

1                   **Assessing recent trends in high-latitude Southern Hemisphere climate**

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51    **Abstract**

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

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66     **1. Introduction**

67           The high latitude of the Southern Hemisphere (SH) is a highly complex and critically  
68        important component of the global climate system that remains poorly understood. The  
69        Antarctic Ice Sheet represents the greatest potential source of global sea level rise<sup>1</sup>, and its  
70        response to climate change is a major source of uncertainty for future projections<sup>2,3</sup>. The  
71        Southern Ocean is important for its ability to uptake heat and carbon dioxide, and thereby  
72        mitigate human-induced atmospheric temperature and CO<sub>2</sub> rise<sup>4,5,6,7,8</sup>. Antarctic sea ice is  
73        important for its role in ocean-atmosphere exchange and provides an important climate  
74        feedback through its influence on albedo and atmospheric and oceanic circulation.

75           The leading mode of atmospheric circulation variability in the SH high latitudes is the  
76        Southern Annular Mode (SAM)<sup>9</sup>. It is a measure of the mid-to-high latitude atmospheric  
77        pressure gradient and reflects the strength and position of the westerly winds that circle  
78        Antarctica. This in turn impacts various aspects of Antarctic climate and controls the timing  
79        and distribution of rainfall received by the mid-latitude SH continents<sup>10</sup>. An almost equally  
80        important aspect of large-scale circulation variability in this region is the mid to high-latitude  
81        response to tropical variability, particularly the El Niño-Southern Oscillation (ENSO)<sup>11</sup>.

82           Over recent decades, multiple changes have been observed in high-latitude SH  
83        climate. However, the brevity and sparse distribution of observational records poses a major  
84        challenge in understanding whether observed changes are anthropogenically forced or  
85        remain within the range of natural climate variability. We can improve our understanding  
86        of SH high latitude climate by combining information from instrumental, satellite,  
87        palaeoclimate and reanalysis data, along with climate model simulations. Here, we provide  
88        an assessment of recent changes in the atmosphere, ocean and sea ice systems of the

89 southern high latitudes (south of 50°S), on timescales from decades to centuries. We  
90 describe SH climate trends using satellite information (1979-2014) and Antarctic station  
91 observations. These are compared with trends and multi-decadal variability from  
92 palaeoclimate data spanning the last 200 years, as well as control and forced climate  
93 simulations from the Fifth Climate Model Intercomparison Project (CMIP5)<sup>12</sup>, to assess  
94 whether recent trends are unusual compared with natural variability. We conclude by  
95 identifying key knowledge gaps where strategically focussed research will improve  
96 understanding of the contribution of SH high latitudes to global climate variability and  
97 change.

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## 99 **2. Antarctic climate monitoring**

100 Coordinated international efforts to monitor Antarctic climate began in the  
101 International Geophysical Year of 1957/58. However, few climate measurements are  
102 available over vast areas of the continent and the adjacent ice-shelves, sea ice and oceans.  
103 The advent of routine satellite sounder observations in 1979 revolutionised knowledge of  
104 climate over Antarctica and the surrounding oceans, although uncertainties remain due to  
105 satellite sensor changes<sup>13</sup>. More uncertain early satellite sea ice estimates extend back to  
106 1972<sup>14</sup>, with ongoing recovery of ice edge information for the 1964-1972 period<sup>15,16</sup>.  
107 Knowledge of recent sub-surface ocean trends remains more limited. The Argo profiling  
108 float program and conductivity-temperature-depth tags mounted on elephant seals have  
109 provided substantial numbers of subsurface ocean profiles only since 2004<sup>7</sup>, and even now,  
110 few ocean profiles are obtained within the sea-ice zone.

111 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<sup>17</sup> (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<sup>17</sup>, 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<sup>18</sup>, and in particular can account for the summer warming over the eastern Antarctic Peninsula<sup>19,20</sup>. Cooling of the surface ocean and warming of the subsurface ocean<sup>21,22,23,24,25</sup> 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

135 variations<sup>26</sup>, and are attributed to stratospheric ozone depletion, and the associated  
136 stratospheric cooling over Antarctica<sup>10,27</sup>. In addition, regional atmospheric circulation  
137 changes led to warming trends in winter and spring, distinct from the summertime warming  
138 associated with the SAM, particularly over the West Antarctic Ice Sheet (WAIS) and the  
139 western Antarctic Peninsula during the second half of the Twentieth Century<sup>11,28,29,30,31,32</sup>.  
140 However, in the last 10-15 years the rate of warming over the Peninsula has slowed  
141 markedly, in all seasons, but most strongly in summer (time series in Supplementary Fig. 2).

142 Regional atmospheric circulation changes are also a potential driver of the recent  
143 trends in Antarctic sea ice<sup>33</sup>, in particular through the strengthening of the Amundsen Sea  
144 Low (ASL)<sup>34</sup>. Deepening of the ASL is linked to both changes in the SAM<sup>35</sup> and to  
145 atmospheric teleconnections with the tropical Pacific<sup>11,29,34,36,37</sup>. The ASL has intensified  
146 onshore warm air flow over the Amundsen-Bellingshausen sector, and colder air flow  
147 offshore in the Ross Sea sector<sup>38</sup>. This has contributed to the characteristic dipole of  
148 contrasting SAT and sea-ice concentration changes between the Ross Sea and the  
149 Amundsen-Bellingshausen/Antarctic Peninsula regions<sup>11,36,39,40</sup>. An additional mechanism  
150 that may partly explain the overall increasing trend in Antarctic sea-ice extent (SIE) involves  
151 the increased meltwater input, which has contributed to freshening of the Southern Ocean  
152 (e.g.<sup>41</sup>), stabilization of the water column<sup>42</sup> and thus potentially a reduction of the vertical  
153 ocean heat flux, enabling more prevalent sea ice formation<sup>43,44</sup>.

154 Changes in SAT, atmospheric and ocean circulation have also affected the ice sheet  
155 itself, through surface melting of ice shelves around the Antarctic Peninsula<sup>45</sup>, and melting  
156 of ice shelves from below owing to the intrusion of warm circumpolar deep water onto the  
157 continental shelf<sup>46</sup>. The importance of the latter process is particularly evident along the

158 margin of the WAIS<sup>47,48,49</sup> and is associated with regional atmospheric circulation changes  
159 forced by teleconnections from the tropics<sup>48,50</sup>.

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

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166

167 **3. Historical records and natural archives**

168 To place these recent observed trends into a longer-term context, we compiled  
169 observational records of SAT longer than 55 years as well as proxy records for SAT, SST and  
170 sea ice, extracted from annually to multi-annually resolved ice and marine sediment cores,  
171 spanning the last 200 years (see Supplementary Table 1 for details of the datasets used, and  
172 Methods for data compilation). Datasets were grouped into four different sectors, which  
173 were designed to group observational and proxy records with similar patterns of variability  
174 while also working within the constraints of data availability. Our regions are comprised of  
175 three near-coastal zones spanning: (1) the Antarctic Peninsula region including the  
176 Bellingshausen and Scotia Seas, (2) the West Antarctic Ice Sheet and the Ross Sea region,  
177 and (3) a broad region spanning coastal East Antarctica and incorporating the adjacent  
178 oceans and the Weddell Sea. The final region is defined over the inland East Antarctic  
179 Plateau above 2000 m elevation (4). The separation of coastal from inland regions reflects  
180 known differences in atmospheric transport dynamics pathways for weather events that

181 impact inland versus coastal sites in Antarctica<sup>53</sup>. Fig. 2 shows these sectors and the data  
182 available for this synthesis, and highlights the paucity of climate information currently  
183 available for many parts of Antarctica.

184

185 **3.1. Antarctic Peninsula sector**

186 Of the four sectors, the Antarctic Peninsula has the longest observed SAT record  
187 (1903-present); prior to the late 1940s, SAT is only available from the single Orcadas station,  
188 located northeast of the Peninsula itself. Instrumental data, proxy palaeotemperature  
189 records (ice cores and a moss bank core), and borehole temperature inversions show that  
190 the Antarctic Peninsula warming trend (Fig. 1) is part of a longer-term regional warming  
191 trend (Fig. 2a). The correspondence between instrumental and proxy data and between  
192 multiple proxy data sources may be stronger here than for any other region, suggesting this  
193 is a robust context for the late 20<sup>th</sup> century temperature trend. The James Ross Island (JRI)  
194 ice core suggests that local warming began in the 1920s and has been statistically-significant  
195 ( $p<0.1$ ) since the 1940s<sup>54</sup>. Ice cores from the Gomez and Ferrigno sites and a moss bank core  
196 demonstrate that the 20<sup>th</sup> century rise in SAT on the northern Peninsula also extends south  
197 to the southwest Antarctic Peninsula<sup>55,56</sup> and was accompanied by increases in snow  
198 accumulation<sup>57,58</sup> and increased biological productivity, suggesting temperature changes  
199 were likely year-round. Antarctic Peninsula warming has been related to intensification of  
200 the circumpolar westerlies in austral summer and autumn<sup>19</sup>, associated deepening of the  
201 Amundsen Sea Low, and to central tropical Pacific warming in austral autumn, winter and  
202 spring<sup>11</sup>.

203        None of the most recent 36-year trends in the proxy SAT records are unprecedented  
204        relative to trends of the same length from earlier portions of the palaeoclimate archives  
205        (Methods, Supplementary Fig. 3a). The most recent 100-year trends do exceed the upper  
206        95% level of all earlier 100-year trends in three of the Antarctic Peninsula ice core isotope  
207        records (JRI, Gomez and Ferrigno; Supplementary Fig. 3c); for the JRI core the most recent  
208        100-year warming trend falls within the upper 0.3% of the distribution of all 100-year trends  
209        over the last 2000 years<sup>54,59</sup>.

210        Two marine SST proxy records from the northern Antarctic Peninsula show a  
211        warming trend over the 20<sup>th</sup> century that was most prominent over the ~1920s to 1950s  
212        (Fig. 2a). A cooling trend in the most recent decades of the proxy stack appears to be of  
213        similar magnitude to earlier episodes of decadal-scale variability. In this sector, sea-ice  
214        information is derived from one historical record, three ice core chemical records<sup>60</sup> and two  
215        marine diatom records spanning the Bellingshausen Sea and Scotia Sea/northern Weddell  
216        Sea. They depict a regionally coherent sea-ice decrease from the 1920s to the 1950s,  
217        coincident with proxy evidence for SST increases. The proxy composite does not clearly  
218        capture the Bellingshausen sea-ice decline observed by satellites since 1979, although  
219        individual studies have demonstrated that this recent observed sea-ice decline is embedded  
220        within a longer-term decreasing trend that persisted through the 20<sup>th</sup> century and was  
221        strongest at mid-century<sup>61,62</sup>.

222

### 223        **3.2. West Antarctica**

224        In West Antarctica, SAT observations<sup>28,30</sup>, a borehole temperature profile<sup>63,64</sup>, and ice  
225        core water stable isotope records<sup>65</sup> all depict a consistent, statistically significant warming

226 trend beginning in the 1950s. These trends are greatest in winter and spring, and closely  
227 associated with the rapid decline in sea ice observed in the Amundsen-Bellingshausen  
228 Seas<sup>40,65,66</sup>. The annual mean SAT trend over West Antarctica may be among the most rapid  
229 warming trends of the last few decades anywhere on Earth (2.2±1.3°C increase during 1958-  
230 2010 at Byrd Station, mostly due to changes in austral winter and spring)<sup>30,67</sup>. Nevertheless,  
231 the natural decadal variability in this region is also large, owing to the strong variability of  
232 the ASL<sup>68</sup>, amplified by teleconnections with the tropical Pacific also during winter and  
233 spring<sup>11,29,69</sup>. This differs markedly from the situation on the Antarctic Peninsula, where the  
234 summertime trends occur against a background of relatively small inter-annual variability<sup>31</sup>.  
235 As a consequence, the large recent trends cannot yet be demonstrated to be outside the  
236 range of natural variability (e.g. 100-year trend analysis in Supplementary Fig. 3c). An  
237 analysis of more than twenty ice core records from West Antarctica<sup>65</sup> concluded that the  
238 most recent decades were likely the warmest in the last 200 years, but with low confidence  
239 because of a similar-magnitude warming event during the 1940s associated with the major  
240 1939-1942 El Niño event<sup>70</sup>.

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

243

### 244 **3.3. Coastal East Antarctica**

245 No recent multi-decadal trend emerges from the compilation of SAT observations  
246 and proxy records in coastal East Antarctica. Recent fluctuations lie within the decadal  
247 variability documented from ice core water isotope records, and recent 36-year and 100-

248 year trends remain within the 5-95% range of earlier trends within each record  
249 (Supplementary Fig. 3a, c). The only available long-term borehole temperature  
250 reconstruction suggests a recent warming trend. This apparent contradiction may arise from  
251 spatial gradients and differences in recent temperature trends (e.g. Fig. 1) across this  
252 geographically extensive but data sparse sector. Indeed, only seven meteorological stations,  
253 two ice core water isotope records of sufficient resolution (see methods) and one 100-year  
254 borehole profile occupy a longitudinal region spanning 150°E to 40°W (Fig. 2a). Networks of  
255 isotope records from shallow ice cores (not compiled in this study due to their limited  
256 temporal coverage) do provide evidence for a statistically significant increasing SAT trend in  
257 the past 30-60 years over the Fimbul Ice Shelf, East Antarctica<sup>71</sup> and over Dronning Maud  
258 Land<sup>72</sup>, despite no observed warming at the nearby Neumayer station<sup>71,72</sup>.

259 The single SST proxy record available from off the coast of Adélie Land<sup>73</sup> (Fig. 2)  
260 shows a strong increase post 1975, and, despite considerable decadal variability, the final  
261 36-year trend exceeds the 95% range of trends in the full record (Supplementary Fig. 3a, c).  
262 Satellite observations, showing a regional SIE increase across this sector since 1979, are not  
263 mirrored by proxy records, which suggest an overall sea-ice decline since the 1950s<sup>74</sup>,  
264 overlaid by strong decadal variability (Fig. 2). This also highlights the challenges in  
265 interpretation of sea-ice proxies, which can be sensitive to variations in sea-ice thickness,  
266 duration or local dynamics. For example, near the Mertz glacier sea-ice proxy records  
267 spanning the past 250 years depict large multi-decadal variations that are attributed to  
268 iceberg calving events and are comparable to, or larger than, the most recent 36-year or  
269 100-year trends<sup>73</sup> (Supplementary Fig. 3b-c).

270

271     **3.4. East Antarctic Plateau**

272                 The stable isotope records for the East Antarctic Plateau do not show statistically  
273                 significant trends in the final 36 years of their record (Supplementary Figure 3a), unlike the  
274                 observed SAT for the region (Fig. 1 inset b). Comparison of Figs. 1 and 2 indicates that the  
275                 East Antarctic Plateau stable water isotope records come from locations spanning differing  
276                 temperature trends in Fig. 1. The Plateau Remote core on the central Plateau is  
277                 characterised by large decadal variability, and the most recent 100-year trend remains well  
278                 within the 5-95 % range of earlier trends. Towards the margins of the East Antarctic Plateau,  
279                 the EDML and Talos Dome ice cores display recent 100-year warming and cooling trends,  
280                 respectively, that are significant with respect to earlier 100-year trends in these cores  
281                 (Supplementary Fig. 3c). Temperature records from borehole inversions<sup>75</sup>, which cannot  
282                 resolve decadal variability, also show evidence for modest temperature increases on the  
283                 Dronning Maud Land side of the East Antarctic Plateau during the late 20<sup>th</sup> Century, with  
284                 warming apparently beginning earlier closer to the coast. The differing characteristics of  
285                 long-term temperature variability and trends at sites across the Antarctic Plateau again  
286                 highlight the importance of increasing the spatial coverage of proxy records from this data  
287                 sparse region.

288

289     **3.5 The Southern Annular Mode**

290                 The history of the SAM over the last 200 years has been assessed in a number of  
291                 previous reconstructions using syntheses of station observations<sup>26,76,77</sup> and palaeoclimate  
292                 networks<sup>18,78,79</sup> (not shown). Reconstructions from station data display strong decadal

293 variability and season-specific trends. The summer SAM exhibits the strongest post-1960s  
294 trend, which is assessed as unusual compared to trends in the earlier part of the century<sup>26</sup>.  
295 A summer SAM index reconstructed from mid-latitude tree rings also indicates that the  
296 recent positive phase of the SAM is unprecedented in the context of at least the past 600  
297 years<sup>79</sup>. Similarly, an annual average SAM index reconstruction based on a network of  
298 temperature-sensitive palaeoclimate records spanning Antarctica and southern South  
299 America indicates that the SAM is currently in its most positive state over at least the last  
300 1000 years<sup>18</sup>. Over the last 200 years, SAM index reconstructions display a steady<sup>79</sup> or  
301 declining<sup>18</sup> SAM index since the early 1800s, reaching a minimum in the early to mid-20<sup>th</sup>  
302 century<sup>18,79</sup>, before commencement of the positive SAM trend that is seen in observations  
303 (Fig. 1).

304

#### 305 **4. Simulated Antarctic climate trends and variability**

306 The satellite observations and longer historical and proxy-based climate records  
307 reviewed in preceding sections reveal significant regional and seasonal climatic trends of  
308 both positive and negative signs and with a range of amplitudes, together with substantial  
309 decadal to centennial variability in the high-latitude SH. To further assess whether recent  
310 climate variations may be attributed to externally forced changes, or can be explained by  
311 unforced multidecadal variability, we now examine statistics of 36-year trends in model  
312 simulations from CMIP5<sup>12</sup> and compare these to observed trends over the 1979-2014  
313 period.

314 Trend distributions from pre-industrial control simulations provide an estimate of

315 internally generated variability under fixed external forcing. The CMIP5 climate models  
316 display large internal multi-decadal variability in the high southern latitudes (Fig. 3), with  
317 satellite-era observational trends remaining within the 5-95% range of simulated internal  
318 variability for the annual means of all four examined variables – SIE, SST, SAT and the SAM  
319 index (Fig. 3a-d). Based on this comparison, the null hypothesis stating that the observed  
320 1979-2014 trends are explained by internal climate system variability alone cannot be  
321 rejected at the 90% confidence level, with the underlying assumption that the simulated  
322 multi-decadal variability is of the correct magnitude. However, a seasonal breakdown of  
323 observed and simulated trends reveals that observed SAM trends in summer and autumn  
324 exceed the 95% level of control variability (Supplementary Fig. 5), consistent with a  
325 dominant role of stratospheric ozone depletion in the recent shift toward positive SAM<sup>10,27</sup>.  
326 The summer SAT trend also stands out as anomalously negative against the modelled  
327 preindustrial variability (Supplementary Fig. 5).

328 In order to estimate the combined influence of the intrinsic variability of the SH  
329 climate system and the response to known historical – natural and anthropogenic – forcings,  
330 we next compare statistics of modelled 1979-2014 trends in externally-forced simulations  
331 against observations (see Methods). With this measure of multi-model variability, the  
332 observed trends in SIE, SST and SAT appear only marginally consistent with the CMIP5  
333 ensemble of simulated trajectories (Fig. 3a-c), in agreement with previous analyses<sup>44,80,81</sup>.  
334 For instance, only 15% of model simulations exhibit sea-ice expansion over 1979-2014, and  
335 only 3% a larger SIE increase than that observed by satellites. Similarly, only 8% of models  
336 predict a negative trend in average SAT south of 50°S. In contrast, the likelihood of positive  
337 trends in the SAM index is increased in the externally forced simulations compared to

338 unforced simulations, resulting in an improved agreement with the observed SAM trend  
339 (Fig. 3d).

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

347 Deficiencies in the model representation of SH climate are likely contributors to the  
348 disagreement between observations and forced climate simulations<sup>82,83</sup>. Inaccurate or  
349 missing Earth system feedbacks in the CMIP5 simulations, such as the absence of the  
350 freshwater input due to ice-sheet mass loss, and unresolved physical processes, related to  
351 sea-ice rheology, thin ice properties, stratospheric processes, katabatic winds, ocean-ice  
352 shelf interactions and sub-grid-scale ocean processes, can bias both the simulated internal  
353 variability and the model response to external forcing. For example, subsurface ocean  
354 warming around Antarctica in response to strengthening of the SH westerly winds has been  
355 found to occur at twice the magnitude in a high-resolution ocean model compared with  
356 coarser CMIP5 simulations<sup>22</sup>. Comparisons of CMIP5 last millennium simulations against  
357 palaeoclimate data have also shown deficiencies in the SH, suggesting that CMIP5 models  
358 may underestimate the magnitude of unforced variability in the SH or overestimate the SH  
359 climate response to external forcing<sup>84</sup>. Understanding the missing processes and the  
360 relationships between these processes and model skill will be crucial for future model

361 developments in order to improve the model ability to simulate variability of the SH high-  
362 latitude climate and its response to forcing.

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

370 We further explore this by calculating the required duration of anthropogenically-  
371 driven trends under the RCP8.5 scenario for SH high-latitude climate variables to emerge as  
372 statistically distinct from pre-industrial control variability. In a perfect model framework,  
373 this could be understood as estimating how long SH observations may need to be sustained  
374 before on-going trends can be definitively attributed to anthropogenic climate change (Fig.  
375 3e-h and Table 1).

376 For each model and variable, we assess whether the simulated trend starting in 1979  
377 falls outside of the matching 5-95% range of preindustrial variability and we calculate trends  
378 of length between 36 years (1979-2014) and 122 years (1979-2100). Our analysis reveals  
379 that, in 2015, over half of the models already simulate “unusual” post-1979 trends in SAT  
380 and the SAM. For SST, 50% of models have linear trends that emerge above unforced  
381 variability by 2021 (43-year trends), and for SIE the majority of CMIP5 models do not display  
382 trends emerging above the 95% significance level (relative to the preindustrial distribution)  
383 until 2031 (i.e. 53-year trends). For a trend emergence threshold of more than 90% of all

384 CMIP5 models, trends do not emerge until between 2044 (66-year trends for SAM) and  
385 2098 (120-year trends for SIE). Our results for the time of emergence of linear trends are in  
386 agreement with an earlier assessment using a different methodology<sup>85</sup>, suggesting that the  
387 mid to high SH latitudes are among the last regions where the signal of anthropogenic  
388 forcing will be sufficiently large to differentiate it from the range of natural variability. These  
389 CMIP5-based estimates may in fact underestimate the true length of time required for  
390 statistically distinct trends to emerge, if CMIP5 models underestimate the magnitude of  
391 internal variability or overestimate the forced climate response. Hence, notwithstanding  
392 known limitations in CMIP5 models, our analysis suggests that 36-years of observations are  
393 simply insufficient to interrogate and attribute trends in SH high latitude surface climate.

394

## 395 **5. Discussion**

396 Climate change and variability over the high latitudes of the SH are characterized by  
397 strong regional and seasonal contrasts for all the variables investigated here. This is valid at  
398 interannual to decadal timescales, as illustrated in instrumental observations, as well as on  
399 longer time scales, as indicated in proxy-based reconstructions. The most unequivocal large-  
400 scale change over recent decades is the increase of the SAM index<sup>19</sup> and the freshening and  
401 subsurface warming of the ocean<sup>23,24,41</sup>. Regionally, a large warming has been observed over  
402 the Antarctic Peninsula and West Antarctic regions across the last 50 years. SIE has  
403 decreased in the Amundsen-Bellingshausen Seas while it has increased in the Ross Sea  
404 sector since 1979.

405        The large multi-decadal variations seen in high-resolution proxy-based  
406    reconstructions of temperature and SIE also have clear regional contrasts. Some estimates  
407    suggest common signals over the whole Southern Ocean, such as the decrease of the ice  
408    extent between the 1950s and the late 1970s deduced from whaling records (e.g.<sup>86,87,88</sup>), but  
409    this remains to be confirmed by the analysis of additional observations. The longer records  
410    independently support the conclusion that most of the recent changes for any single  
411    variable largely result from natural variability, and are not unprecedented over the past two  
412    centuries. This is consistent with results from state-of-the-art climate models showing that,  
413    except for the SAM index, most recent changes remain in the range of large-scale simulated  
414    internal variability. When analysing specifically the 1979-2014 period, including forced  
415    changes and internal variability, models struggle to track the observed trends in SST, SAT  
416    and sea-ice cover. This suggests that either a singular event associated with internal  
417    variability has been able to overwhelm the forced response in observations, or that CMIP5  
418    models overestimate the forced response (potentially partly due to key processes missing in  
419    the models), or a combination of both.

420        Recent observations and process understanding of the atmosphere, sea ice, ocean  
421    and ice sheets suggest strong coupling, which means that investigations need to encompass  
422    and understand the dynamics of the whole climate system. Statistics independently applied  
423    to a few large-scale metrics may not allow a robust comparison between observed and  
424    simulated trends. Regional and seasonal complexity<sup>89</sup> as well as physical relationships  
425    between different climate variables must be taken into account to evaluate the overall  
426    consistency of observed and modelled time-evolving climate states, and to identify caveats.  
427    We advocate process-oriented studies in which the primary mechanisms behind modelled

428 behaviour are identified and their plausibility evaluated against available observations and  
429 theory.

430 In particular, the accelerating melting and calving of Antarctic ice shelves<sup>46,90,91</sup> could  
431 have a pronounced influence on the recent and future evolution of the high-latitude  
432 Southern Ocean<sup>41,43,92-94</sup>. Understanding and quantifying the role of changing glacial  
433 discharge in past and on-going climatic trends is an important unresolved question requiring  
434 attention.

435 To improve the sampling of forced and natural variability for the recent period, we  
436 also emphasize the importance of considering multiple models, as well as multiple  
437 realizations of different models. In this sense large ensembles, such as those recently  
438 released by some modelling groups<sup>95</sup>, are particularly useful for improving estimates of  
439 internal variability compared with forced signals.

440 Atmospheric reanalyses are strongly dependent on the prescribed surface boundary  
441 conditions that are particularly uncertain before the 1970s in the Southern Ocean<sup>96</sup> and  
442 therefore have limited skills prior to the satellite era. Alternative approaches involve  
443 assimilation methods using proxy records and climate simulations in order to best  
444 reconstruct the past state of the Antarctic atmospheric circulation. Coupled ocean – sea ice  
445 – atmosphere reanalysis<sup>97</sup>, with specific attention to the high latitudes of the Southern  
446 Ocean, should thus be a target for the future. Preliminary studies have demonstrated the  
447 feasibility of this approach for ensuring the consistency between the various components of  
448 the system and the study of their interactions<sup>98</sup>.

449 Our synthesis has emphasized that less than 40 years of instrumental climate data is  
450 insufficient to characterize the variability of the high southern latitudes or to robustly  
451 identify an anthropogenic contribution, except for the changes in the SAM. Although  
452 temperature changes over 1950-2008 from the average of individual stations have been  
453 attributed to anthropogenic causes<sup>99</sup>, only low confidence can be assigned due to  
454 observational uncertainties<sup>100</sup> and large-scale decadal and multidecadal variability.  
455 Detection and attribution studies depend on the validity of estimates of natural variability  
456 from climate model simulations. This is particularly the case for variables such as Antarctic  
457 sea ice which have problematic representation in climate models<sup>36</sup>, and short observational  
458 time series from which to estimate real multi-decadal variability. The strong regional  
459 variability on all time scales implies that the sparsity of observations and proxy data is a  
460 clear limitation, especially in the ocean, and that averaging climate properties over the  
461 entire Antarctic or Southern Ocean potentially aliases the regional differences.

462 The Antarctic climate system is strongly coupled, and future investigations need to  
463 combine information from different climate variables to identify the causes and  
464 mechanisms driving SH high-latitude climate variations. Process studies are essential to this  
465 task, along with a continued effort to maintain current observations from stations and  
466 satellites, and to expand the observational network in undocumented areas. The rescue of  
467 historical data is also critical to obtain a longer perspective. New high-resolution proxy data  
468 should be collected, both by expanding existing data types (e.g. lake sediments and deep  
469 sea sediments) and by investing in new records such as moss banks. Improved spatial  
470 coverage of ice core records and a requirement for a minimum suite of information from  
471 these archives (e.g. accumulation, water isotopes, borehole temperatures) are desirable,

472 together with multiple records allowing improvement of the signal-to-noise ratio. Improved  
473 calibration of these proxy records (e.g. water stable isotopes against temperature) is critical  
474 for the uncertainties associated with past temperature reconstructions. Progress is expected  
475 from the use of historical data, but also through improved proxy modelling; for example by  
476 incorporating water stable isotopes in high-resolution atmospheric models and quantifying  
477 post-deposition effects. Not least important is the use of non-linear statistical analysis tools  
478 to improve the statistical analysis of observations and proxy data as well as model output  
479 evaluation. Gathering, utilising, combining, and improving the interpretation of data from  
480 all available sources are imperative to understand recent climate changes in this data  
481 sparse, but climatically important, region.

482

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762 **Author Contributions**

763 All authors conceived the paper. JMJ, HG and STG organised the contributions to the  
764 manuscript, and contributed to writing and editing the manuscript. NJA, undertook data  
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776 manuscript. XC provided paleo sea ice data, and undertook editing/revision of the  
777 manuscript, writing of methods section (diatoms). VMD contributed to discussion associated  
778 with Section 3, and selection of records for data analysis, provided advice on Fig. 2, and  
779 contributed to writing and editing/revision of the manuscript. MHE contributed to design of  
780 the analyses for Fig. 1 and Fig. 3, and to writing (Section 2), and editing/revision of the  
781 manuscript. TRV wrote the first draft of Section 3, and helped design Fig. 2.

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786 writing of the methodology, and editing/revision of the manuscript.

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791 **Competing financial interests**

792 The authors declare no competing financial interests.

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800 Tables

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803

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

804

805

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

811

812    **Figure Legends**

813

814    **Figure 1 | Antarctic atmosphere-ocean-ice changes over the satellite-observing era. a)**

815    Total changes over 1979-2014 in annual mean surface air temperature (blue-red shading),  
816    station-based surface air temperature (SAT, blue-red shaded shapes), sea-ice concentration  
817    (contours, 10% intervals; red and blue contours, alongside light pink and blue shading  
818    beneath, denote negative and positive trends, respectively), sea surface temperature (SST,  
819    purple-red shading), and 10m winds (vectors). Only SST trends equatorward of the  
820    climatological September sea-ice extent (SIE, black contour) are shown. Hatching and teal  
821    vectors highlight trends significant at the 95% level according to two-tailed student t-tests.  
822    Note that SAT trends are calculated over 1979-2012 but scaled to represent trends over the  
823    36-year period, 1979-2014. Surrounding figures show time-series of **b)** East Antarctic SAT  
824    (circles; red line denotes multi-station mean, grey lines those of individual East Antarctic  
825    stations), **c)** the Marshall Southern Annular Mode index (difference in station sea level  
826    pressure between 40° and 65°S), **d)** Southern Ocean zonal mean SST (averaged over 50°–  
827    70°S), **e)** Southern Hemisphere SIE, **f)** Ross-Amundsen SIE, **g)** West Antarctic SAT (square;  
828    Byrd Station), **h)** Amundsen-Bellingshausen SIE , and **i)** Antarctic Peninsula SAT (hexagons;  
829    red line denotes multi-station mean, grey lines those of individual Antarctic Peninsula  
830    stations). For all time-series, blue lines highlight the linear trend, and red asterisk where the  
831    trend is significant at the 95% level according to a two-tailed student t-test. See methods for  
832    details on datasets and trend significance calculation.

833

834 **Figure 2 | Antarctic climate variability and trends over the last 200 years from long**  
835 **observational and proxy-derived indicators.** Records were regionally compiled for (a) the  
836 Antarctic Peninsula, (b) West Antarctica, (c) coastal East Antarctica and (d) the Antarctic  
837 Plateau (Methods). Central map shows the location of records according to environmental  
838 indicator (colours) and record type (symbols), as well as the boundaries of the four  
839 geographic regions (black lines), the 2000m elevation contour (grey curve), and the trend in  
840 sea ice concentration over the 1979–2014 interval (shading). Within each region (a-d),  
841 records were compiled as 5y averages (dark lines) according to the environmental  
842 parameter that they represent; observed surface air temperature (SAT) (red); proxy for SAT  
843 (orange); borehole inversion reconstruction of surface temperatures (greens); proxy for sea  
844 surface temperature (blue); and proxy for sea ice conditions (cyan). Shadings (or thin  
845 vertical lines) denote range of estimates across records within each 5-year bin, with the  
846 exception of borehole temperature inversions. All records are expressed as anomalies ( $^{\circ}\text{C}$   
847 units) or normalised data ( $\sigma$  units) relative to 1960–1990. With the exception of borehole  
848 temperature records which are shown individually with uncertainty bounds (see  
849 Supplementary Figure 4 for additional details). Details of datasets used in this figure  
850 provided in Supplementary Table 1.

851

852 **Figure 3 | Antarctic climate trends in CMIP5 simulations.** (a-d) Distributions of (blue) 36-  
853 year linear trends in an ensemble of CMIP5 preindustrial simulations and (black/grey) 1979-  
854 2014 trends in an ensemble of CMIP5 historical (1979-2005)-RCP8.5 (2006-2014)  
855 simulations (see Methods). Red vertical lines correspond to observed 36-year linear trends  
856 (1979-2014). Horizontal bars depict (red) the 90 % confidence interval of the observed  
857 trend, (blue) the 5-95 % range of the simulated preindustrial distribution and (black) the 5-  
858 95% range of the simulated 1979-2014 trend distribution. The dark blue error bars on the  
859 pre-industrial histograms and horizontal ranges are 5-95% uncertainty intervals based on  
860 Monte Carlo analysis (see Methods) (e-h) Proportion of CMIP5 model experiments whose  
861 linear trends starting in 1979 are above the 95% level (below the 5% level for panel e) of the  
862 distribution of trends of the same length in their matching control simulation. Simulations  
863 follow the RCP8.5 scenario after year 2005. Dashed and solid red lines highlight the 50% and  
864 90% levels of the cumulative distributions (Table 1). The orange bars are 5-95% uncertainty  
865 ranges based on Monte Carlo analysis of equal length segments from the preindustrial  
866 simulations (see Methods). Chosen climate variables are (a, e) Southern Hemisphere sea-ice  
867 extent, (b, f) mean SST south of 50°S, (c, g) mean SAT south of 50°S and (d, h) SAM index.  
868 Model details given in Supplementary Table 2. Observations used to compute observed sea  
869 ice extent and SST trends over the 1979-2014 period are referenced in Figure 1. The  
870 observed 1979-2014 SAT trend is derived from ERA-Interim 2-m air temperature fields.  
871 Modelled and observed SAM indices were calculated from annual mean time series using  
872 Empirical Orthogonal Function analysis applied on 500 hPa geopotential height fields over  
873 the 90°S-20°S region, with observation-based geopotential height fields taken from the ERA-  
874 Interim reanalysis.





