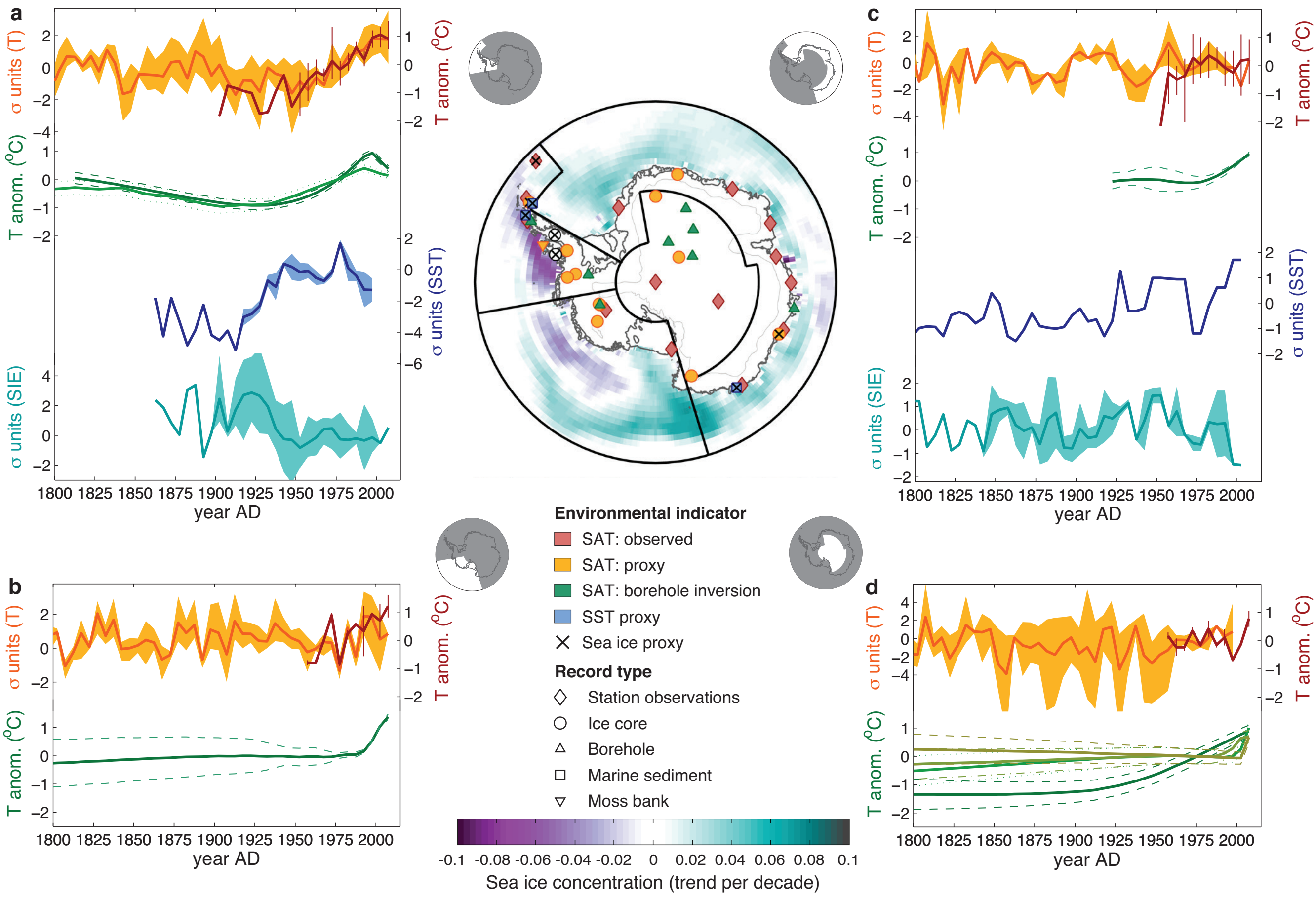
Figure 1 | Antarctic atmosphere-ocean-ice changes over the satellite-observing era. a) Total changes over 1979-2014 in annual mean surface air temperature (blue-red shading), station-based surface air temperature (SAT, blue-red shaded shapes), sea-ice concentration (contours, 10% intervals; red and blue contours, alongside light pink and blue shading beneath, denote negative and positive trends, respectively), sea surface temperature (SST, purple-red shading), and 10m 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 t-tests. Note that SAT trends are calculated over 1979-2012 but scaled to represent trends over the 36-year period, 1979-2014. Surrounding figures show time-series of **b)** East Antarctic SAT (circles; red line denotes multi-station mean, grey lines those of individual East Antarctic stations), **c)** the Marshall Southern Annular Mode index (difference in station sea level pressure between 40° and 65°S), **d)** Southern Ocean zonal mean SST (averaged over 50°–70°S), **e)** Southern Hemisphere SIE, **f)** Ross-Amundsen SIE, **g)** West Antarctic SAT (square; Byrd Station), **h)** Amundsen-Bellingshausen SIE , and **i)** Antarctic Peninsula SAT (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 asterisk where the trend is significant at the 95% level according to a two-tailed student t-test. See methods for details on datasets and trend significance calculation.

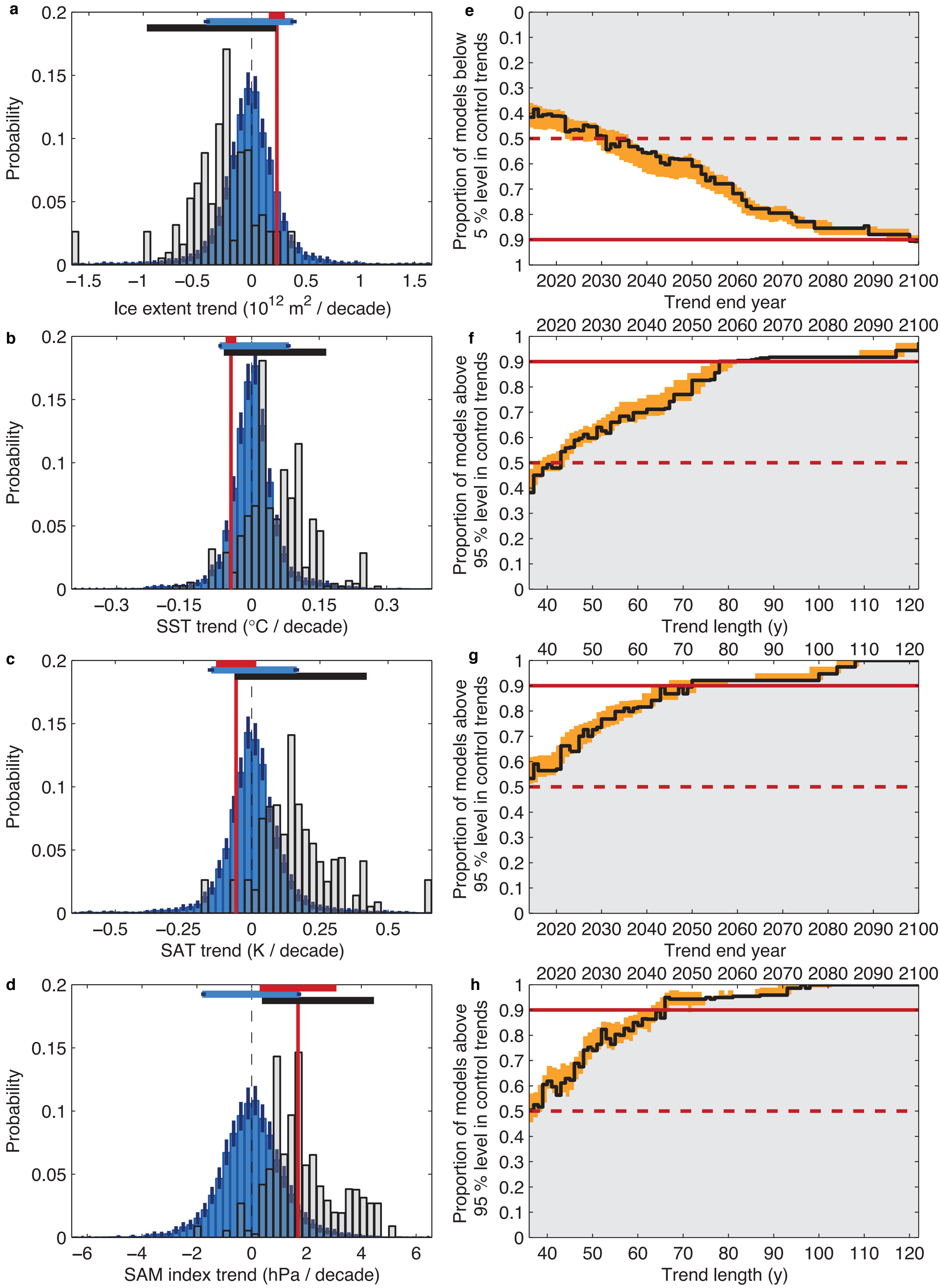
<u>Figure 2 |</u> Antarctic climate variability and trends over the last 200 years from long observational and proxy-derived indicators. Records were regionally compiled for (a) the Antarctic Peninsula, (b) West Antarctica, (c) coastal East Antarctica and (d) the Antarctic Plateau (Methods). Central 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 2000m 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 (or thin vertical lines) denote range of estimates across records within each 5-year bin, with the exception of borehole temperature inversions. All records are expressed as anomalies (^{o}C units) or normalised data (σ units) relative to 1960-1990. With the exception of borehole temperature records which are are shown individually with uncertainty bounds (see Supplementary Figure 4 for additional details). Details of datasets used in this figure are provided in Supplementary Table 1.

<u>Figure 3 |</u> Antarctic climate trends in CMIP5 simulations. (a-d) Distributions of (blue) 36-year linear trends in an ensemble of CMIP5 preindustrial simulations and (black/grey) 1979-2014 trends in an ensemble of CMIP5 historical (1979-2005)-RCP8.5 (2006-2014) simulations (see 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 preindustrial 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 preindustrial simulations (see Methods). Chosen climate variables are **(a, e)** Southern Hemisphere sea-ice extent, **(b, f)** mean SST south of 50°S, **(c, g)** mean SAT south of 50°S and **(d, h)** SAM index. Model details given in Supplementary Table 2. Observations used to compute observed sea ice extent and SST trends over the 1979-2014 period are referenced in Figure 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-20°S region, with observation-based geopotential height fields taken from the ERA-Interim reanalysis.



b) East Antarctic Plateau SAT*
SAT Anomaly (°C)
j) Antarctic Peninsula SAT
c) East Antarctic Coast SAT
0°E
a)
Amundsen-Bellingshausen
i) A-B SIE
SIE Anomaly (x10⁵ km²)
d) Marshall SAM Index*
SAM Index
90°E
h) West Antarctic (Byrd) SAT
e) Zonal Mean SST (50-70°S)*
SST Anomaly (°C)
Ross-Amundsen
180°E
2 ms⁻¹
g) Ross-Amundsen SIE*
f) Hemispheric SIE*
SAT Change over 1979-2014 (°C)
SST Change over 1979-2014 (°C)
1979 1984 1989 1994 1999 2004 2009 2014


a
b
c
d
σ units (T)
T anom. (°C)
σ units (SST)
σ units (SIE)
year AD
1800 1825 1850 1875 1900 1925 1950 1975 2000
Environmental indicator
SAT: observed
SAT: proxy
SAT: borehole inversion
SST proxy
Sea ice proxy
Record type
Station observations
Ice core
Borehole
Marine sediment
Moss bank
-0.1 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1
Sea ice concentration (trend per decade)



a
b
c
d
e
f
g
h
Probability
Ice extent trend (10^12 m^2 / decade)
SST trend (°C / decade)
SAT trend (K / decade)
SAM index trend (hPa / decade)
Proportion of models below 5 % level in control trends
Proportion of models above 95 % level in control trends
Trend end year
Trend length (y)