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

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51 **Preface**

52 In southern high latitudes, satellite records document regional climate changes during the
53 last few decades (since 1979). For many variables, the satellite-derived trends are not
54 consistent with output from the suite of current climate models over the same period
55 (1979-2015). The recent climate variations are compared with a synthesis of instrumental
56 and palaeoclimate records spanning the last 200 years, which document large pre-satellite
57 Antarctic climate fluctuations. We conclude that the available 36-years of satellite-derived
58 observations are generally not yet long enough to distinguish forced trends from natural
59 variability in the high-latitude Southern Hemisphere.

60

61 **Abstract**

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

74

75

76 **1. Introduction**

77 The high latitude Southern Hemisphere (SH) is a highly complex and critically
78 important component of the global climate system that remains poorly understood. The
79 Antarctic Ice Sheet represents the greatest potential source of global sea level rise¹, and its
80 response to climate change is a major source of uncertainty for future projections^{2,3}. The
81 Southern Ocean is important for its ability to uptake heat and carbon dioxide, and thereby
82 mitigate human-induced atmospheric temperature and CO₂ rise^{4,5,6,7,8}. Antarctic sea ice is
83 important for its role in ocean-atmosphere exchange and provides an important climate
84 feedback through its influence on albedo and atmospheric and oceanic circulation.

85 The leading mode of atmospheric circulation variability in the SH high latitudes is the
86 Southern Annular Mode (SAM)⁹. It is a measure of the mid-to-high latitude atmospheric
87 pressure gradient and reflects the strength and position of the westerly winds that circle
88 Antarctica. This in turn impacts various aspects of Antarctic climate and controls the timing
89 and distribution of rainfall received by the mid-latitude SH continents¹⁰. An almost equally
90 important aspect of large-scale circulation variability in this region is the mid to high-latitude
91 response to tropical variability, particularly the El Niño-Southern Oscillation (ENSO)¹¹.

92 Over recent decades, multiple changes have been observed in high-latitude SH
93 climate. However, the brevity and sparse distribution of observational records pose major
94 challenges to understanding whether observed changes are anthropogenically forced or
95 remain within the range of natural climate variability. We can improve our understanding
96 of SH high latitude climate by combining information from instrumental, satellite,
97 palaeoclimate and reanalysis data, along with climate model simulations. Here, we provide
98 an assessment of recent changes in the atmosphere, ocean and sea ice systems of the

99 southern high latitudes (south of 50°S), on timescales from decades to centuries. We
100 describe SH climate trends using satellite information (1979-2014) and Antarctic station
101 observations. These are compared with trends and multi-decadal variability from
102 palaeoclimate data spanning the last 200 years, as well as control and forced climate
103 simulations from the Fifth Climate Model Intercomparison Project (CMIP5)¹², to assess
104 whether recent trends are unusual compared with natural variability. We conclude by
105 identifying key knowledge gaps where strategically focussed research will improve
106 understanding of the contribution of SH high latitudes to global climate variability and
107 change.

108

109 **2. Antarctic climate monitoring**

110 Coordinated international efforts to monitor Antarctic climate began in the
111 International Geophysical Year of 1957/58. However, few climate measurements are
112 available over vast areas of the continent and the adjacent ice-shelves, sea ice and oceans.
113 The advent of routine satellite sounder observations in 1979 revolutionised knowledge of
114 climate over Antarctica and the surrounding oceans, although uncertainties remain due to
115 satellite sensor changes¹³. More uncertain early satellite sea ice estimates extend back to
116 1972¹⁴, with ongoing recovery of ice edge information for the 1964-1972 period^{15,16}.
117 Knowledge of recent sub-surface ocean trends remains more limited. The Argo profiling
118 float program and conductivity-temperature-depth tags mounted on elephant seals have
119 provided substantial numbers of subsurface ocean profiles only since 2004⁷, and even now,
120 few ocean profiles are obtained within the sea-ice zone.

121 Antarctic annual mean climate trends over the 1979-2014 interval covered by

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

135 Time series of summer anomalies in hemispherically averaged SST, zonal wind, and
136 sea ice extent exhibit consistent multi-decadal variability since 1950¹⁷, suggesting that
137 recent changes in multiple variables are strongly coupled. Many of the observed changes in
138 SH high-latitude climate can be related to changes in atmospheric circulation. Strengthening
139 of the westerly winds associated with the positive SAM trend causes spatially coherent
140 changes in surface air temperature over Antarctica¹⁸, and in particular can account for the
141 summer warming over the eastern Antarctic Peninsula^{19,20}. Cooling of the surface ocean and
142 warming of the subsurface ocean^{21,22,23,24,25} throughout the Southern Ocean can also be
143 partly attributed to a westerly wind-forced increase in northward Ekman transport of cold
144 subantarctic surface waters. Summer trends in the SAM are distinct from natural

145 variations²⁶, and are attributed to stratospheric ozone depletion, and the associated
146 stratospheric cooling over Antarctica^{10,27}. In addition, regional atmospheric circulation
147 changes led to warming trends in winter and spring, distinct from the summertime warming
148 associated with the SAM, particularly over the West Antarctic Ice Sheet (WAIS) and the
149 western Antarctic Peninsula during the second half of the Twentieth Century^{11,28,29,30,31,32}.
150 However, in the last 10-15 years the rate of warming over the Peninsula has slowed
151 markedly, in all seasons, but most strongly in summer (time series in Supplementary Fig. 2).

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

164 Changes in SAT, atmospheric and ocean circulation have also affected the ice sheet
165 itself, through surface melting of ice shelves around the Antarctic Peninsula⁴⁵, and melting
166 of ice shelves from below owing to the intrusion of warm circumpolar deep water onto the
167 continental shelf⁴⁶. The importance of the latter process is particularly evident along the

168 margin of the WAIS^{47,48,49} and is associated with regional atmospheric circulation changes
169 forced by teleconnections from the tropics^{48,50}.

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

175

176

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

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

191 impact inland versus coastal sites in Antarctica⁵³. Fig. 2 shows these sectors and the data
192 available for this synthesis, and highlights the paucity of climate information currently
193 available for many parts of Antarctica.

194

195 **3.1. Antarctic Peninsula sector**

196 Of the four sectors, the Antarctic Peninsula has the longest observed SAT record
197 (1903-present); prior to the late 1940s, SAT is only available from the single Orcadas station,
198 located northeast of the Peninsula itself. Instrumental data, proxy palaeotemperature
199 records (ice cores and a moss bank core), and borehole temperature inversions show that
200 the Antarctic Peninsula warming trend (Fig. 1) is part of a longer-term regional warming
201 trend (Fig. 2a). The correspondence between instrumental and proxy data and between
202 multiple proxy data sources may be stronger here than for any other region, suggesting this
203 is a robust context for the late 20th century temperature trend. The James Ross Island (JRI)
204 ice core suggests that local warming began in the 1920s and has been statistically-significant
205 ($p < 0.1$) since the 1940s⁵⁴. Ice cores from the Gomez and Ferrigno sites and a moss bank core
206 demonstrate that the 20th century rise in SAT on the northern Peninsula also extends south
207 to the southwest Antarctic Peninsula^{55,56} and was accompanied by increases in snow
208 accumulation^{57,58} and increased biological productivity, suggesting temperature changes
209 were likely year-round. Antarctic Peninsula warming has been related to intensification of
210 the circumpolar westerlies in austral summer and autumn¹⁹, associated deepening of the
211 Amundsen Sea Low, and to central tropical Pacific warming in austral autumn, winter and
212 spring¹¹.

213 None of the most recent 36-year trends in the proxy SAT records are unprecedented
214 relative to trends of the same length from earlier portions of the palaeoclimate archives
215 (Methods, Supplementary Fig. 3a). The most recent 100-year trends do exceed the upper
216 95% level of all earlier 100-year trends in three of the Antarctic Peninsula ice core isotope
217 records (JRI, Gomez and Ferrigno; Supplementary Fig. 3c); for the JRI core the most recent
218 100-year warming trend falls within the upper 0.3% of the distribution of all 100-year trends
219 over the last 2000 years^{54,59}.

220 Two marine SST proxy records from the northern Antarctic Peninsula show a
221 warming trend over the 20th century that was most prominent over the ~1920s to 1950s
222 (Fig. 2a). A cooling trend in the most recent decades of the proxy stack appears to be of
223 similar magnitude to earlier episodes of decadal-scale variability. In this sector, sea-ice
224 information is derived from one historical record, three ice core chemical records⁶⁰ and two
225 marine diatom records spanning the Bellingshausen Sea and Scotia Sea/northern Weddell
226 Sea. They depict a regionally coherent sea-ice decrease from the 1920s to the 1950s,
227 coincident with proxy evidence for SST increases. The proxy composite does not clearly
228 capture the Bellingshausen sea-ice decline observed by satellites since 1979, although
229 individual studies have demonstrated that this recent observed sea-ice decline is embedded
230 within a longer-term decreasing trend that persisted through the 20th century and was
231 strongest at mid-century^{61,62}.

232

233 **3.2. West Antarctica**

234 In West Antarctica, SAT observations^{28,30}, a borehole temperature profile^{63,64}, and ice
235 core water stable isotope records⁶⁵ all depict a consistent, statistically significant warming

236 trend beginning in the 1950s. These trends are greatest in winter and spring, and closely
237 associated with the rapid decline in sea ice observed in the Amundsen-Bellingshausen
238 Seas^{40,65,66}. The annual mean SAT trend over West Antarctica may be among the most rapid
239 warming trends of the last few decades anywhere on Earth ($2.2 \pm 1.3^\circ\text{C}$ increase during 1958-
240 2010 at Byrd Station, mostly due to changes in austral winter and spring)^{30,67}. Nevertheless,
241 the natural decadal variability in this region is also large, owing to the strong variability of
242 the ASL⁶⁸, amplified by teleconnections with the tropical Pacific also during winter and
243 spring^{11,29,69}. This differs markedly from the situation on the Antarctic Peninsula, where the
244 summertime trends occur against a background of relatively small inter-annual variability³¹.
245 As a consequence, the large recent trends cannot yet be demonstrated to be outside the
246 range of natural variability (e.g. 100-year trend analysis in Supplementary Fig. 3c). An
247 analysis of more than twenty ice core records from West Antarctica⁶⁵ concluded that the
248 most recent decades were likely the warmest in the last 200 years, but with low confidence
249 because of a similar-magnitude warming event during the 1940s associated with the major
250 1939-1942 El Niño event⁷⁰.

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

253

254 **3.3. Coastal East Antarctica**

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

258 year trends remain within the 5-95% range of earlier trends within each record
259 (Supplementary Fig. 3a, c). The only available long-term borehole temperature
260 reconstruction suggests a recent warming trend. This apparent contradiction may arise from
261 spatial gradients and differences in recent temperature trends (e.g. Fig. 1) across this
262 geographically extensive but data sparse sector. Indeed, only seven meteorological stations,
263 two ice core water isotope records of sufficient resolution (see methods) and one 100-year
264 borehole profile occupy a longitudinal region spanning 150°E to 40°W (Fig. 2a). Networks of
265 isotope records from shallow ice cores (not compiled in this study due to their limited
266 temporal coverage) do provide evidence for a statistically significant increasing SAT trend in
267 the past 30-60 years over the Fimbul Ice Shelf, East Antarctica⁷¹ and over Dronning Maud
268 Land⁷², despite no observed warming at the nearby Neumayer station^{71,72}.

269 The single SST proxy record available from off the coast of Adélie Land⁷³ (Fig. 2)
270 shows a strong increase post 1975, and, despite considerable decadal variability, the final
271 36-year trend exceeds the 95% range of trends in the full record (Supplementary Fig. 3a, c).
272 Satellite observations, showing a regional SIE increase across this sector since 1979, are not
273 mirrored by proxy records, which suggest an overall sea-ice decline since the 1950s⁷⁴,
274 overlaid by strong decadal variability (Fig. 2). This also highlights the challenges in
275 interpretation of sea-ice proxies, which can be sensitive to variations in sea-ice thickness,
276 duration or local dynamics. For example, near the Mertz glacier sea-ice proxy records
277 spanning the past 250 years depict large multi-decadal variations that are attributed to
278 iceberg calving events and are comparable to, or larger than, the most recent 36-year or
279 100-year trends⁷³ (Supplementary Fig. 3b-c).

280

281 **3.4. East Antarctic Plateau**

282 The stable isotope records for the East Antarctic Plateau do not show statistically
283 significant trends in the final 36 years of their record (Supplementary Figure 3a), unlike the
284 observed SAT for the region (Fig. 1 inset b). Comparison of Figs. 1 and 2 indicates that the
285 East Antarctic Plateau stable water isotope records come from locations spanning differing
286 temperature trends in Fig. 1. The Plateau Remote core on the central Plateau is
287 characterised by large decadal variability, and the most recent 100-year trend remains well
288 within the 5-95 % range of earlier trends. Towards the margins of the East Antarctic Plateau,
289 the EDML and Talos Dome ice cores display recent 100-year warming and cooling trends,
290 respectively, that are significant with respect to earlier 100-year trends in these cores
291 (Supplementary Fig. 3c). Temperature records from borehole inversions⁷⁵, which cannot
292 resolve decadal variability, also show evidence for modest temperature increases on the
293 Dronning Maud Land side of the East Antarctic Plateau during the late 20th Century, with
294 warming apparently beginning earlier closer to the coast. The differing characteristics of
295 long-term temperature variability and trends at sites across the Antarctic Plateau again
296 highlight the importance of increasing the spatial coverage of proxy records from this data
297 sparse region.

298

299 **3.5. The Southern Annular Mode**

300 The history of the SAM over the last 200 years has been assessed in a number of
301 previous reconstructions using syntheses of station observations^{26,76,77} and palaeoclimate
302 networks^{18,78,79} (not shown). Reconstructions from station data display strong decadal

303 variability and season-specific trends. The summer SAM exhibits the strongest post-1960s
304 trend, which is assessed as unusual compared to trends in the earlier part of the century²⁶.
305 A summer SAM index reconstructed from mid-latitude tree rings also indicates that the
306 recent positive phase of the SAM is unprecedented in the context of at least the past 600
307 years⁷⁹. Similarly, an annual average SAM index reconstruction based on a network of
308 temperature-sensitive palaeoclimate records spanning Antarctica and southern South
309 America indicates that the SAM is currently in its most positive state over at least the last
310 1000 years¹⁸. SAM index reconstructions display a steady⁷⁹ or declining¹⁸ SAM index since
311 the early 1800s, reaching a minimum in the early to mid-20th century^{18,79}, before
312 commencement of the positive SAM trend that is seen in observations (Fig. 1).

313

314 **4. Simulated Antarctic climate trends and variability**

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

323 Trend distributions from pre-industrial control simulations provide an estimate of
324 internally generated variability under fixed external forcing. The CMIP5 climate models

325 display large internal multi-decadal variability in the high southern latitudes (Fig. 3), with
326 satellite-era observational trends remaining within the 5-95% range of simulated internal
327 variability for the annual means of all four examined variables – SIE, SST, SAT and the SAM
328 index (Fig. 3a-d). Based on this comparison, the null hypothesis stating that the observed
329 1979-2014 trends are explained by internal climate system variability alone cannot be
330 rejected at the 90% confidence level, with the underlying assumption that the simulated
331 multi-decadal variability is of the correct magnitude. However, a seasonal breakdown of
332 observed and simulated trends reveals that observed SAM trends in summer and autumn
333 exceed the 95% level of control variability (Supplementary Fig. 5), consistent with a
334 dominant role of stratospheric ozone depletion^{10,27} in the recent shift toward positive SAM.
335 The summer SAT trend also stands out as anomalously negative against the modelled
336 preindustrial variability (Supplementary Fig. 5).

337 In order to estimate the combined influence of the intrinsic variability of the SH
338 climate system and the response to known historical – natural and anthropogenic – forcings,
339 we next compare statistics of modelled 1979-2014 trends in externally-forced simulations
340 against observations (see Methods). With this measure of multi-model variability, the
341 observed trends in SIE, SST and SAT appear only marginally consistent with the CMIP5
342 ensemble of simulated trajectories (Fig. 3a-c), in agreement with previous analyses^{44,80,81}.
343 For instance, only 15% of model simulations exhibit sea-ice expansion over 1979-2014, and
344 only 3% a larger SIE increase than that observed by satellites. Similarly, only 8% of models
345 predict a negative trend in average SAT south of 50°S. In contrast, the likelihood of positive
346 trends in the SAM index is increased in the externally forced simulations compared to
347 unforced simulations, resulting in an improved agreement with the observed SAM trend

348 (Fig. 3d).

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

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

371 latitude climate and its response to forcing.

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

379 We further explore this by calculating the required duration of anthropogenically-
380 driven trends under the RCP8.5 scenario for SH high-latitude climate variables to emerge as
381 statistically distinct from pre-industrial control variability. In a perfect model framework,
382 this could be understood as estimating how long SH observations may need to be sustained
383 before on-going trends can be definitively attributed to anthropogenic climate change (Fig.
384 3e-h and Table 1).

385 For each model and variable, we assess whether the simulated trend starting in 1979
386 falls outside of the matching 5-95% range of preindustrial variability and we calculate trends
387 with lengths between 36 years (1979-2014) and 122 years (1979-2100). Our analysis reveals
388 that, in 2015, over half of the models already simulate “unusual” post-1979 trends in SAT
389 and the SAM. For SST, 50% of models have linear trends that emerge above unforced
390 variability by 2021 (43-year trends), and for SIE the majority of CMIP5 models do not display
391 trends emerging above the 95% significance level (relative to the preindustrial distribution)
392 until 2031 (i.e. 53-year trends). For a trend emergence threshold of more than 90% of all
393 CMIP5 models, trends do not emerge until between 2044 (66-year trends for SAM) and

394 2098 (120-year trends for SIE). Our results for the time of emergence of linear trends are in
395 agreement with an earlier assessment using a different methodology⁸⁵, suggesting that the
396 mid to high SH latitudes are among the last regions where the signal of anthropogenic
397 forcing will be sufficiently large to differentiate it from the range of natural variability. These
398 CMIP5-based estimates may in fact underestimate the true length of time required for
399 statistically distinct trends to emerge, if CMIP5 models underestimate the magnitude of
400 internal variability or overestimate the forced climate response. Hence, notwithstanding
401 known limitations in CMIP5 models, our analysis suggests that 36-years of observations are
402 simply insufficient to interrogate and attribute trends in SH high latitude surface climate.

403

404 **5. Discussion**

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

414 The large multi-decadal variations seen in high-resolution proxy-based
415 reconstructions of temperature and SIE also have clear regional contrasts. Some estimates

416 suggest common signals over the whole Southern Ocean, such as the decrease of the ice
417 extent between the 1950s and the late 1970s deduced from whaling records (e.g.^{86,87,88}), but
418 this remains to be confirmed by the analysis of additional observations. The longer records
419 independently support the conclusion that most of the recent changes for any single
420 variable largely result from natural variability, and are not unprecedented over the past two
421 centuries. This is consistent with results from state-of-the-art climate models showing that,
422 except for the SAM index, most recent changes remain in the range of large-scale simulated
423 internal variability. When analysing specifically the 1979-2014 period, including forced
424 changes and internal variability, models struggle to track the observed trends in SST, SAT
425 and sea-ice cover. This suggests that either a singular event associated with internal
426 variability has been able to overwhelm the forced response in observations, or that CMIP5
427 models overestimate the forced response (potentially partly due to key processes missing in
428 the models), or a combination of both.

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

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

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

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

458 Our synthesis has emphasized that less than 40 years of instrumental climate data is
459 insufficient to characterize the variability of the high southern latitudes or to robustly
460 identify an anthropogenic contribution, except for the changes in the SAM. Although
461 temperature changes over 1950-2008 from the average of individual stations have been

462 attributed to anthropogenic causes⁹⁹, only low confidence can be assigned due to
463 observational uncertainties¹⁰⁰ and large-scale decadal and multidecadal variability.
464 Detection and attribution studies depend on the validity of estimates of natural variability
465 from climate model simulations. This is particularly the case for variables such as Antarctic
466 sea ice, which have problematic representation in climate models³⁶ and short observational
467 time series from which to estimate real multi-decadal variability. The strong regional
468 variability on all time scales implies that the sparsity of observations and proxy data is a
469 clear limitation, especially in the ocean, and that averaging climate properties over the
470 entire Antarctic or Southern Ocean potentially aliases the regional differences.

471 The Antarctic climate system is strongly coupled, and future investigations need to
472 combine information from different climate variables to identify the causes and
473 mechanisms driving SH high-latitude climate variations. Process studies are essential to this
474 task, along with a continued effort to maintain current observations from stations and
475 satellites, and to expand the observational network in undocumented areas. The rescue of
476 historical data is also critical to obtain a longer perspective. New high-resolution proxy data
477 should be collected, both by expanding existing data types (e.g. lake sediments and deep
478 sea sediments) and by investing in new records such as moss banks. Improved spatial
479 coverage of ice core records and a requirement for a minimum suite of information from
480 these archives (e.g. accumulation, water isotopes, borehole temperatures) are desirable,
481 together with multiple records allowing improvement of the signal-to-noise ratio. Improved
482 calibration of these proxy records (e.g. water stable isotopes against temperature) is critical
483 for the uncertainties associated with past temperature reconstructions. Progress is expected
484 from the use of historical data, but also through improved proxy modelling; for example by

485 incorporating water stable isotopes in high-resolution atmospheric models and quantifying
486 post-deposition effects. Not least important is the use of non-linear statistical analysis tools
487 to improve the statistical analysis of observations and proxy data as well as model output
488 evaluation. Gathering, utilising, combining, and improving the interpretation of data from
489 all available sources are imperative to understand recent climate changes in this data
490 sparse, but climatically important, region.

491

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793 All authors conceived the paper. JMJ, HG and STG organised the contributions to the
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807 and to writing and revising Section 4 and associated methods.

808 All authors reviewed the full manuscript.

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813 **Competing financial interests**

814 The authors declare no competing financial interests.

815 **Materials and Correspondence**

816 Correspondence and requests for materials should be addressed to Julie Jones.

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822 Tables

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	50% of models exceeding		90% of models exceeding		
	control trends		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

826

827

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

833

834 **Figure Legends**

835

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

837 Total changes over 1979-2014 in annual mean surface air temperature (blue-red shading),
838 station-based surface air temperature (SAT, blue-red shaded shapes), sea-ice concentration
839 (contours, 10% intervals; red and blue contours, alongside light pink and blue shading
840 beneath, denote negative and positive trends, respectively), sea surface temperature (SST,
841 purple-red shading), and 10m winds (vectors). Only SST trends equatorward of the
842 climatological September sea-ice extent (SIE, black contour) are shown. Hatching and teal
843 vectors highlight trends significant at the 95% level according to two-tailed student t-tests.
844 Note that SAT trends are calculated over 1979-2012 but scaled to represent trends over the
845 36-year period, 1979-2014. Surrounding figures show time-series of **b)** East Antarctic SAT
846 (circles; red line denotes multi-station mean, grey lines those of individual East Antarctic
847 stations), **c)** the Marshall Southern Annular Mode index (difference in station sea level
848 pressure between 40° and 65°S), **d)** Southern Ocean zonal mean SST (averaged over 50°–
849 70°S), **e)** Southern Hemisphere SIE, **f)** Ross-Amundsen SIE, **g)** West Antarctic SAT (square;
850 Byrd Station), **h)** Amundsen-Bellingshausen SIE, and **i)** Antarctic Peninsula SAT (hexagons;
851 red line denotes multi-station mean, grey lines those of individual Antarctic Peninsula
852 stations). For all time series, blue lines highlight the linear trend, and red asterisk where the
853 trend is significant at the 95% level according to a two-tailed student t-test. See methods for
854 details on datasets and trend significance calculation.

855

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

873

874 **Figure 3 | Antarctic climate trends in CMIP5 simulations. (a-d)** Distributions of (blue) 36-
875 year linear trends in an ensemble of CMIP5 preindustrial simulations and (black/grey) 1979-
876 2014 trends in an ensemble of CMIP5 historical (1979-2005)-RCP8.5 (2006-2014)
877 simulations (see Methods). Red vertical lines correspond to observed 36-year linear trends
878 (1979-2014). Horizontal bars depict (red) the 90 % confidence interval of the observed
879 trend, (blue) the 5-95 % range of the simulated preindustrial distribution and (black) the 5-
880 95% range of the simulated 1979-2014 trend distribution. The dark blue error bars on the
881 pre-industrial histograms and horizontal ranges are 5-95% uncertainty intervals based on
882 Monte Carlo analysis (see Methods) **(e-h)** Proportion of CMIP5 model experiments whose
883 linear trends starting in 1979 are above the 95% level (below the 5% level for panel **e**) of the
884 distribution of trends of the same length in their matching control simulation. Simulations
885 follow the RCP8.5 scenario after year 2005. Dashed and solid red lines highlight the 50% and
886 90% levels of the cumulative distributions (Table 1). The orange bars are 5-95% uncertainty
887 ranges based on Monte Carlo analysis of equal length segments from the preindustrial
888 simulations (see Methods). Chosen climate variables are **(a, e)** Southern Hemisphere sea-ice
889 extent, **(b, f)** mean SST south of 50°S, **(c, g)** mean SAT south of 50°S and **(d, h)** SAM index.
890 Model details given in Supplementary Table 2. Observations used to compute observed sea
891 ice extent and SST trends over the 1979-2014 period are referenced in Figure 1. The
892 observed 1979-2014 SAT trend is derived from ERA-Interim 2-m air temperature fields.
893 Modelled and observed SAM indices were calculated from annual mean time series using
894 Empirical Orthogonal Function analysis applied on 500 hPa geopotential height fields over
895 the 90°S-20°S region, with observation-based geopotential height fields taken from the ERA-
896 Interim reanalysis.





