Attribution of polar warming to human influence

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The polar regions have long been expected to warm strongly as a result of anthropogenic climate change, because of the positive feedbacks associated with melting ice and snow[1,2]. Several studies have noted a rise in Arctic temperatures over recent decades[2–4], but have not formally attributed the changes to human influence, owing to sparse observations and large natural variability[5,6]. Both warming and cooling trends have been observed in Antarctica[7], which the Intergovernmental Panel on Climate Change Fourth Assessment Report concludes is the only continent where anthropogenic temperature changes have not been detected so far, possibly as a result of insufficient observational coverage[8]. Here we use an up-to-date gridded data set of land surface temperatures[9,10] and simulations from four coupled climate models to assess the causes of the observed polar temperature changes. We find that the observed changes in Arctic and Antarctic temperatures are not consistent with internal climate variability or natural climate drivers alone, and are directly attributable to human influence. Our results demonstrate that human activities have already caused significant warming in both polar regions, with likely impacts on polar biology, indigenous communities[2], ice-sheet mass balance and global sea level[11].

We use the CRUTEM3 (refs 9,10) near-surface temperature data set, which consists of land station temperature observations gridded on a $5^\circ \times 5^\circ$ grid, with no infilling of missing data. We use data from January 1900–July 2008 and take 5-yr means at locations where at least 50% of the monthly data are present. Supplementary Information, Fig. S1 shows the number of grid cells with data for the Arctic (65° N–90° N) and the Antarctic (65° S–90° S) in each 5-yr period. Most 5-yr mean grid cell temperatures in the polar regions are based on data from a single station, and in these cases gridded data are single-station temperature anomalies. In the Antarctic there are no station data before 1945 and we therefore restrict our analysis to the period 1950–1999. Expedition records, mainly located in the Antarctic Peninsula and Ross Sea sectors, suggest that Antarctica was $\sim$1 °C colder in the first half of the twentieth century compared with the 1957–1975 period[12]. In the Arctic, there are at least fifteen cells with data throughout the twentieth century; therefore, we use the whole century for our analysis of Arctic temperature.

Figure 1 shows mean observed Arctic and Antarctic temperature in black, based on the 1900–2008 and 1950–2008 periods respectively[13]. As data coverage is sparse, we give equal weight to each cell containing data when calculating areal means, rather than weighting by the areas of the grid cells. Both polar regions have exhibited warming over the periods considered, with large variability superposed. We compare observed temperatures with simulations from four CMIP3-coupled climate models (UKMO-HadCM3, PCM, CCSM3 and MIROC3.2(medres)). We choose all CMIP3 models for which an ensemble with natural forcings alone is available, and which include stratospheric ozone depletion in their combined anthropogenic and natural forcings simulations. Previous work has shown that, as a group, these four models perform better than average at simulating Antarctic climate[14], climate and variability in the northern extratropics[15] and variability in Arctic temperature[4]. Model monthly mean land temperature anomalies were regridded onto the observational $5^\circ \times 5^\circ$ grid and were masked with the observational coverage before calculating 5-yr mean spatial means. The ensemble mean temperature anomaly in 27 simulations including anthropogenic and natural forcings is shown in red in Fig. 1, and the ensemble mean temperature anomaly in 23 simulations including natural forcing alone is shown in blue. In the Arctic, the simulations including both anthropogenic and natural forcings reproduce the overall observed warming trend well. However, although these simulations show some predominantly anthropogenic early century warming[8], the warm anomaly in the 1930s and 1940s is not reproduced, suggesting that this was largely unforced variability, consistent with other analysis[4]. The number of observed 5-yr mean anomalies that lie outside the 2.5–97.5th percentile range associated with the ALL ensemble is not significant at the 5% level, indicating consistency between simulated and observed variability.

In the Antarctic, the simulations with natural and anthropogenic forcing show a warming trend. A warming trend is also observed[16], significant at the 5% level allowing for

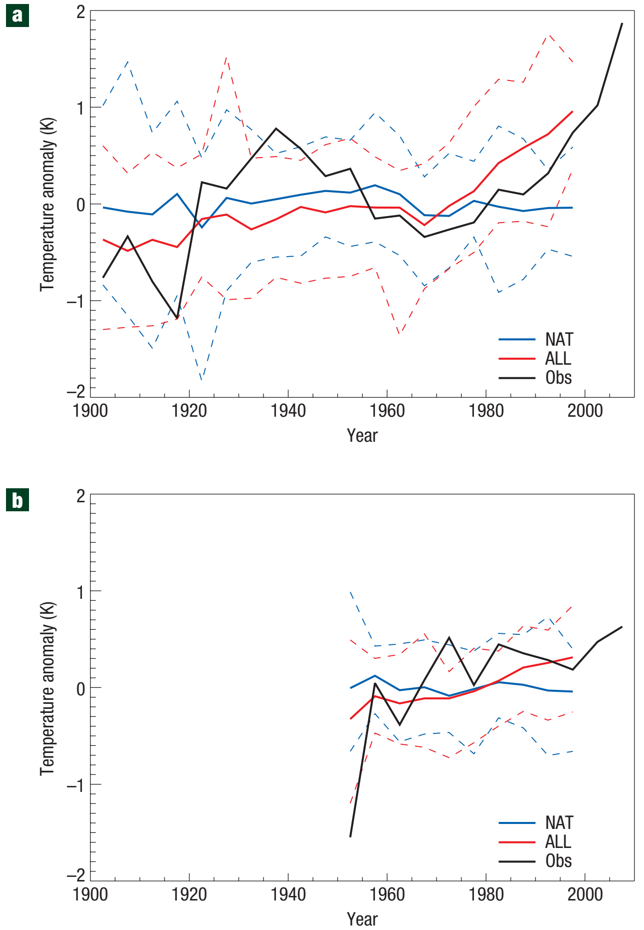

Figure 1 Simulated and observed Arctic and Antarctic mean temperature anomalies. a,**b**, Five-yr mean Arctic (**a**) and Antarctic (**b**) mean land temperature anomalies. Solid lines show observed temperature anomalies (black), the mean simulated response to natural forcings (solar irradiance changes and volcanic aerosol, denoted NAT; blue) and the mean simulated response to natural and anthropogenic forcings (greenhouse gas changes, stratospheric ozone depletion, sulphate aerosol, solar irradiance changes and volcanic aerosol, denoted ALL; red). Dashed lines show the warmest and coldest NAT (blue) and ALL (red) simulation in each 5-yr period, approximately representing 2.5th and 97.5th percentiles. Anomalies for 2005–2009 are based on observations up to July 2008.

autocorrelation. This warming trend observed at station locations, many situated on the coast and on the Antarctica Peninsula, may be larger than the warming in an area mean over the whole of Antarctica[16], although this is difficult to assess. Although observed Antarctic mean temperature is outside the 2.5–97.5th percentile range associated with the ALL ensemble more than would be expected by chance (the difference is significant at the 5% level), we find that simulated and observed Antarctic mean temperature trends are consistent, in contrast to a study using a different subset of CMIP3 models and an infilled observational data set[17]. The large cold anomaly in 1950–1954 is based on data from Faraday (now named Vernadsky) station in the grid cell at 65° S–70° S, 60° E–65° E: we demonstrate that our detection and attribution results are robust to the exclusion of data from this period. In neither polar region is the warming trend reproduced in response to natural forcings alone. Simulated temperatures are plotted only up to 1999, as many simulations end then; observed temperatures are plotted up to the present, and show continued warming over both polar regions since 2000.

In the Arctic, generally positive trends are apparent at individual grid cells in the observations and in the simulations with anthropogenic and natural forcings (Fig. 2a), but, after subtracting the mean trend, the pattern of trends is not similar in the models (Fig. 2c) and observations ($r = -0.25$). This difference in simulated and observed trend patterns in the Arctic is larger than would be expected based on the difference between individual model simulations in the multi-model ensemble, at the 5% level. However, we should not expect climate models to realistically simulate the grid-box scale response to climate forcings[18], and partly for this reason most detection and attribution studies use means over larger areas[8], such as the 90° sectors we use in this study. In the Antarctic, whereas the ensemble mean of the model simulations shows warming everywhere (Fig. 2d), the observations show strong warming on the Antarctic Peninsula[14,19], cooling at the South Pole and a mixture of positive and negative trends elsewhere, although positive trends predominate (Fig. 2b). A similar, albeit smoother, pattern of trends is seen in a spatially complete reconstruction of Antarctic temperature based on station data and sea surface temperature observations[20] (see Supplementary Information, Fig. S2). Another spatially complete reconstruction[16] shows more cooling over east Antarctica over the period 1960–1999, probably in part owing to the later start date (see Supplementary Information, Fig. S2). The simulated and observed trend patterns are correlated ($r = 0.24$), and consistent to within intra-ensemble variability. In neither hemisphere are comparable warming trends simulated in response to natural forcings alone (Fig. 2e,f). In both hemispheres, warming trends are larger and more widespread when calculated up to 2008 (Fig. 2g,h).

Parts of the observed and simulated trend patterns are associated with an upward trend in the Southern Annular Mode (SAM) index (Fig. 3), which has probably been forced by a combination of greenhouse gas increases and stratospheric ozone depletion[8]. The pattern of temperature trends associated with the trend in the SAM consists of warming of the Antarctic Peninsula and cooling elsewhere[19,21], but the effect on the observed trends seems weaker here than in previous studies[21], partly because we are considering annual mean changes rather than just summer and autumn, and partly because there was a maximum in the SAM in the early 1960s (ref. 22), making the SAM trend over the period considered here smaller than that over the 1969–2000 period[21]. After the SAM-congruent component of the observed temperature trends has been removed, residual trends show warming everywhere except for at the South Pole (Fig. 3c), making them more similar to simulated residual trends (Fig. 3d) than the corresponding raw trends. The CMIP3 models simulate a SAM-congruent temperature trend pattern that is weaker than that observed, owing to a smaller mean SAM trend in the models ($0.05\,\mathrm{hPa\,yr^{-1}}$) than that observed ($0.06\,\mathrm{hPa\,yr^{-1}}$) and a weaker temperature response to the SAM: the r.m.s. amplitude of the mean simulated temperature regression on the SAM is 79% of that observed.

To objectively test for the presence of an anthropogenic or natural response in observations of polar temperature, we use a detection and attribution analysis to compare simulated and observed changes[23–25]. Such methods, first developed to detect anthropogenic influence on global temperature, have more recently been used to detect anthropogenic influence on temperature on continental scales[8]. To reduce the number of spatial degrees of freedom, and focus on the more realistically simulated large-scale spatial patterns[18], we take four 90° sector means of simulated and observed 5-yr mean temperatures over each polar region (0° E–90° E, 90° E–180° E, 180° W–90° W and 90° W–0° E). We

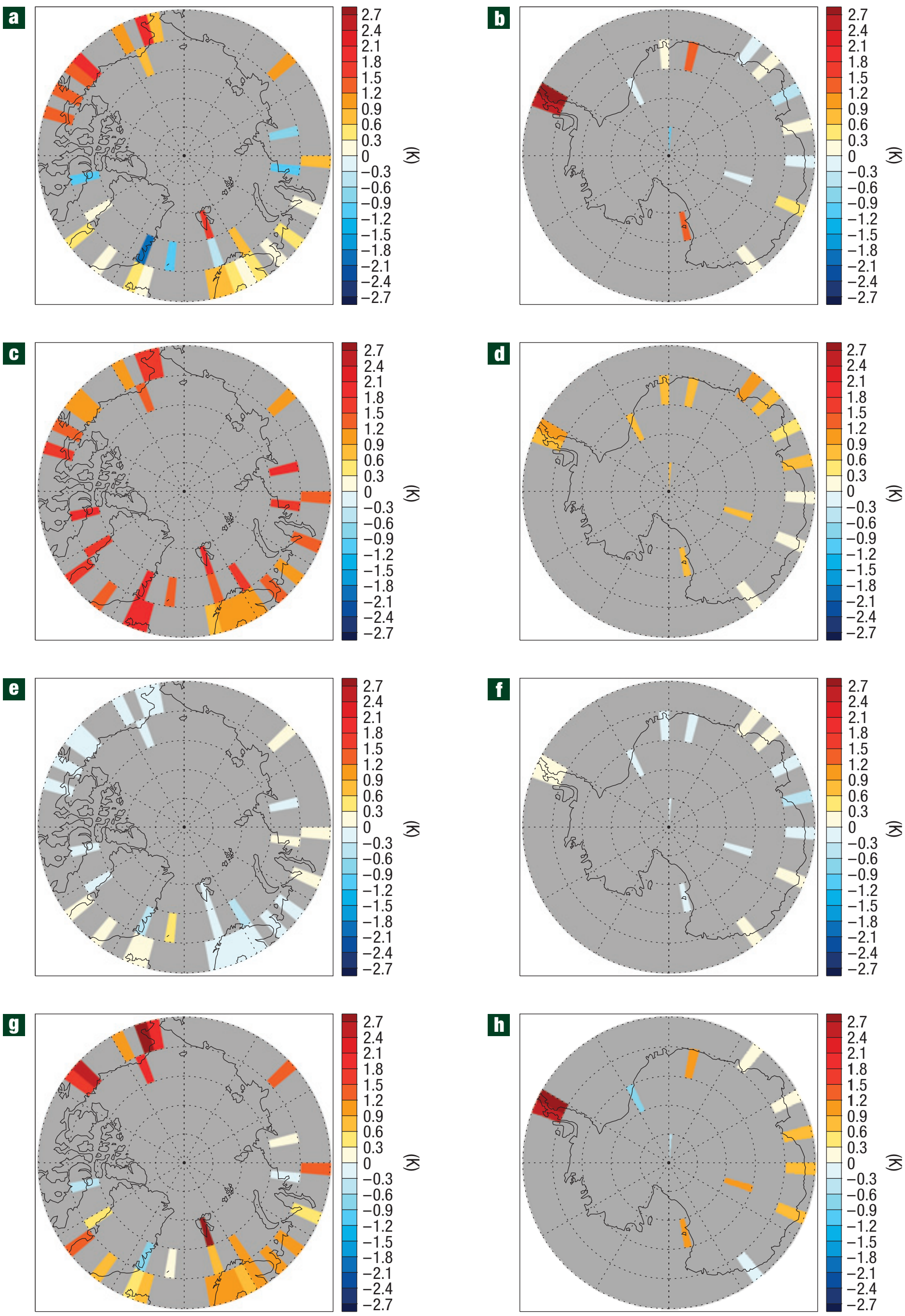

Figure 2 Simulated and observed grid cell temperature trends. Trends were calculated for grid cells with at least 70% of 5-yr means present in the Arctic (1900–1999) and Antarctic (1950–1999). **a**–**f**, Observed trends (**a**,**b**), simulated ALL trends (**c**,**d**) and simulated NAT trends (**e**,**f**). In **b**, locally significant warming at the 5% level, allowing for autocorrelation, was found in the cells containing the stations Vernadsky, Rothera, Novolarevskaja and Byrd, with significant cooling at the South Pole. **g**,**h**, Observed trends calculated in the same way up to July 2008.

regress observed 5-yr mean sector mean temperatures onto the simulated response to combined anthropogenic and natural forcings, and the simulated response to natural forcings alone in a total least-squares optimal regression[24]. We apply a transform to the regression coefficients[26] to obtain separate regression coefficients for the anthropogenic and natural responses. Sectors and periods containing no observations were excluded from the analysis. We use 1900–1999 data for the Arctic and 1950–1999 data for the Antarctic, and an empirical orthogonal function truncation of 28 (the maximum possible for the Antarctic), although comparable results were obtained at other truncations (see Supplementary Information, Fig. S3). Figure 4 shows regression coefficients for the responses to anthropogenic and natural forcings, together with their uncertainties evaluated from control variability. In both the Arctic and the Antarctic, the anthropogenic regression coefficient is significantly greater than zero, indicating a detectable response

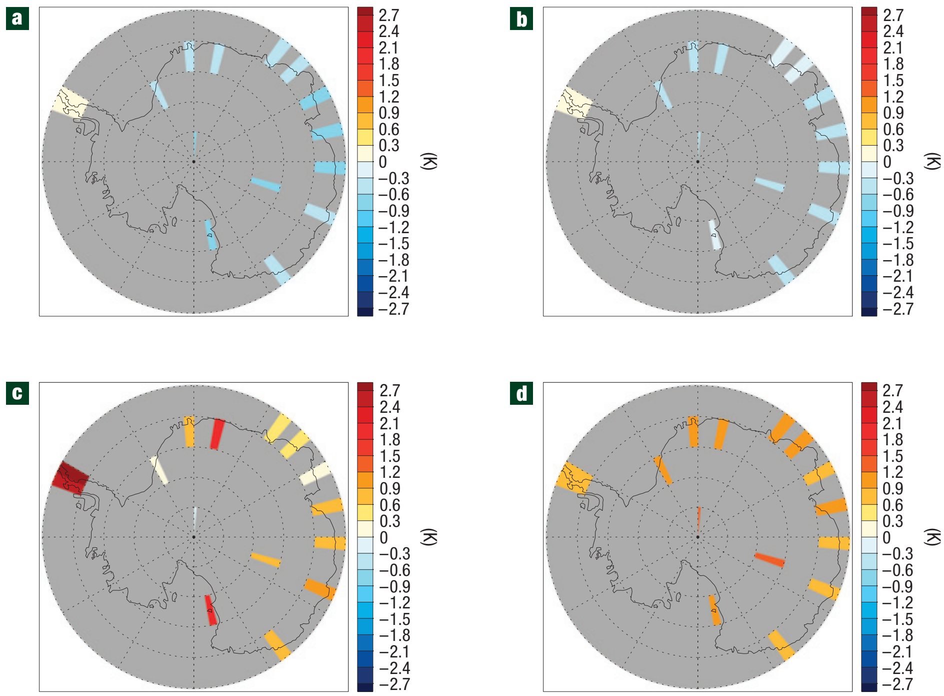

Figure 3 Observed and simulated SAM-congruent and SAM-residual temperature trends over the period 1950–1999. a, Observed SAM-congruent temperature trends, calculated by multiplying the observed regression pattern of monthly temperature anomalies on the SAM by the trend in the SAM[21]. The SAM trend was calculated from 5-yr means of a non-normalized Marshall SAM index[22] over the period 1955–1999 and extrapolated to 1950. **b**, Simulated SAM-congruent trends, calculated from the ALL ensemble in the same way. **c**,**d**, Observed (**c**) and simulated (**d**) residual trends, calculated by subtracting SAM-congruent trends from actual trends (Fig. 2a,b).

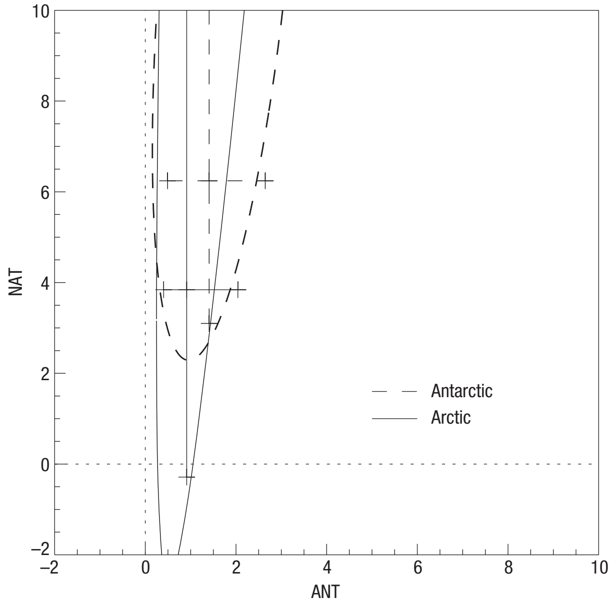

Figure 4 Regression coefficients of observed polar temperature anomalies against the simulated response to anthropogenic (*x* axis) and natural (*y* axis) forcing. Results are based on 5-yr mean Arctic 90° sector mean temperature anomalies between 1900 and 1999 (solid lines) and 5-yr mean Antarctic 90° sector mean temperature anomalies between 1950 and 1999 (dashed lines). One-dimensional 5–95% uncertainty ranges and curves enclosing 90% of the estimated joint distributions were estimated from simulated internal variability.

to anthropogenic forcing. In both cases, the anthropogenic regression coefficient is also consistent with one, indicating consistency between the magnitude of the simulated and observed anthropogenic response and that part of the observed temperature changes in both polar regions is attributable to anthropogenic influence. A residual test[26] indicates no inconsistency between simulated and observed variability in either region. The response to natural forcings was also detected over both poles at some truncations, although its regression coefficient was often greater than one, and it was found to be sensitive to variations in empirical orthogonal function truncation (see Supplementary Information, Fig. S3). As observational coverage was particularly limited at the start of the record in the Antarctic, we repeated the detection and attribution analysis for the Antarctic over the periods 1955–1999 and 1960–1999 and found a detectable anthropogenic response in both cases. We also found that anthropogenic influence was robustly detectable in Antarctic surface temperature after subtracting the component of surface temperature change linearly congruent with the SAM (see Supplementary Information, Fig. S3). It was not possible to robustly separate the greenhouse gas and ozone influence on surface temperature in either polar region, probably because of the sparse observational coverage and low signal-to-noise ratio.

The IPCC Fourth Assessment Report[8] concluded that 'Anthropogenic influence has been detected in every continent except Antarctica (which has insufficient observational coverage to make an assessment)'. Our findings demonstrate that anthropogenic influence is detectable in Antarctic land surface temperature, and distinguishable from a naturally forced response, even given the limited station network and short period for which data are available, and that circulation changes, which are largely anthropogenic[8], have reduced warming rates over most of Antarctica in models and observations in recent decades. In the Arctic, some authors have suggested that observed Arctic temperature changes are inconsistent with climate model predictions[27], and dominated by internal variability[28,29], and indeed so far no formal attribution studies of Arctic temperature change exist. We find that anthropogenic influence on Arctic temperature is detectable and distinguishable from the influence of natural forcings. Although climate models may not realistically simulate the recent decline in Arctic sea ice[30], we find no evidence in twentieth-century land temperature changes to suggest that climate models systematically underestimate high-latitude climate feedbacks. Overall, despite the paucity of observations, we find that human-induced warming is detectable in both these regions of high vulnerability to climate change.

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Author contributions

N.P.G. carried out most of the analysis and wrote the paper. D.A.S., P.A.S., T.N. and M.F.W. assisted with the provision of model data. A.Y.K. calculated SAM trends and regression patterns. G.C.H. proposed the study. P.D.J. provided advice on observations.

Author information

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