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Significant Warming of the Antarctic Winter Troposphere

J. Turner,* T. A. Lachlan-Cope, S. Colwell, G. J. Marshall, W. M. Connolley

We report an undocumented major warming of the Antarctic winter troposphere that is larger than any previously identified regional tropospheric warming on Earth. This result has come to light through an analysis of recently digitized and rigorously quality controlled Antarctic radiosonde observations. The data show that regional midtropospheric temperatures have increased at a statistically significant rate of 0.5° to 0.7°Celsius per decade over the past 30 years. Analysis of the time series of radiosonde temperatures indicates that the data are temporally homogeneous. The available data do not allow us to unambiguously assign a cause to the tropospheric warming at this stage.

Meteorological observations from the Antarctic research stations provide the most accurate data to investigate long-term climate change across the continent. Many of the surface records extend back to the International Geophysical Year of 1957 to 1958. These records indicate that the western side of the Antarctic Peninsula has experienced the largest measured annual near-surface warming (0.55°C per decade at Faraday/Vernadsky station) on Earth over the past 50 years (*1*). However, there have been few statistically significant temperature changes at the surface across the rest of the continent (*2*, *3*), and some studies have suggested a slight cooling in recent decades (*4*). This is in contrast to a mean near-surface warming across the Earth of 0.11°C per decade during the past 50 years (*5*).

Although there have been several investigations concerned with surface temperature change across the Antarctic (*6–8*), there have not been any comparable investigations of changes at upper levels, because many of the radiosonde observations were not available. Recently, many of the important radiosonde records have been digitized and intensively quality controlled in a project funded by the Scientific Committee on Antarctic Research (*9*). In particular, the Russian radiosonde observations are now available (www.antarctica.ac.uk/met/READER/). This represents a considerable increase in the coverage and completeness over the Antarctic component of previous global radiosonde compilations (*10–12*).

A summary of the annual and seasonal temperature trends at the 500-hPa level for the period from 1971 to 2003 is presented in Fig. 1A. We have concentrated on nine stations (most of which are in East Antarctica) that have reasonably complete records for this period; only five of these stations were included in the Angell studies of global upper air temperature trends (*10*, *11*). In this study, a monthly mean temperature was only computed if at least 30% of the daily ascents were available. Only 8% of the monthly means (*9*) were missing across the records of the nine stations, allowing reliable temperature trends to be computed. Figure 1A shows that there have been statistically significant increases in seasonal temperature at many of the stations across the continent, both in the coastal region, where most of the stations are located, and at Amundsen-Scott station at the South Pole.

We examined the mean vertical profile of the temperature trends for winter for the nine stations (Fig. 1B), because this is the season of maximum warming across most of the continent (compare with Fig. 1A). Warming has occurred throughout the troposphere, with the maximum increase in temperature in the midtroposphere (400 to 600 hPa). The mean winter trend for the nine stations from 1971 to 2003 was a 0.15°C increase per decade at the surface and a 0.70°C increase per decade in the midtroposphere. In the stratosphere, there has been cooling between 200 and 50 hPa, and the largest decrease in temperature was –0.16°C per decade at 100 hPa. The standard deviation (SD) of the station trends is large at the surface (Fig. 1B) because the pattern of change at this level is variable across the continent, and in the stratosphere because the impact of the Antarctic ozone hole has varied around the continent. However, the SD values are small in the midtroposphere, indicating that a fairly uniform warming has occurred across the Antarctic at this level.

The Angell analysis of global radiosonde data (*10*, *11*) considered changes over the layer from 850 to 300 hPa. For the period from 1971 to 2003, there was an annual global warming trend of 0.11°C per decade; the largest trend of 0.15°C per decade was during the Austral winter. The annual trend for the Southern Hemisphere was 0.07°C, and the greatest change took place during the winter when the trend was 0.10°C per decade. Within the Southern Hemisphere winter, the trends vary strongly by latitude: Equatorward of 60°S, the trend is 0.06°C per decade (*13*), whereas the data from the nine Antarctic stations analyzed in this paper have a mean temperature trend of 0.43°C per decade for 850 to 300 hPa. Thus, the trend for the Southern Hemisphere is dominated by the changes that have taken place across the Antarctic.

The 40-year European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data set (ERA-40) (www.ecmwf.int/research/era) provides an extremely valuable means of examining spatial variability of atmospheric parameters and change in recent decades. Although ERA-40 begins in 1957, there are problems with the quality of the high-latitude fields before 1979 (*14*, *15*). Therefore, we compared the 500-hPa temperature trends in ERA-40 (Fig. 2) with equivalent values from the radiosonde data for the period from 1979 to 2001 (the last full year of the reanalysis). The general pattern of the ERA-40 temperature trends is in broad agreement with the trends from the radiosonde data. However, ERA-40 has larger warming trends than the in situ data, except over the Antarctic Peninsula. For example,

British Antarctic Survey, Natural Environment Research Council, Cambridge CB3 0ET, UK.

*To whom correspondence should be addressed. E-mail: j.turner@bas.ac.uk

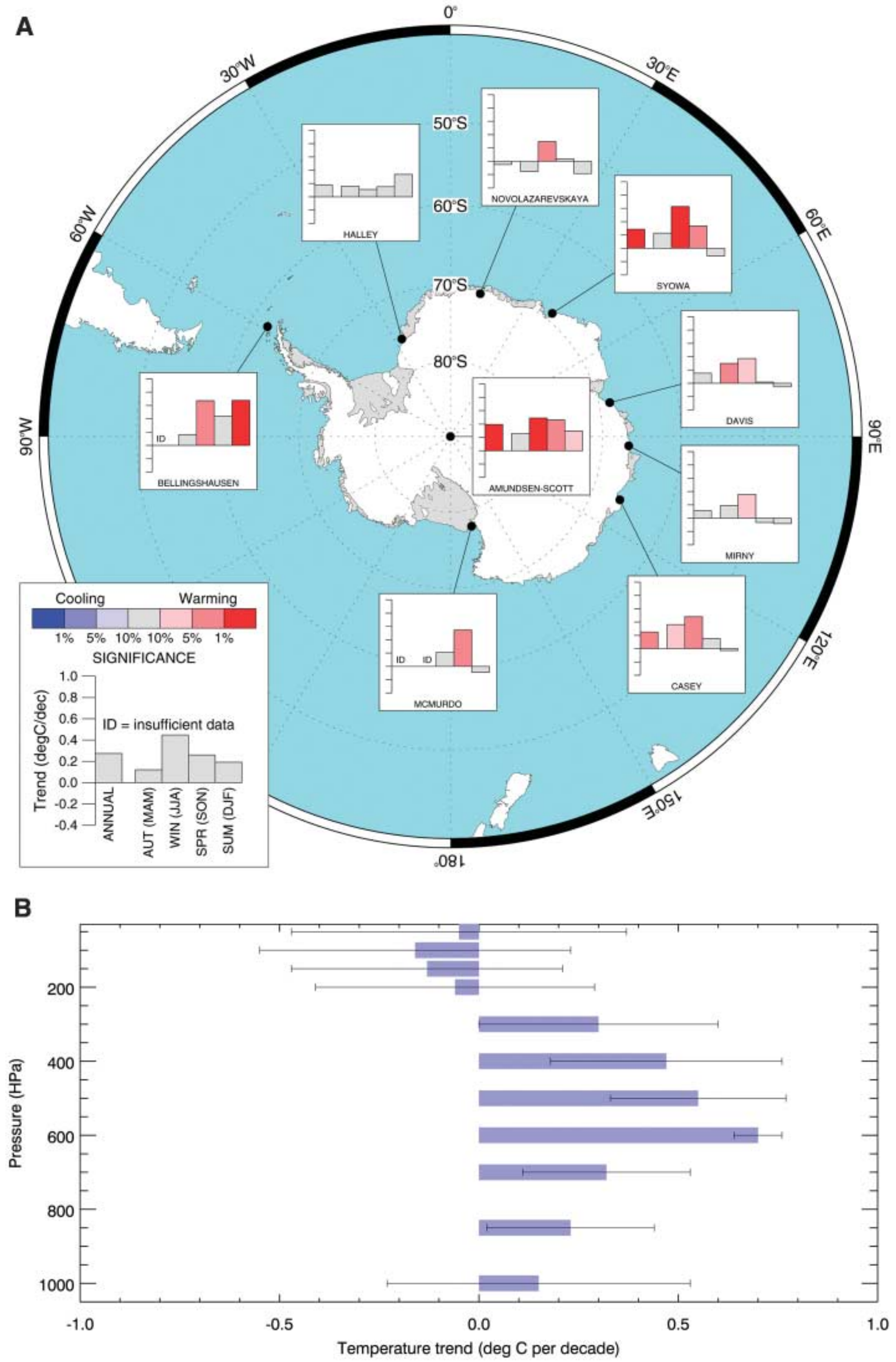

Fig. 1. (**A**) Annual and seasonal 500-hPa temperature trends (°C per decade) from 1971 to 2003 for nine radiosonde stations with long records. The shading indicates the statistical significance. ID indicates that less than 80% of annual/seasonal data were available. (**B**) The mean vertical profile of winter temperature trends and the SD (°C per decade for 1971 to 2003) at standard atmospheric levels for nine Antarctic radiosonde stations.

from 1979 to 2001, winter season 500-hPa temperature trends for Syowa and Casey were 0.92° and 0.73°C per decade, respectively, but Fig. 2 shows that ERA-40 had trends of more than 1°C per decade for this period. Figure 2 indicates that the midtropospheric winter warming observed in the radiosonde data encompasses the whole continent and much of the Southern Ocean. Notably, the largest warming trend in Fig. 2 is located over West Antarctica where there are no radiosonde records to confirm this feature.

The observed winter temperature trends at 850 to 300 hPa for the period from 1979 to 2001 were also compared with comparable trends from the satellite Microwave Sounder Unit measurements (*16*). Although the satellite data showed areas of warming (up to 1°C per decade), it also showed areas of cooling not seen in the radiosonde data nor in the ERA-40 fields. There is, however, evidence (*17*) that the satellite product may not be reliable around Antarctica in the winter because of the effects of the sea ice. Therefore, we did not use these products to interpret the radiosonde trends.

The major source of uncertainty in radiosonde temperatures and trends in their time series is the radiation correction (*18*), which is applied because of radiative effects on the temperature sensor. However, here we focused principally on winter season tropospheric data, when the radiative correction is small. This is because at the latitudes of Antarctica, the Sun is close to or below the horizon in winter. Assessments of radiosonde temperature biases resulting from radiation errors (*19*) suggest that any such errors are much smaller than those needed to give the trends we observed in the Antarctic data.

The trends presented in Fig. 1 were derived from data collected by a number of different national programs, and they used a variety of radiosonde types, so it is unlikely that changes of equipment or observing practice were responsible for an artificial Antarctic-wide temperature trend. Also, we examined the available metadata for changes of radiosonde type, given that instrumental changes can result in jumps in the record (*20*), and found no evidence of discontinuities at these times. We also performed an objective test for discontinuities in the time series of 500-hPa temperatures using the method of Lund and Reeves (*21*), which tests for both jumps and changes in trend. In all cases, the test results indicated no significant discontinuities. Therefore, we are confident that the observed trends are not a result of instrumental changes. Figure 3 shows the 500-hPa winter temperatures from the nine stations and their mean, which reveals a gradual increase in temperatures for all of the stations. However, there is considerable interannual variability in the data.

Changes in the heat budget of the Antarctic may be ascribed to a number of processes. Our data set of daily ascents allows us to examine the changes in the advection of energy into the region or modifications to the radiation regime. Alterations to the poleward flux of heat were investigated by computing the horizontal thermal advection ($-V_g \nabla_p T$, where V_g is the geostrophic wind and $\nabla_p T$ is the horizontal gradient of temperature) from the radiosonde ascents at the coastal stations (*22*). For the period from 1971 to 2003, there was no evidence of a greater horizontal flux of heat into the Antarctic; indeed, during the winter season there was a very small trend toward a slightly reduced poleward heat flux at a number of the stations.

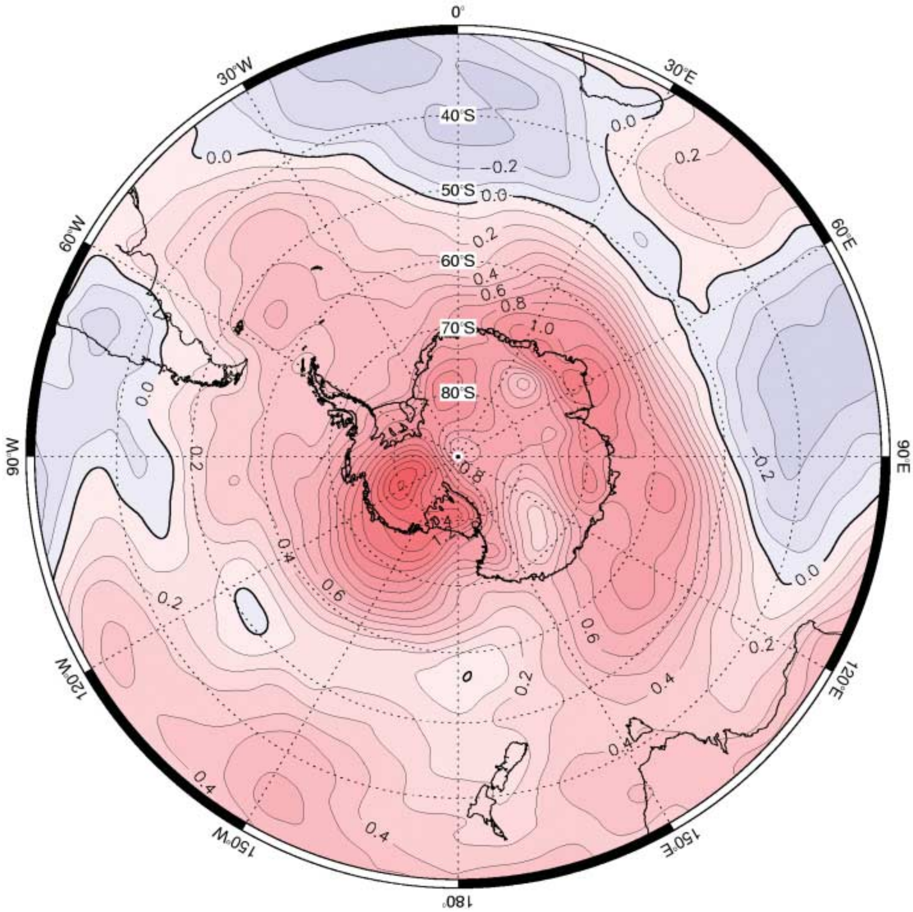

Fig. 2. Trends (°C per decade) in the winter season 500-hPa temperatures from 1979 to 2001 from the ECMWF reanalysis.

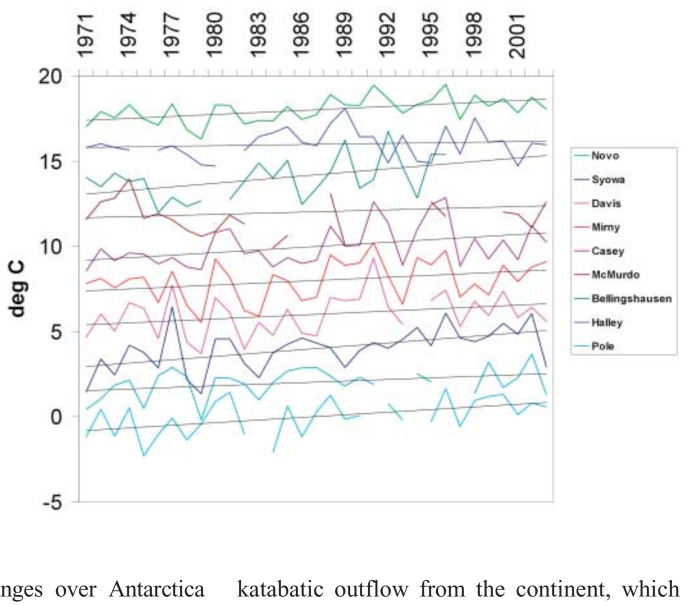

Fig. 3. Time series of winter 500-hPa temperature anomalies (°C) from 1971 to 2003 for the nine stations, along with the mean. Linear regression lines have been added. The data have been offset as follows: South Pole (+0°C), Novolazarevskaja (+2°C), Syowa (+4°C), Davis (+6°C), Mirny (+8°C), Casey (+10°C), McMurdo (+12°C), Bellingshausen (+14°C), Halley (+16°C), and the mean (+18°C).

Vertical velocity changes over Antarctica can modify the temperature regime by means of enhanced subsidence and adiabatic heating. Detecting changes in vertical velocity is extremely difficult, so we have investigated variability in the flow in the high-latitude circulation cell by means of variations in the katabatic outflow from the continent, which is a major feature of East Antarctica. Analysis of the meridional component of the surface winds from the nine stations suggests that there has been no significant change in the katabatic flow and therefore the circulation cell over the past 30 years. Although no relevant circulation changes can be found with the use of the above diagnostic techniques, it is possible that changes below the detection threshold could have contributed to the observed warming.

General circulation models (GCMs) are a very powerful tool for investigating the mechanisms responsible for changes in the Earth system, and climate model runs spanning the instrumental period were examined to see if they reproduced the large warming during the winter. We examined output from a four-member ensemble of the Hadley Centre coupled atmosphere-ocean GCM (HadCM3) (*23*), which was run from 1880 to 1999 forced with realistic greenhouse gases, aerosols, volcanic aerosols, and solar variability. For the period from 1970 to 1999, the four members of the ensemble showed a large variability in the Antarctic tropospheric temperature trends, indicating the difficulty of reproducing climate change across the region. However, on average, the runs had a maximum warming in the midtroposphere, although the winter season trends were only ~0.2°C per decade. Although the trends in the model runs are smaller than in the observations, they are not statistically significantly different.

The available observations and current state of climate models do not allow us to unambiguously assign a cause to the tropospheric warming. The lack of a clear change to the atmospheric circulation suggests in situ effects, such as changes in cloud amount or particle size, and increases in the greenhouse gas concentration may well be playing a part. The temperature changes observed in the radiosonde data of a warming troposphere and cooling stratosphere are what would be expected as a result of increasing greenhouse gases. However, because the climate model runs we examined did not reproduce the observed high-latitude changes, we are unable to attribute these changes to increasing greenhouse gas levels at this time. The lack of a similar warming trend at the surface, the evidence that much of the ocean around the Antarctic is sea ice covered in winter, and the midtropospheric warming observed at the South Pole together make it unlikely that the ocean is playing a major role. The observation of significant tropospheric warming at southern high latitudes, decoupled from a similar surface change, is therefore very important for those investigating natural climate variability and the possible impact of increasing greenhouse gases.

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Changes in Surface Water Supply Across Africa with Predicted Climate Change

Maarten de Wit* and Jacek Stankiewicz

Across Africa, perennial drainage density as a function of mean annual rainfall defines three regimes separated by threshold values of precipitation. This nonlinear response of drainage to rainfall will most seriously affect regions in the intermediate, unstable regime. A 10% decrease in precipitation in regions on the upper regime boundary (1000 millimeters per year) would reduce drainage by 17%, whereas in regions receiving 500 millimeters per year, such a drop would cut 50% of surface drainage. By using predicted precipitation changes, we calculate that a decrease in perennial drainage will significantly affect present surface water access across 25% of Africa by the end of this century.

Water is essential to human survival, and changes in its supply from overland flow can potentially have devastating implications, particularly in Africa, where much of the population relies on local rivers for water. Future climate change poses one of the greatest threats to poverty eradication on this continent, and related changes in surface water supply will exacerbate this threat (*1*). To predict future supply, it is necessary to understand how the drainage relates to biological, geological, and atmospheric parameters. These form a highly complex system, but simpler relationships can be identified within it, in particular relating drainage to precipitation. Even this relationship is nonlinear (*2*, *3*). Our detailed analysis of the African river systems identifies three climatic regimes. Areas receiving a low rainfall have virtually no perennial drainage. Above a threshold rainfall, there exists an intermediate range in which the drainage density increases with increasing rainfall. This regime can be termed "unstable": A change in climate would directly result in a change in surface water supply. This relationship is not indefinite; in high-rainfall areas other factors, like vegetation, begin to play a role, and a slight decrease in drainage density with increasing rainfall is observed. Here, we quantify how a moderate but variable change in precipitation across Africa by the second part of this century, as predicted by an ensemble of global climate-change models, would directly affect African countries, 75% of which fall at least partially into the unstable intermediate rainfall regime.

Africa Earth Observatory Network (AEON) and Department of Geological Sciences, University of Cape Town, Rondebosch 7701, South Africa.

*To whom correspondence should be addressed. E-mail: maarten@cigces.uct.ac.za

Our studies make use of AEON's Africa Database (*4*). This geographic information system (GIS) database includes all rivers and lakes in Africa (Fig. 1), manually digitized from topographic maps of individual countries on the basis of their own cadastral databases (figs. S1 to S4). The average stream separation (ratio of land area to total stream length) of the set is 15 km. This corresponds to about 2 million km of digitized rivers. Streams were checked against the 90-m SRTM (Shuttle Radar Topography Mission) digital elevation model (DEM) and were found to be within 300 m from valleys seen on the DEM. This uncertainty is two orders of magnitude less than the resolution of the database. All streams have also been classified as either perennial or nonperennial (as defined on local cadastral maps), and all river networks were ordered according to the Horton-Strahler ordering scheme (*5*). The database also includes climatic conditions over the African continent, such as seasonal rainfall and temperatures (*6*).

To understand the relationship between rainfall and drainage in Africa, we did a continental scale analysis by subdividing Africa into square blocks of 1000 km across [giving areas of 1,000,000 km^2; smaller areas near the coast were combined into bigger blocks (Fig. 1 inset)]. For each of the 37 blocks, we computed the mean annual precipitation as well as the perennial drainage density. This latter quantity is the total perennial stream length per unit area. The exact value of the total length, and thus of the density, depends on the resolution of the map from which the streams were obtained. There are also many finer points of what exactly constitutes a stream (*2*, *4*, *7*). For this reason, it is meaningless to compare density values from different studies on other continents, for example, unless the same resolution and standardized parameters are used. It is also important that these parameters are constant throughout the analysis; otherwise density variations could be observed where none really exist. The plot of perennial density as a function of mean annual precipitation is shown in Fig. 2A. A similar regional analysis was done for southern Africa (south of the Zambezi river, Fig. 1). Here, 24 blocks 500 km across were used (figs. S1 and S2), and the observed results are shown in Fig. 2B.

From the plots in Fig. 2, perennial drainage density as a function of mean annual rainfall consists of regimes separated by threshold values of precipitation. Areas receiving less than 400 mm $year^{-1}$ have almost no perennial drainage (*8*). Above this threshold of ~400 mm $year^{-1}$, the perennial drainage density initially increases with increasing precipitation, but this does not go on indefinitely. The next threshold is defined statistically at ~1000 mm $year^{-1}$ (*9*).

We therefore propose a model for the relationship between mean annual precipitation and perennial drainage that comprises three scaling regimes separated by two thresholds. Areas receiving less than 400 mm $year^{-1}$ have no perennial drainage, unless they are mountainous regions conducive to runoff (*8*). Above that threshold, density increases linearly with increasing precipitation until another threshold of ~1000 mm $year^{-1}$ is reached. Above that value, the density decreases slightly with increasing rainfall (*8*). We do not know whether there is