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ANTARCTIC CLIMATE CHANGE DURING THE LAST 50 YEARS

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ABSTRACT

The Reference Antarctic Data for Environmental Research (READER) project data set of monthly mean Antarctic near-surface temperature, mean sea-level pressure (MSLP) and wind speed has been used to investigate trends in these quantities over the last 50 years for 19 stations with long records. Eleven of these had warming trends and seven had cooling trends in their annual data (one station had too little data to allow an annual trend to be computed), indicating the spatial complexity of change that has occurred across the Antarctic in recent decades. The Antarctic Peninsula has experienced a major warming over the last 50 years, with temperatures at Faraday/Vernadsky station having increased at a rate of 0.56 °C decade^{-1} over the year and 1.09 °C decade^{-1} during the winter; both figures are statistically significant at less than the 5% level. Overlapping 30 year trends of annual mean temperatures indicate that, at all but two of the 10 coastal stations for which trends could be computed back to 1961, the warming trend was greater (or the cooling trend less) during the 1961–90 period compared with 1971–2000. All the continental stations for which MSLP data were available show negative trends in the annual mean pressures over the full length of their records, which we attribute to the trend in recent decades towards the Southern Hemisphere annular mode (SAM) being in its high-index state. Except for Halley, where the trends are constant, the MSLP trends for all stations on the Antarctic continent for 1971–2000 were more negative than for 1961–90. All but two of the coastal stations have recorded increasing mean wind speeds over recent decades, which is also consistent with the change in the nature of the SAM. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: Antarctica; climate variability; temperature; pressure; wind speed

1. INTRODUCTION

A number of recent studies concerned with Antarctic climate variability have highlighted the marked warming observed on the western side of the Antarctic Peninsula (King, 1994; Vaughan *et al*., 2001; Marshall *et al*., 2002) coupled with disintegration of several floating ice shelves (Vaughan, 1993). The warming at low elevations on the Bellingshausen Sea (western) coast of the Antarctic Peninsula is as large as any increase observed on Earth over the last 50 years, and at Faraday (now Vernadsky) station (see Figure 1) the annual mean surface temperature has risen by about 2.5 °C since the 1950s. On the eastern side of the peninsula there are very few occupied stations, but the disintegration of the northern part of the Larsen Ice Shelf implies major climate changes are also taking place in this area. Although the temperature rise at Faraday/Vernadsky has been substantial, there are indications (King and Comiso, 2003) that the region of marked warming is

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quite limited and is restricted to an arc from the southwestern part of the peninsula, through Faraday to a little beyond the tip of the peninsula.

Other environmental indicators point to a cooling over parts of the high southern latitudes. For example, Zwally *et al*. (2002) noted that the areal extent of Antarctic sea ice computed from satellite passive microwave imagery had increased around much of the continent over the last 20 years, suggesting either colder near-surface air temperatures over the Southern Ocean or changes in oceanic conditions. In addition, Comiso (2000) found a small cooling in surface skin temperatures across much of the continent in his study based on cloud-cleared infra-red satellite imagery covering the period 1979 to 1998.

In recent years a number of studies have examined climate change across the Antarctic using station observations. Jacka and Budd (1991) used data from 1956 to the late 1980s and suggested that there had been a warming of around 0.28 °C decade^{-1}. They updated their work (Jacka and Budd, 1998) to cover the period up to 1996 and found a warming of 0.12 °C decade^{-1}.

A further study of trends in Antarctic near-surface temperatures was carried out by Jones (1995). He considered the temperature records from 16 stations that covered 1957–94 and found an increase of 0.57 °C over this period, which was statistically significant at the <5% level. This rate of change is

Figure 1. A map of Antarctica with locations of selected research stations indicated

of the same order of magnitude as that reported by Jacka and Budd (1998). The Jones (1995) study has recently been updated (Jones and Reid, 2001) and can be found as a Web-based publication at http://cdiac.esd.ornl.gov/epubs/ndp/ndp032/ndp032.html.

The question of whether the Antarctic as a whole has warmed or cooled in recent decades has been considered in a number of papers. Raper *et al*. (1984) attempted to derive the mean annual temperature of the Antarctic continent by computing an areally weighted mean of the station data and found that there had been a warming of 0.29 °C decade^{-1} for 1957–82, a result that was significant at the <5% level. Doran *et al*. (2002) derived annual and seasonal temperature trends (1966–2000) for the Antarctic using the University of East Anglia HadCRUT data set and claimed that there had been a net cooling of the entire continent over this period. However, Turner *et al*. (2002) argued that it was not possible to derive a trend for the whole continent because the limited amount of data had to be extrapolated across unrealistically large distances.

All the above studies have been based upon monthly mean near-surface temperature data from a limited number of Antarctic climate data sets assembled by individual workers or research groups. One such data set was created by Jacka *et al*. (1984) and consists of annual and monthly mean surface temperature data for the continent and a number of island stations across the Southern Ocean and South Pacific. Schwerdtfeger (1984) included some annual and monthly mean temperature data for selected stations in his textbook on the weather of the Antarctic. One of the most comprehensive data sets of mean Antarctic temperatures and MSLP values was created by Jones and Limbert (1987). This covered 29 stations south of 60 °S and was originally published in hardcopy form, but has recently been updated and made available on the Web at http://cdiac.esd.ornl.gov/epubs/ndp/ndp032/ndp032.html. A further data set has been created by the Goddard Institute for Space Studies (GISS) and can be found at http://www.giss.nasa.gov/.

The above data sets suffer from a number of problems, including:

- Data from different stations have been combined to create single time series.
- No metadata were provided, so it is not clear when stations have moved or when new observing instruments were introduced.
- It is often not stated what quality control has been carried out on the observations.
- It is unclear how the daily mean temperatures were produced prior to the monthly means being computed. At some stations the daily mean is calculated from the three- or six-hourly synoptic observations, whereas at other stations it is taken as the mean of the daily maximum and minimum temperatures.

The Scientific Committee on Antarctic Research (SCAR), therefore, established the Reference Antarctic Data for Environmental Research (READER) project to produce a new, improved data set of mean Antarctic climate data for use in climate-change studies. The details of the data collected and quality control of the observations are described in detail in Turner *et al*. (2004), so here we only provide a brief account of these matters in Section 2. Section 3 considers the trends in the surface temperature, MSLP and surface wind speed data and relates these to the climatic cycles observed in the mid- and high-latitude areas of the Southern Hemisphere. Section 4 includes a discussion of how the trends computed here compare with earlier estimates and describes how the project might develop in the future.

2. THE READER DATABASE

The READER database consists of monthly mean near-surface and upper air temperature, MSLP or surface pressure, near-surface and upper air wind speed, and heights of standard pressure surfaces. Surface wind direction data were not included, as many Antarctic stations are often heavily influenced by the local orography and are frequently not representative of the broad-scale flow. Where available, extensive metadata are provided on the changes that have taken place in the observing practices, station locations and instrumentation, in order that the possible impact of changes could be examined.

Our primary goal within READER has been to recompute monthly mean climatic data from the synoptic reports from the occupied Antarctic stations and automatic weather stations (AWSs) that have long records.

We did not attempt to include data for all stations that had operated in the Antarctic; rather, we present data for a number of key sites distributed around the continent with long records. For some important stations where the synoptic reports were not available, the means were computed from other sources of data, as discussed below.

Surface data were included for occupied stations operating year-round with records extending back at least 25 years, although not necessarily in a continuous period, or stations currently in operation that had operated for the last 10 years. Preference was given to using the six-hourly synoptic reports, but CLIMAT messages were used if these were not available. A final option was to use the synoptic reports off the Global Telecommunications System (GTS).

AWS data were included for systems that had operated for the last 5 years, or for at least 10 years at some previous time, not necessarily in a continuous period. Although many AWSs provide data at high temporal frequency, means for READER were computed using the six-hourly observations obtained from the AWS operators in the USA, Australia, Germany and Italy, since these observations will have been quality controlled.

A thorough quality control of the data was carried out before the monthly means were computed. This was relatively easy when the six-hourly synoptic data were available, compared with trying to detect errors in the CLIMAT messages where the individual synoptic reports were not available.

As a second phase of the project, upper air wind speed and temperature, along with geopotential height for selected levels, are also being collected.

The READER dataset can be accessed via the World Wide Web at http://www.antarctica.ac.uk/met/programs-hosted.html.

3. TRENDS IN THE SURFACE DATA

3.1. Temperature trends

Table I gives the annual and seasonal near-surface temperature trends for the 19 stations over the full length of the records, with a graphical representation of the trends being shown in Figure 2 for the period 1971–2000. Table I also indicates whether the means were produced primarily from the synoptic observations or taken from the CLIMAT messages. The trends were computed using a standard least-squares method, with the methodology used to calculate the significance levels based upon Santer *et al*. (2000). Briefly, an effective sample size was calculated based on the lag-1 autocorrelation coefficient of the regression residuals. This effective sample size was used for the computation of the standard error and in indexing the critical values of Student's t distribution.

The largest annual warming trends are found on the western and northern parts of the Antarctic Peninsula, with Faraday/Vernadsky having the largest statistically significant trend at $+0.56\,^{\circ}\mathrm{C}$ decade^{-1} over 1951–2000, a figure that is significant at the $<5\%$ level. Rothera station, some 300 km to the south of Faraday, has a larger annual warming trend, but the shortness of the record and the large interannual variability of the temperatures means that the trend is not statistically significant. Although the region of marked warming extends from the southern part of the western Antarctic Peninsula to the South Shetland Islands, the rate of warming decreases away from Faraday, with the long record from Orcadas only having experienced a warming of $+0.20\,^{\circ}\mathrm{C}$ decade^{-1}. However, it should be noted that this record covers a 100 year period rather than the 50 years for Faraday.

Around the rest of the Antarctic the annual temperature trends are much more variable. The greatest warming outside the peninsula region is at Scott Base, where temperatures have risen at a rate of $+0.29\,^{\circ}\mathrm{C}$ decade^{-1}, although this is not statistically significant. The high spatial variability of the changes is apparent from the data for Novolazarevskya and Syowa, which are 1000 km apart. The former station has warmed at a rate of $+0.25\,^{\circ}\mathrm{C}$ decade^{-1} over 1962–2000, which is significant at the 10% level, whereas the record from Syowa shows almost no change over this period.

The seasonal temperature trends in Table I indicate that at 14 out of the 19 stations, and at all the stations on the Antarctic Peninsula except Esperanza, the greatest warming has occurred during the winter. This is the time of year when air–sea-ice feedback mechanisms are most effective and when a small reduction in

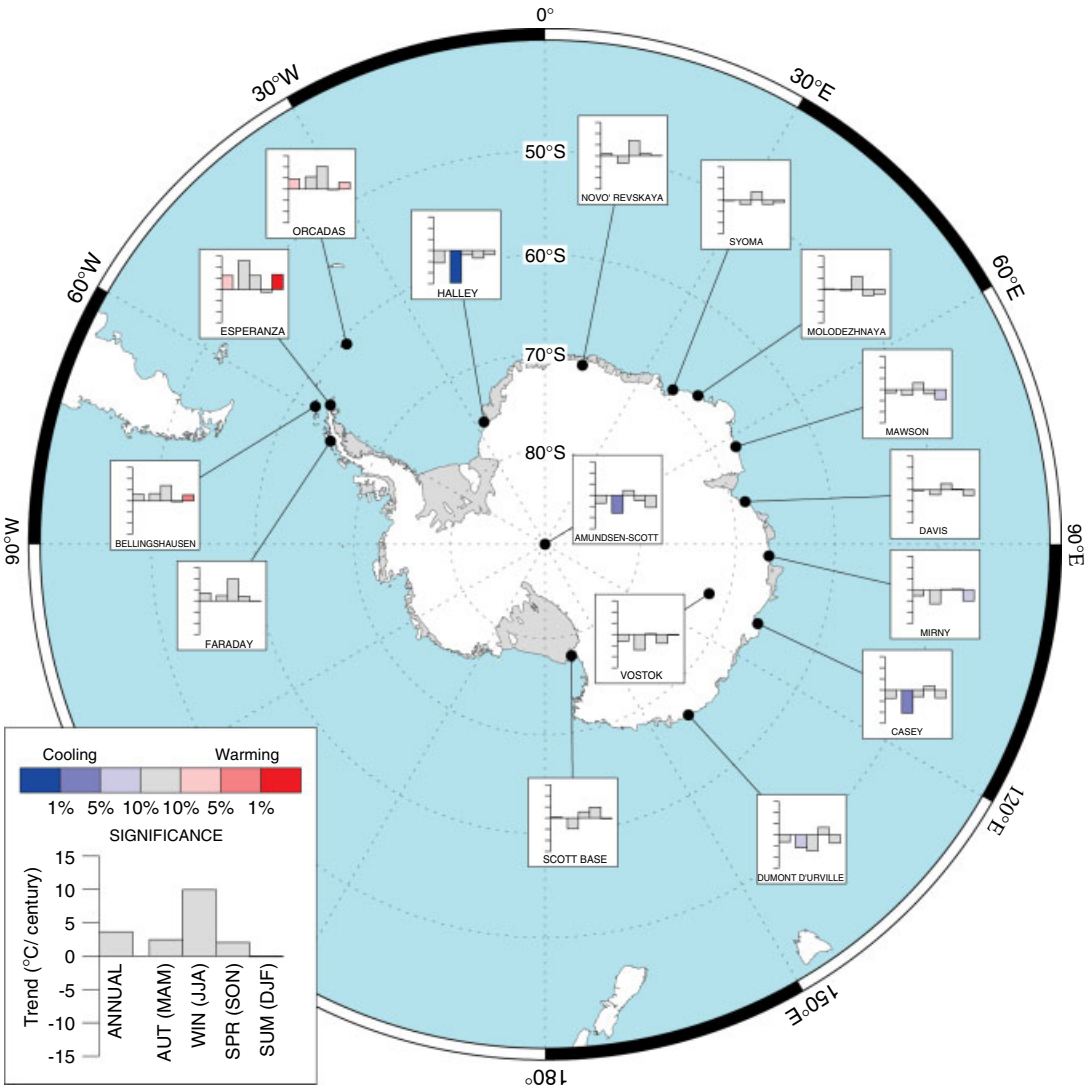

Figure 2. Antarctic near-surface temperature trends for 1971–2000. A minimum of 27 years of data are required for inclusion. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

sea ice can have a large impact on the air temperatures. However, the relationship between the temperatures at coastal stations and sea ice off the coast is complex and varies around the continent, and it is only on the western side of the Antarctic Peninsula that there is a high correlation between these two quantities. This can be seen from Figure 3, which shows the winter-season mean sea-ice concentration at 70 °W and the mean Faraday/Vernadsky temperature. The correlation between these two quantities is −0.64, with higher (lower) temperatures being associated with lower (higher) sea-ice concentrations to the west of the peninsula. Reliable satellite-derived sea-ice extent and concentration data only became available in the late 1970s, but since that time the mean winter temperature at Faraday/Vernadsky has been increasing and the sea-ice concentrations to the west of the peninsula decreasing (Figure 3). However, it is unlikely that the winter-season warming at the coastal stations beyond the Antarctic Peninsula is a result of changes in sea-ice extent since 1979, since Zwally *et al*. (2002) showed that sea ice has been increasing since this time.

The changing nature of the temperature trends over recent decades is indicated in Table II, which shows overlapping 30 year trends in the annual mean surface temperatures. For most stations, only 1961–90 and

Table I. Annual and seasonal surface temperature trends at selected Antarctic stations. Bold plus underlined values: significant at the 1% level. Bold values: significant at the 5% level. Italicized text: significant at the 10% level. Trends included if 90% of the observations are available

Station	Temperature trend (°C decade^{-1})					Period	Data used[a]
	Annual	Spring	Summer	Autumn	Winter		
Novolazarevskya	*+0.25 ± 0.27*	+0.25 ± 0.41	+0.19 ± 0.34	+0.08 ± 0.46	+0.44 ± 0.66	1962–2000	S & C
Syowa	+0.01 ± 0.35	+0.01 ± 0.48	−0.01 ± 0.27	−0.12 ± 0.67	+0.14 ± 0.58	1960–61 1967–2000	S
Molodezhnaya	−0.06 ± 0.29	−0.18 ± 0.50	−0.14 ± 0.32	−0.21 ± 0.43	+0.30 ± 0.77	1964–95, 1997–98	C & G
Mawson	−0.11 ± 0.23	−0.04 ± 0.33	−0.09 ± 0.26	−0.30 ± 0.40	+0.03 ± 0.58	1955–2000	S & G
Davis	+0.03 ± 0.35	+0.05 ± 0.50	+0.05 ± 0.30	−0.26 ± 0.60	+0.15 ± 0.67	1958–63, 1970–2000	S & G
Mirny	−0.01 ± 0.26	+0.09 ± 0.46	−0.14 ± 0.30	−0.28 ± 0.45	+0.31 ± 0.56	1956–2000	S & G
Vostok	−0.02 ± 0.34	−0.11 ± 0.51	+0.13 ± 0.42	−0.32 ± 0.63	+0.14 ± 0.85	1958–2000	C & G
Casey	+0.01 ± 0.40	+0.13 ± 0.50	−0.09 ± 0.30	−0.14 ± 0.90	+0.22 ± 0.83	1962–2000	S & G
Dumont d'Urville	+0.02 ± 0.27	+0.23 ± 0.45	0.00 ± 0.31	*−0.34 ± 0.35*	+0.17 ± 0.60	1956–2000	S & C
Scott Base	+0.29 ± 0.36	+0.34 ± 0.68	+0.05 ± 0.38	+0.18 ± 0.65	+0.43 ± 0.71	1958–2000	C
Rothera	+1.01 ± 1.42	+1.06 ± 1.53	+0.36 ± 0.57	+1.37 ± 1.46	+1.73 ± 2.79	1978–2000	S
Faraday/Vernadsky	**+0.56 ± 0.43**	+0.25 ± 0.4.4	**+0.24 ± 0.17**	**+0.63 ± 0.60**	**+1.09 ± 0.88**	1951–2000	S
Bellingshausen	+0.35 ± 0.46	−0.10 ± 0.47	**+0.30 ± 0.20**	+0.51 ± 1.05	+0.58 ± 0.97	1969–2000	S
Esperanza	*+0.41 ± 0.42*	−0.07 ± 0.57	**+0.43 ± 0.34**	+0.82 ± 1.11	+0.51 ± 0.82	1961–2000	C
Marambio	<90%	−0.8 ± 10.5	<90%	<90%	+0.81 ± 1.53	1971–2000	C
Orcadas	**+0.20 ± 0.10**	**+0.15 ± 0.14**	**+0.15 ± 0.06**	**+0.21 ± 0.16**	**+0.27 ± 0.24**	1904–2000	C
Halley	−0.11 ± 0.47	0.00 ± 0.53	+0.12 ± 0.28	−0.56 ± 0.81	+0.02 ± 0.76	1957–2000	S
Neumayer	−0.13 ± 1.03	−0.01 ± 1.69	−0.02 ± 1.25	**−1.37 ± 1.32**	+0.30 ± 2.23	1982–2000	S
Amundsen–Scott	*−0.17 ± 0.21*	−0.12 ± 0.63	−0.21 ± 0.49	−0.19 ± 0.45	−0.20 ± 0.50	1958–2000	S

[a] S: synoptic data; C: CLIMAT; G: GTS.

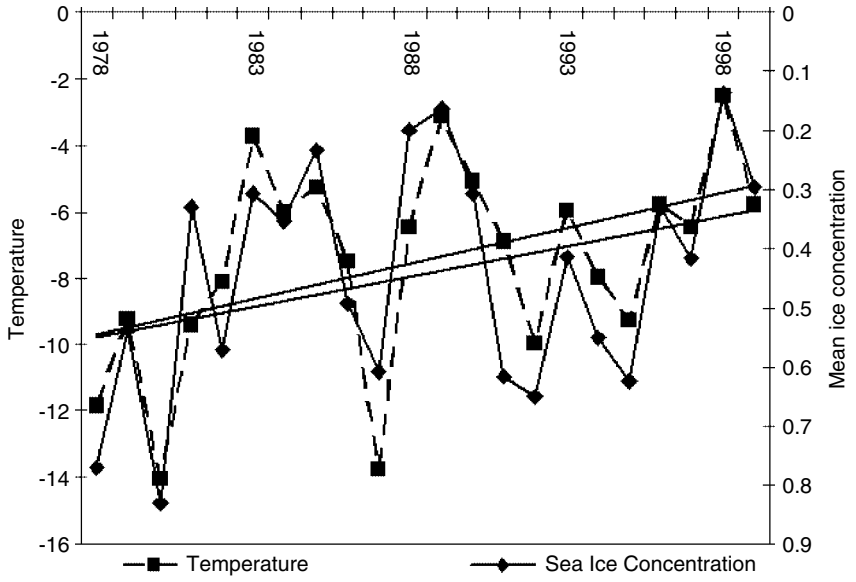

Figure 3. Winter season (June–August) mean sea-ice concentration at 70°W and Faraday/Vernadsky mean winter near-surface temperature. Trend lines produced by linear regression are shown for both time series

1971–2000 can be considered because of the shortness of the records, although three 30 year trends can be examined for Faraday/Vernadsky, and the Orcadas record extends back to 1903. For all the continental stations in Table II, except Esperanza and Molodezhnaya, the warming trend was greater (or the cooling trend less) during the 1961–90 period compared with 1971–2000. The reasons for the more marked warming in the earlier period are not fully understood at present, but could be associated with changes in the major modes of Antarctic climate variability discussed below. Alternately, changes in sea-ice extent could have played a role, but there is very little data on the extent of Antarctic sea ice in the period before the late 1970s. King and Harangozo (1998) found a number of ship reports from the Bellingshausen Sea in the 1950s and 1960s when sea ice was well north of the locations found in the period of availability of satellite data, suggesting some periods of greater sea-ice extent than found in recent decades. Similarly, Kukla and Gavin (1981) reported a decrease in Antarctic sea ice over the period 1973 to 1980 based on satellite imagery, and de la Mare (1997) estimated that the summer sea-ice edge had moved several degrees further south between the mid-1950s and early 1970s based on whaling records. However, at present it is not possible to attribute the temperature changes observed at coastal stations to variations in sea-ice conditions prior to the late 1970s.

Only two stations from the interior of the Antarctic have long temperature records, so it is not possible to make any clear statement about change over this vast area. However, the data from Vostok shows no statistically significant change over a record that extends back over 40 years. Comiso (2000) found a slight cooling on the high plateau of East Antarctica over the period 1979 to 1998, and this is also reflected in the READER data for Vostok over this period. However, this occurred after several decades of slight warming since the station was established in 1958. Clearly, more work is needed on this decadal time scale variability of temperatures over East Antarctica.

At Amundsen–Scott Station there is a cooling in all seasons, but only the annual trend of $-0.17\,^{\circ}\mathrm{C}$ decade^{-1} is statistically significant at the 10% level. However, it should be noted that it has not been possible to obtain much metadata for the station, and the study of Hogan *et al*. (1993) has highlighted changes in the nature of the temperature record around the time of the relocation of the station in December 1974. Clearly the South Pole temperature record requires further investigation.

Table II. Overlapping 30 year trends in the annual mean surface temperature at selected Antarctic stations. Bold plus underlined values: significant at the 1% level. Bold values: significant at the 5% level. Italicized text: significant at the 10% level

Station	Temperature trend (°C decade^{-1})							
	1901–30	1911–40	1921–50	1931–60	1941–70	1951–80	1961–90	1971–2000
Novolazarevskya	—	—	—	—	—	—	**+0.41 ± 0.38**	+0.10 ± 0.41
Syowa	—	—	—	—	—	—	—	−0.02 ± 0.45
Molodezhnaya	—	—	—	—	—	—	−0.11 ± 0.43	−0.04 ± 0.43
Mawson	—	—	—	—	—	—	−0.13 ± 0.52	−0.15 ± 0.43
Davis	—	—	—	—	—	—	—	−0.04 ± 0.54
Mirny	—	—	—	—	—	—	+0.16 ± 0.45	−0.26 ± 0.49
Vostok	—	—	—	—	—	—	+0.11 ± 0.53	−0.31 ± 0.51
Casey	—	—	—	—	—	—	+0.37 ± 0.54	−0.37 ± 0.57
Dumont Durville	—		—	—	—	—	+0.14 ± 0.41	−0.33 ± 0.46
Scott Base	—	—	—	—	—	—	+0.32 ± 0.67	+0.05 ± 0.60
Rothera	—	—	—	—	—	—	—	—
Faraday/Vernadsky	—	—	—	—	—	+0.48 ± 0.97	+0.45 ± 0.89	+0.36 ± 0.88
Bellingshausen	—	—	—	—	—	—	—	+0.31 ± 0.49
Esperanza	—	—	—	—	—	—	+0.36 ± 0.72	*+0.62 ± 0.69*
Marambio	—	—	—	—	—	—	—	—
Orcadas	−0.44 ± 0.70	−0.03 ± 0.66	+0.19 ± 0.70	+0.41 ± 0.79	+0.37 ± 0.65	−0.21 ± 0.84	+0.24 ± 0.68	*+0.47 ± 0.57*
Halley	—	—	—	—	—	—	+0.41 ± 0.65	−0.56 ± 0.71
Neumayer	—	—	—	—	—	—	—	—
Amundsen–Scott	—	—	—	—	—	—	−0.06 ± 0.39	−0.36 ± 0.46

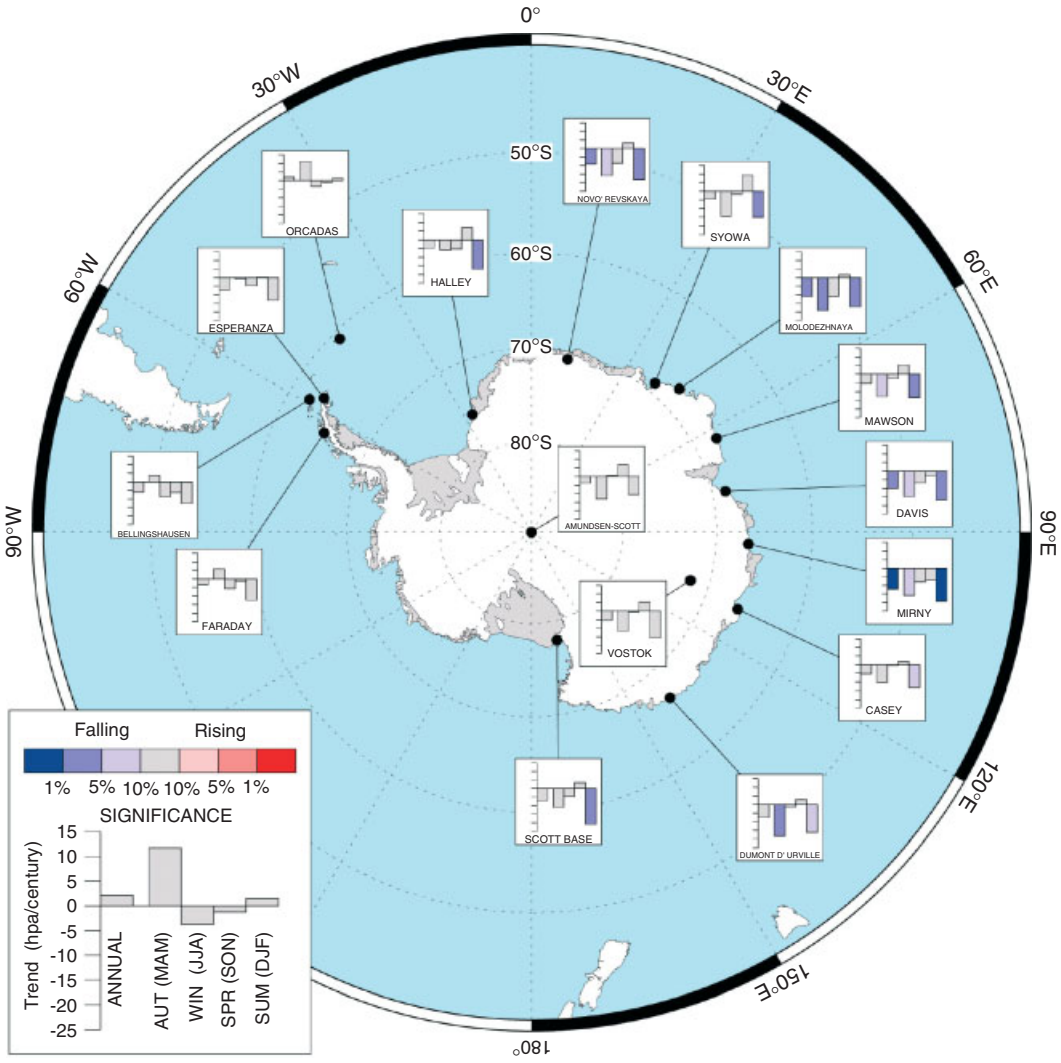

Figure 4. Antarctic MSLP/surface pressure trends for 1971–2000. A minimum of 27 years of data are required for inclusion. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

Longer time-scale trends in Antarctic temperatures have been considered by Jones (1990).

3.2. Pressure trends

Annual and seasonal MSLP trends for the various stations (station-level pressure for Amundsen–Scott and Vostok) are summarized in Table III, with a graphical representation being included in Figure 4. All the stations show negative trends in the annual mean pressures over the periods considered, except for Orcadas, which has no overall trend. Decreases in pressure occurred in all sectors of the Antarctic, with the most negative trends being at Molodezhnaya (statistically significant at the 1% level) and Mirny. A consistent decrease of pressure at Mawson and Davis on either side of the Amery Ice Shelf of -0.48 hPa decade^{-1} can be seen in Table III, with similar seasonal trends also occurring at these locations. At other locations there is a greater spatial variability of the pressure trends, such as between Novolazarveskya and Syowa. In the Antarctic Peninsula and Weddell Sea sectors, the trends in annual mean MSLP are generally smaller, although Bellingshausen has experienced a pressure decrease of -0.57 hPa decade^{-1}.

Table III. Annual and seasonal MSLP/station pressure trends at selected Antarctic stations. Bold plus underlined values: significant at the 1% level. Bold values: significant at the 5% level. Italicized text: significant at the 10% level. Trends included if 90% of the observations are available

Station	Pressure trend (hPa decade^{-1})					Period	Data used[a]
	Annual	Spring	Summer	Autumn	Winter		
Novolazarevskya	**−0.67 ± 0.58**	+0.02 ± 1.18	*−1.17 ± 1.26*	−0.77 ± 1.43	−0.56 ± 1.14	1962–2000	S & C
Syowa	−0.24 ± 0.62	+0.18 ± 1.04	−0.90 ± 1.10	−1.01 ± 1.27	−0.02 ± 1.17	1959–61, 1967–2000	
Molodezhnaya	**−0.98 ± 0.68**	−0.16 ± 1.16	**−1.63 ± 1.13**	−1.12 ± 1.54	*−1.09 ± 1.28*	1964–1998	S & C
Mawson	**−0.48 ± 0.43**	−0.10 ± 0.68	*−0.71 ± 0.77*	−0.53 ± 0.80	−0.73 ± 0.89	1955–2000	
Davis	*−0.48 ± 0.51*	−0.34 ± 0.90	−0.52 ± 1.05	−0.63 ± 0.96	−0.94 ± 1.19	1958–63, 1970–2000	
Mirny	**−0.95 ± 0.45**	−0.53 ± 0.90	**−1.09 ± 0.05**	**−1.11 ± 0.92**	**−1.23 ± 1.03**	1956–2000	
Vostok	−0.09 ± 0.74	+0.56 ± 1.02	−0.67 ± 1.18	−0.42 ± 1.30	+0.11 ± 1.53	1958–2000	
Casey	−0.51 ± 0.71	−0.06 ± 1.13	−0.81 ± 1.15	−0.77 ± 1.27	−0.41 ± 1.41	1962–2000	
Dumont d'Urville	<90%	<90%	<90%	<90%	−0.11 ± 1.27	1957–2000	
Scott Base	−0.37 ± 0.61	+0.10 ± 1.15	−0.44 ± 1.17	−0.91 ± 1.19	−0.59 ± 1.52	1958–1998	C
Rothera	−0.42 ± 2.22	+0.27 ± 4.89	−2.02 ± 3.39	−0.64 ± 3.52	+0.01 ± 5.28	1978–2000	S
Faraday/Vernadsky	−0.03 ± 0.49	−0.08 ± 1.16	−0.31 ± 0.84	+0.55 ± 0.96	−0.27 ± 1.14	1951–2000	S
Bellingshausen	−0.57 ± 1.08	−0.37 ± 2.14	−1.17 ± 2.05	+0.39 ± 1.49	−0.64 ± 2.32	1969–2000	S
Esperanza	−0.34 ± 0.52	−0.01 ± 0.91	−0.54 ± 0.94	+0.13 ± 1.27	−0.56 ± 1.17	1952–2000	C & S
Marambio	<90%	<90%	<90%	<90%	−1.12 ± 2.39	1971–1998	C
Orcadas	0.00 ± 0.15	−0.02 ± 0.30	−0.02 ± 0.28	+0.23 ± 0.29	−0.13 ± 0.26	1904–2000	C
Halley	−0.31 ± 0.58	+0.12 ± 0.93	−0.73 ± 0.96	−0.39 ± 1.10	−0.37 ± 1.04	1957–2000	S
Neumayer	−0.07 ± 2.37	+2.80 ± 4.20	−1.89 ± 5.82	−0.60 ± 3.81	+0.63 ± 4.74	1982–2000	S
Amundsen–Scott	−0.03 ± 0.60	+0.38 ± 1.01	−0.37 ± 0.93	−0.43 ± 1.03	−0.02 ± 0.99	1958–2000	S

[a] S: synoptic data; C: CLIMAT; G: GTS.

The seasonal pressure trends in Table III show the variability of the changes that have taken place over the last few decades. Eight of the stations in Table III have their largest negative pressure trends in the summer, which is the season when the smallest number of synoptic-scale depressions are found in the circumpolar trough (Jones and Simmonds, 1993). A further five stations have the largest negative trends in the winter, which is the secondary minimum of cyclonic activity as the circumpolar trough moves north as a result of the semi-annual oscillation (SAO; van Loon, 1967). The trends for Faraday/Vernadsky, of large pressure falls in the summer and winter, and a pressure rise in the autumn, coupled with a small drop in the spring, indicate the extent to which the SAO has been weakening in recent decades (Van den Broeke, 1998).

Simmonds and Keay (2000) carried out an analysis of cyclone density and depth around the Antarctic based on National Centers for Environmental Prediction reanalysis fields for 1958–97 and using an objective depression tracking procedure. They reported a negative (positive) trend in the surface pressures south (north) of 40 °S, which they attributed to the 'high latitude mode'. This is a see saw of atmospheric conditions between the middle and high latitude areas of the Southern Hemisphere. In parallel with the drop of pressure south of 40 °S they found that there had been a reduction in the number of cyclones over the period, with the greatest decrease near 60 °S. However, the apparent inconsistency of falling station pressure and fewer cyclones was explained by the fact that the mean depth and size of the systems had decreased over this period.

The 'high-latitude mode', also known as the Southern Hemisphere annular mode (SAM) and the Antarctic oscillation, is attributed to fluctuations in the strength of the circumpolar vortex. Thompson and Solomon (2002) examined the trends in Antarctic tropospheric heights throughout the year via the radiosonde data from seven stations and found a maximum decrease in height throughout the troposphere during the summer months, with a secondary height drop during the winter. Our longer time series of *in situ* data allows us to examine overlapping 30 year trends of MSLP, which are shown in Table IV. Except for Halley, where the trends are constant, these data indicate that the trends for 1971–2000 were more negative than for 1961–90 for all stations on the Antarctic continent. The record for Faraday/Vernadsky extends back to 1950 and allows us to examine three 30 year overlapping trends. These indicate an increasing negative pressure trend through this period.

When the SAM is in its high-index state, polar temperatures, geopotential heights and surface pressures are low and strong circumpolar winds are found near 60 °S. Low-index periods are characterized by anomalies in the opposite sense. As discussed in Thompson and Solomon (2002), the data in Table IV indicate a trend towards the high-index form of the SAM, with stronger westerly winds around the Antarctic and lower MSLP over the Antarctic continent. The long record from Orcadas (Figure 5) is valuable in providing a time series of pressure data on the other side of the 'seesaw' that extends back to the start of the 20th century. Since 1961 there has been a small positive trend in the pressure values, although this is not statistically significant. And since 1901 the pressure data from the station have fluctuated considerably, with the only long fall in pressure being during the two overlapping 30 year periods from 1931 to 1970.

3.3. Wind speed trends

The trends in near-surface wind speed for the main Antarctic stations are shown in Table V. Because of the lack of reliable, long-term records of wind speed data at some stations, long-term trends can only be computed for 11 coastal sites. However, eight of these have experienced wind speed increases over their periods of operation, with the only coastal stations having had wind speed decreases being Mirny and Halley. But the increasing wind speeds at the majority of the stations is consistent with the change in the nature of the SAM over recent decades. The reasons why two of the stations have experienced decreasing wind speeds is not clear. Halley is the most southerly of the coastal stations and, therefore, may not register the impact of the changes in the SAM. But Mirny is close to Davis, yet has quite a different trend in wind speed. These two stations are only about 700 km apart, yet have trends of -0.324 kts decade^{-1} and $+0.428$ kts decade^{-1} respectively over approximately the same period. This may point to changes in the equipment used to measure wind speed at the stations, to modifications to the instrument exposure, or to changes in the local wind flow.

On the western side of the Antarctic Peninsula there is a consistent picture of wind speeds increasing, although only the Faraday/Vernadsky trend is statistically significant. In the interior of the Antarctic, only

Table IV. Overlapping 30 year trends in the annual MSLP at selected Antarctic stations. Bold plus underlined values: significant at the 1% level. Bold values: significant at the 5% level. Italicized text: significant at the 10% level

Station	MSLP trend (hPa decade^{-1})							
	1901–30	1911–40	1921–50	1931–60	1941–70	1951–80	1961–90	1971–2000
Novolazarevskya	—	—	—	—	—	—	-0.20 ± 0.91	**-0.98 ± 0.97**
Syowa	—	—	—	—	—	—	—	-0.50 ± 0.96
Molodezhnaya	—	—	—	—	—	—	*-0.89 ± 0.95*	**-1.17 ± 1.03**
Mawson	—	—	—	—	—	—	-0.43 ± 0.77	-0.59 ± 0.90
Davis	—	—	—	—	—	—	—	**-1.06 ± 0.91**
Mirny	—	—	—	—	—	—	**$\underline{-1.11 \pm 0.73}$**	**$\underline{-1.30 \pm 0.79}$**
Vostok	—	—	—	—	—	—	-0.25 ± 1.13	-0.57 ± 1.45
Casey	—	—	—	—	—	—	-0.45 ± 1.12	-0.58 ± 1.07
Dumont Durville	—	—	—	—	—	—	-0.04 ± 1.03	-0.85 ± 1.32
Scott Base	—	—	—	—	—	—	-0.40 ± 0.92	-0.76 ± 1.10
Faraday	—	—	—	—	—	$+0.30 \pm 0.93$	-0.08 ± 0.88	-0.35 ± 1.43
Bellingshausen	—	—	—	—	—	—	—	-0.63 ± 1.24
Esperanza	—	—	—	—	—	—	-0.45 ± 1.16	-0.77 ± 1.19
Orcadas	$+0.09 \pm 1.19$	-0.30 ± 1.05	$+0.14 \pm 0.89$	-0.24 ± 0.82	-0.39 ± 1.01	$+0.15 \pm 0.98$	$+0.06 \pm 0.85$	$+0.24 \pm 1.32$
Halley	—	—	—	—	—	—	-0.50 ± 0.91	-0.50 ± 1.02
Amundsen–Scott	—	—	—	—	—	—	-0.19 ± 1.01	-0.40 ± 0.91

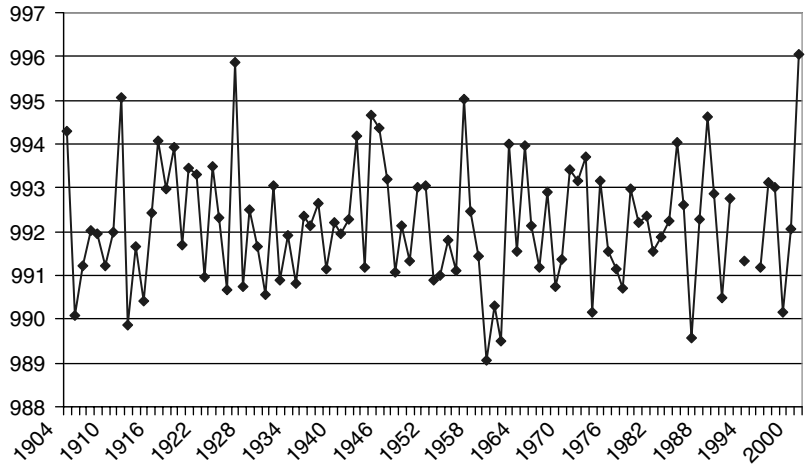

Figure 5. The Orcadas annual MSLP for 1904–2000

Amundsen–Scott Station has a sufficiently complete record of wind speeds to allow the determination of trends, and these show a decrease that is statistically significant at the 5% level. However, there is little metadata for the site, so it is not possible to take into account any changes of instrumentation or observing site in relation to the station.

The seasonal wind speed trends in Table V present a varied picture of change across the Antarctic. Around the coast of East Antarctica, three of the stations have had their greatest wind speed increases during the winter, yet Novolazarevskya and Mirny, which bracket the stations, have their greatest wind speed decreases in this season. However, Novolazarevskya and Mirny are to the immediate west of the climatological position of the separate low-pressure systems that sit off the coast during winter. Each of the stations in between is either central or to the east of low-pressure systems located off the coast.

On the other hand, on the western side of the Antarctic Peninsula, where the greatest increases in temperatures have been during the winter, none of the stations had their largest wind speed increases during this season, and the largest trends are spread across the three other seasons.

4. DISCUSSION AND FUTURE WORK

This paper has examined the temporal variability and change in some of the key meteorological parameters at Antarctic stations. The temperature trends are very variable across the continent: rapid warming has occurred over the Antarctic Peninsula, which stands out as a clear and consistent region of rapid change, whereas conditions have been much more variable in other sectors. Whereas earlier studies (e.g. Raper *et al*., 1984; Doran *et al*., 2002) have derived mean temperature trends for the continent based on all the station trends, we have deliberately not attempted to produce such a figure as we feel that this gives an oversimplified view of change in the Antarctic and does not reflect the regional variability. Invariably, such mean figures give a small warming trend, but this is always dominated by the large warming on the western side of the Antarctic Peninsula. A more realistic picture of temperature change over the Antarctic is obtained by noting that, of the 19 stations examined in this study for which annual trends could be computed, 11 stations have experienced warming over their whole length, seven stations have cooled, and one station had too little data to allow an annual trend to be computed. However, it should be noted that only three of these trends are statistically significant: Faraday/Vernadsky on the peninsula, Novolazarevskya in East Antarctic, which are both warming, and Amundsen–Scott at the South Pole, which has cooled. The cooling at Amundsen–Scott has not been investigated in detail to date, probably as a result of the lack of reliable synoptic-scale analyses on the plateau. In addition, there are very limited amounts of metadata available for the station, precluding any investigation

Table V. Annual and seasonal wind speed trends at selected Antarctic stations. Bold plus underlined values: significant at the 1% level. Bold values: significant at the 5% level. Italicized text: significant at the 10% level. For full records. Trends included if 90% of the observations are available

Station	Wind speed trend (kts decade^{-1})					Period (annual)	
	Annual	Spring	Summer	Autumn	Winter		
Novolazarevskya	$+0.243 \pm 0.572$	$+0.178 \pm 0.889$	$+0.557 \pm 0.761$	$+0.330 \pm 0.926$	-0.214 ± 1.018	1963–2000	
Syowa	$+0.085 \pm 0.231$	$+0.028 \pm 0.270$	$+0.056 \pm 0.241$	$+0.081 \pm 0.215$	$+0.174 \pm 0.215$	1960–61, 1967–2000	<90%?
Molodezhnaya	n/a	n/a	n/a	n/a	n/a	—	
Mawson	$+0.046 \pm 0.519$	$+0.061 \pm 0.483$	$+0.133 \pm 0.442$	-0.020 ± 0.452	$+0.140 \pm 0.616$	1955–2000	
Davis	$+0428 \pm 0.545$	$+0.411 \pm 0.558$	$+0.385 \pm 0.647$	*+0.383 ± 0.456*	$+0.435 \pm 0.660$	1958–63, 1970–2000	<90%?
Mirny	-0.324 ± 0.693	-0.242 ± 0.497	-0.083 ± 0.484	-0.322 ± 0.684	-0.483 ± 0.899	1957–2000	
Vostok	<90%	<90%	<90%	<90%	<90%	1958–2000	
Casey (+Wilkes)	<90%	<90%	<90%	*+0.383 ± 0.456*	$+0.435 \pm 0.660$	1958–2000	
Dumont Durville	<90%	<90%	<90%	**−1.200 ± 0.964**	<90%	1956–2000	
Scott	n/a	n/a	n/a	n/a	n/a	—	
Rothera	$+0.537 \pm 1.442$	$+0.565 \pm 1.564$	$+0.624 \pm 1.834$	$+1.060 \pm 2.146$	$+0.397 \pm 1.765$	1978–2000	
Faraday	*+0.275 ± 0.291*	$+0.032 \pm 0.352$	**+0.421 ± 0.416**	$+0.272 \pm 0.482$	$+0.291 \pm 0.525$	1951–2000	
Bellingshausen	$+0.081 \pm 0.485$	$+0.369 \pm 0.682$	-0.086 ± 0.518	$+0.178 \pm 0.693$	$+0.187 \pm 0.578$	1969–2000	
Esperanza	n/a	n/a	n/a	n/a	n/a	—	
Marambio	n/a	n/a	n/a	n/a	n/a	—	
Orcadas	n/a	n/a	n/a	n/a	n/a	—	
Halley	-0.135 ± 0.882	-0.158 ± 0.712	$+0.082 \pm 0.480$	-0.431 ± 1.109	-0.047 ± 0.862	1957–2000	
Neumayer	$+0.642 \pm 1.665$	-0.523 ± 2.220	$+1.500 \pm 2.599$	-0.673 ± 1.761	$+0.797 \pm 2.647$	1982–2000	
Amundsen–Scott	**−0.668 ± 0.546**	**−0.602 ± 0.531**	-0.324 ± 0.395	**−0.804 ± 0.657**	**<u>−0.976 ± 0.660</u>**	1958–2000	

into the possible effects of changes in instrumentation or the location of the meteorological instruments. However, as can be seen in Table V, the wind speeds at the station have decreased at a statistically significant level in three of the four seasons and in the annual data. A decrease in wind speed would result in a more stable boundary layer and colder conditions at the surface, which would explain the trend towards colder surface conditions. Without reliable surface-pressure analyses it is not clear why the winds, and therefore the pressure gradient, has changed, although the modelling investigation by van den Broeke and van Lipzig (2002) has shown that surface conditions in the interior of Antarctica are sensitive to variations in the circumpolar vortex.

Although there is no evidence of Antarctic-wide warming or cooling over the last 40 to 50 years, Table II does suggest that there has been a broad-scale change in the nature of the temperature trends between 1961–90 and 1971–2000. Ten of the coastal stations in Table II have long enough records to allow 30-year temperature trends to be computed for both these periods; of these, eight had a larger warming trend (or a smaller cooling trend) in the earlier period. In the Antarctic Peninsula region there were some very cold years during the 1960s and suggestions that there was more extensive sea ice (King and Harangozo, 1998). Since there is a close association between near-surface temperature and sea-ice extent in this area, it may be that there was more sea ice to the west of the peninsula in the 1950s and 1960s compared with later decades; but there are few sea-ice observations prior to the late 1970s, so this is difficult to investigate.

The Antarctic Peninsula is the region of the continent where there is the strongest influence of the El Niño–southern oscillation, with a Rossby wave train often extending towards the Bellingshausen Sea from the tropical Pacific during El Niño events (Turner, 2004). In recent decades, El Niño events have been more frequent and of greater intensity, raising the possibility that tropical forcing may have played a role in some of the climatic changes observed in the Antarctic Peninsula. However, as discussed in Turner (2004), El Niño events, on average, result in fewer depressions/greater blocking over the Bellingshausen Sea, which results in more southerly winds and, therefore, colder conditions. So, stronger and more frequent El Niño events would tend to give colder conditions rather than the warming observed. So, at the moment, the role of changes in tropical forcing on the climate of the Antarctic is not clear.

The clear decrease in surface pressures at the coastal stations over the full periods of the station data is indicative of the SAM moving towards a high-index state in recent decades. The SAM is a seesaw of pressures over high and mid latitudes and the trend towards high pressures at Orcadas is consistent with this out-of-phase relationship between surface pressures over the Antarctic continent and at lower latitudes. The climate record from Orcadas started at the beginning of the 20th century and provides a longer term perspective on the variability of the SAM. As can be seen from Figure 5 and Table IV, the recent trend towards high surface pressures is a result of relatively low pressure during the 1970s, but before this the trends were quite variable, switching sign several times during the first 70 years of the 20th century.

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