Short Communication:

Half-century seasonal relationships between the Southern Annular Mode and Antarctic temperatures

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Abstract

Here we examine the relationship between the Southern Hemisphere (SH) Annular Mode (SAM) and Antarctic near-surface temperatures using data from Antarctic stations for 1957-2004. This near half-century period is significantly longer than analysed in previous studies. Furthermore, the four seasons are considered independently while the longer datasets allow the temporal stability of the relationship to be investigated.

A general pattern of positive (negative) correlations between the strength of the SAM and temperatures in the northern Antarctic Peninsula (East Antarctica) is shown to be valid for the last half century but detailed differences are observed between the seasons. These include a change in the sign of the relationship at one station, while at others there are single seasons when temperatures there are or, in some cases, are not significantly related to the SAM. Generally, SAM-temperature correlations are stronger across Antarctica in austral autumn and summer. Estimates of the contribution that trends in the SAM have made to Antarctic near-surface temperature change between 1957 and 2004 are greatest in autumn: in this season they exceed 1°C at half the 14 stations examined with a maximum change of –1.4°C.

There does not appear to have been any significant long-term change in the strength of SAM-temperature relationships over the period examined, even with the onset of ozone depletion. However, on an annual basis, the long-term relationship between the SAM and near-surface temperatures can be disrupted and even reversed at some stations, although coastal East Antarctica appears stable in this respect. These findings give support to the exploitation of appropriate ice core data to determine longer-term changes in the SAM based upon transfer-functions derived from recent data.

Keywords (up to 8)

Southern Hemisphere Annular Mode (SAM), Antarctica, temperature, climate change

Introduction

The Southern Hemisphere (SH) Annular Mode (SAM) or Antarctic Oscillation is the principal mode of variability of the extra-tropical atmospheric circulation, and typically describes ~35% of total SH climate variability. Essentially it is an annular structure with synchronous pressure anomalies of opposite sign in mid- and high-latitudes: when pressures are below (above) average over Antarctica the SAM is said to be in its high (low) index or positive (negative) phase. Fyfe and Lorenz (2005) proposed that annular modes are more accurately characterised as a north-south shift in the midlatitude jet, the result of both latitudinal shifts in the jet and independent fluctuations in jet strength.

The SAM has shown significant positive trends during autumn and summer over the past few decades (e.g. Thompson *et al*., 2000; Marshall, 2003), resulting in a strengthening of the circumpolar westerlies. These trends have contributed to the spatial variability in Antarctic temperature change (e.g. Thompson and Solomon, 2002; Kwok and Comiso, 2002; Schneider *et al.*, 2004), specifically a warming in the northern Peninsula region and a cooling over much of the rest of the continent.

The studies of Kwok and Comiso (2002) and Schneider *et al.* (2004) employed satellite-derived temperature data to examine the relationships between the SAM and Antarctic temperatures. While satellite data allow an accurate mapping of these relationships across the entire Antarctic continent, they are limited temporally to the period from 1982 onwards. Moreover, gridded datasets from reanalyses are generally poor across high southern latitudes before the mid-1970s — when the assimilation of satellite data over the Southern Ocean began — including the accuracy of near-surface Antarctic temperatures (Bromwich and Fogt, 2004). An alternative is to use the relatively sparse ground-based network of Antarctic stations (e.g. Turner *et al.*, 2004) to examine SAM-temperature relationships. Thompson and Solomon (2002) showed that Antarctic temperature change congruent with the SAM for the December-May period from 1969-2000 varied from an average of –1.0°C in East Antarctica to +0.7°C in the Antarctic Peninsula.

In this paper we extend previous work examining SAM-Antarctic temperature relationships in several ways: (i) the 48-year time period utilised, 1957-2004, is much longer than those examined in earlier studies ; (ii) the four austral seasons are considered separately because significant differences exist in the magnitude of seasonal trends in the SAM (cf. Table 1); and (iii) the longer period examined allows us to ascertain whether SAM-temperature relationships have changed over time: this is achieved by studying running 20-year periods.

Data

Monthly Antarctic near-surface temperatures from 14 stations with long records (see Figure 1) were obtained from the Antarctic READER (Reference Antarctic Data for Environmental Research) project (Turner *et al.*, 2004) with updates from http://www.nerc-bas.ac.uk/icd/gjma/temps.html. These stations were chosen because they had seasonal data from at least 85% of the 48-year period examined.

The SAM index used in this study was developed by Marshall (2003) based on the definition of Gong and Wang (1999), which is simply the difference in normalised mean zonal pressure at 40°S and 65°S. To overcome the problems of early gridded datasets, as described previously, the author used monthly mean sea level pressure (MSLP) data at 12 stations in the SH extra-tropics to derive zonal mean pressures. This

SAM index is currently available for the period from 1957 onwards at http://www.nerc-bas.ac.uk/icd/gjma/sam.html. The principal advantages of the Marshall (2003) index are its simplicity and temporal consistency across its entire time-span and between different seasons. Conversely, the main disadvantage compared to empirical orthogonal function (EOF) based SAM indices is that because it does not account for the changing non-zonal spatial SAM variability across the different seasons, which may be significant (e.g. Fogt and Marshall, submitted), it does not describe the complete variability of the SAM. All seasons refer to the Southern Hemisphere annual cycle: autumn is March-April-May; winter is June-July-August; spring is September-October-November; and summer is December-January-February.

Methodology

Correlation and linear regression coefficients between the SAM and Antarctic temperatures were derived using detrended data. This methodology assumes that no link exists between linear trends in the predictor (SAM) and predictand (temperature). Using the original, undetrended data assumes that the entire trend in the predictand that covaries with the predictor is due to the latter. The reality, of course, is likely to lie somewhere between the two methodologies, although in this study statistics obtained using the two methodologies differ only slightly. In general, the detrended data produced larger (smaller) coefficients than the original data across East Antarctica (Antarctic Peninsula) because trends in the SAM and near-surface temperatures tend to be of the opposite (same) sign, especially in autumn and summer when the SAM trends are greatest (cf. Table 1). Autocorrelation at lag –1 was accounted for when considering the significance of the correlations.

Regression coefficients were calculated for a positive unit change in the SAM index; i.e. a regression coefficient of 0.5 (−0.5) means that if the SAM index increases by one then the temperature warms (cools) by 0.5°C. When the statistical coefficients over running 20-year periods were calculated the SAM was recomputed for each period, otherwise the relationship would be partially dependent on data outside the particular 20-year period of interest.

Results

Correlations

Maps showing the magnitude and significance of the correlation between the SAM and Antarctic near-surface temperatures for 1957-2004 in autumn, winter, spring and summer are shown in Figs 2a, 2b, 2c and 2d, respectively. In general, in each season there are positive correlations in the Antarctic Peninsula region and negative correlations across East Antarctica, as determined by previous studies. Note that there are no stations with long-term records in West Antarctica but satellite data indicate negative correlations, similar to East Antarctica but of smaller magnitude (Kwok and Comiso, 2002; Schneider *et al.*, 2004). There are, however, seasonal differences in the size, significance and, at some locations, the sign of the relationship between the SAM and temperature.

In autumn (Fig. 2a) there are significant positive correlations between the SAM and temperature at stations in the northern Peninsula (Esperanza and Orcadas), particularly at the former where the relationship is significant at <1% level. At Faraday, slightly further south, the correlation is positive but not statistically significant. Across East Antarctica most correlations are negative and highly significant (<1%): the strongest correlation is –0.64 at Vostok. The single exception is Halley, where the relationship is weaker and not significant.

The broad spatial pattern of SAM-temperature correlations is similar in winter (Fig. 2b) to autumn and only the differences will be noted here. In general the correlations are smaller than in autumn and in some cases this means a reduction in the significance of the relationships: across East Antarctica this includes Syowa and Dumont D'Urville (<5%), Scott Base (<10%) and Casey, where the relationship is no longer significant: this is the only season where the strong relationship between the SAM and Casey temperatures breaks down. The significance of the positive correlation at Esperanza also declines to <5%. However at Amundsen-Scott, Halley, Novolazarevskaya and Mawson the magnitude of the correlation is actually greater in winter than autumn, with the maximum correlation of –0.61 found at Mawson. The correlation of −0.54 at Amundsen-Scott is the largest observed there in any season.

In spring (Fig. 2c) the correlations between the SAM and Peninsula temperatures are less positive. The correlation at Esperanza is only significant at <10%, that at Orcadas is no longer significant, while at Faraday there has actually been a change in sign of the relationship as compared to the previous two seasons. The negative correlation of –0.28 is significant at <10%. Thus, in spring the boundary between those regions of Antarctica where temperatures are positively and negatively correlated with the SAM is located towards the very north of the Antarctic Peninsula, whereas in autumn and winter it is positioned south of Faraday. The magnitude of negative correlations at East Antarctic stations in spring lies broadly between those of autumn and winter. The main differences compared to other seasons are the reduction in the magnitude (and significance) of the correlation at Vostok and the zero correlation between the SAM and temperatures at Halley.

The correlation between the SAM and Esperanza temperatures is strongest in summer (Fig. 2d) with a magnitude of 0.52 and a significance of <1%: the physical mechanisms for this relationship involve the advection of warm air across the northern Peninsula to the east coast, where Esperanza is located, and are described in detail by Marshall *et al.* (2006). Elsewhere in the Peninsula region the correlations at Orcadas and Faraday are similar to those observed in spring. Summer has the strongest seasonal correlations across most of coastal East Antarctica, the exception being Scott Base. Note that summer is the only season when a significant relationship exists between the SAM and Halley temperatures. The strongest summer correlation is at Syowa: the value of –0.74 there is much larger than in other seasons.

Regression and temperature change

Based on the observed trends in the SAM (Table 1) and the computed regression coefficients between the SAM and temperatures derived from detrended data (not shown), Figure 3 displays the estimated seasonal near-surface temperature changes for 1957-2004 that are congruent with the SAM.

Autumn has the largest seasonal trend in the SAM from 1957-2004 (cf. Table 1) and the resultant temperature changes are, at most stations, greater than in other seasons. At several stations the positive trend in the SAM has resulted in contemporaneous temperature changes that exceed 1°C: a warming at Esperanza and coolings at Mawson, Davis, Mirny, Casey, Vostok and Scott Base (Fig. 3a). The single largest SAM-related cooling (and regression coefficient) is at Vostok (–1.4°C, regression coefficient of

–0.66°C). The proportion of total temperature change in autumn that might be attributed to the SAM varies significantly across Antarctica. At Amundsen-Scott the 'SAM-related cooling' is five times that actually observed, at Mawson it is very similar to the total cooling, a finding that is valid for other coastal East Antarctic stations, while at Esperanza the warming congruent with the SAM is approximately one third of that observed.

In winter the smaller trend in the SAM (about half that in autumn) means that at most stations the impact of the SAM on temperatures is reduced (Fig. 3b), although some stations do have their greatest regression coefficient between the SAM and temperature in this season (Amundsen-Scott, Syowa, Mawson and Halley). However, at Faraday the SAM-related winter warming is actually larger than that in autumn, although comprising only a very small proportion (3%) of the total. This is perhaps surprising given the strong relationship between sea ice west of the Peninsula and winter temperatures at Faraday (e.g. King *et al.*, 2003) and that (admittedly weaker) between the SAM and regional sea ice (Liu *et al.*, 2004). In winter the proportion of total temperature change attributable to the SAM is generally significantly less than in autumn and indeed may be of opposite sign to the overall temperature trend. Thus, it is likely that mechanisms other than changes in the SAM are primarily responsible for driving temperature variability in this season; for example surface radiation changes on the Antarctic Plateau, the influence of winter sea-ice extent in the Peninsula and katabatic flow strength at some coastal stations in East Antarctica.

There is no overall trend in the SAM for spring during 1957-2004 (cf. Table 1) and consequently it has had essentially no impact on contemporaneous Antarctic near-surface temperature trends in this season (Fig. 3c, shown for completeness). However the SAM still plays a role in inter-annual variability as regression coefficients are often not insignificant (typically 0.2-0.3): indeed at Faraday the largest seasonal regression between the SAM and temperature occurs in spring.

In summer the SAM has been responsible for a warming in the northern Peninsula and a cooling elsewhere across the continent (Fig. 3d). The temperature changes are, in general, not as large as in autumn. Statistically, as the trends in the SAM in these two seasons are nearly identical (cf. Table 1) the greater temperature changes congruent with the SAM in autumn are because of larger regression coefficients, which in turn result from Antarctic temperatures having a higher standard deviation in autumn than in summer. At Faraday there has been a highly significant observed warming in summer: Fig. 3d indicates that without the apparent negative influence of a changing SAM on temperatures at this location the warming would be even greater. The largest SAM-related cooling (–0.73°C) in summer is at Amundsen-Scott. Temperature trends across most of Antarctica are smaller in summer than autumn. Thus, despite the greater SAM-related temperature change in autumn, the SAM has generally contributed a higher proportion of observed temperature change in summer, often exceeding the overall change. For example, the cooling at Mawson associated with the SAM is approximately four times that observed there during 1957-2004.

Long term changes in SAM-temperature relationships

To investigate the temporal stability of the relationship between the SAM and Antarctic near-surface temperatures we calculate the correlation between them for running 20-year periods, from 1957-1976 to 1985-2004. Data for winter and summer are shown for Amundsen-Scott (Fig. 4a), Mawson (Fig. 4b) and Esperanza (Fig. 4c).

These stations represent three different climatic regions: the Antarctic Plateau, coastal East Antarctica and the northern Antarctic Peninsula, respectively.

At Amundsen-Scott the winter correlation has been reasonably stable through time, varying from –0.41 to –0.61 and always remaining statistically significant (Fig. 4a). However, in summer the correlations are only of comparable magnitude to winter and statistically significant for 20-year periods at the beginning and end of the period encompassed by this study. Correlation magnitudes for periods in between are much smaller, reaching as low as –0.03. Fig. 4a indicates that the correlations for 20-year periods entirely before and entirely after 1980 have higher correlations. Analysis of the data indicates that although 1980 was the second warmest summer on record at Amundsen-Scott, the summer SAM was positive. Hence the usual strong negative correlation between station temperatures and the SAM did not apply in the summer of 1980 and this single highly anomalous year reduces the strength of the correlation for all the 20-year periods in which it occurs.

Both the winter and summer correlation coefficients between the SAM and temperatures at Mawson have remained fairly constant (Fig. 4b). However, there has been a general decrease in the winter correlation from 1962-1981 onwards—the strongest correlation is –0.80 and the weakest –0.51—with the significance of the relationship reduced to <5% level during the last four 20-year periods. In contrast, the recent summer periods have shown larger correlation coefficients, with a maximum of –0.78 in 1985-2004. All summer 20-year period correlations are significant at <1%, indicating that the SAM has a strong and temporally stable role in driving summer temperatures in coastal East Antarctica.

There is a similar temporal variability in the SAM-temperature correlations at Esperanza in both winter and summer (Fig 4c). Although the correlation for the entire 1957-2004 period is much greater in summer than winter at Esperanza (0.52 and 0.36, significant at <1% and <5%, respectively), Fig. 4c indicates that there are relatively few periods, most noticeably the recent period from 1981-2000 onwards when the significance is at least <5%, where such a marked difference is observed in the 20-year periods. This increase in the strength of the correlation appears to match the physical mechanism proposed by Marshall *et al.* (2006): the stronger summer SAM in recent years means that warm westerlies pass over the Peninsula more frequently and thus have had an increasingly direct influence on Esperanza temperatures.

However, for 1963-1982 and 1964-1983 the winter correlation is significant at <5% while that in summer is not significant at all. Moreover, there are many 20-year periods when one or both the winter and summer correlations between the SAM and Esperanza temperatures are not statistically significant. Similar to the summer Amundsen-Scott data the reduced correlations can be accounted for by one or two years where there is a dramatic change (a change in sign) in the usual regional and seasonal relationship between the strength and phase of the SAM and temperatures. This suggests that while the SAM may play an important role in driving decadal changes in temperature and consequent climate change in the north-east Peninsula, especially in summer the relationship between the SAM and temperatures is less stable on an inter-annual basis, in contrast to that at Mawson in East Antarctica.

Conclusions

This study has demonstrated that the general pattern of SAM-Antarctic near-surface temperature relationships described in previous studies with shorter datasets—positive in the Antarctic Peninsula and negative elsewhere on the continent—is generally valid for the last half century. There are, however, some detailed differences between the seasons. Most noticeably, the sign of the relationship between the SAM and temperatures at Faraday, on the western side of the Peninsula, changes from weakly positive in autumn and winter to significantly negative in spring and summer. Thus the line that separates those regions of Antarctica that are positively and negatively correlated to the SAM moves through the latitude of Faraday twice a year. Elsewhere, the strength and significance of the SAM-temperature relationship may vary considerably between seasons. For example, winter is the only season when the negative correlation between the SAM and temperatures at Casey is not significant—in the other three seasons it is significant at <1% level. Conversely, summer is the only season when there is any significant relationship between the SAM and Halley temperatures. Generally, SAM-temperature correlations are stronger across Antarctica in austral autumn and summer.

Estimates of the contribution that trends in the SAM have made to Antarctic near-surface temperature change between 1957 and 2004 exceed 1°C in autumn at seven of the 14 stations examined, with a maximum change of –1.4°C at Vostok. The impact of the SAM on temperatures has been less in other seasons due to smaller changes in the SAM itself, in the cases of winter and especially spring, or reduced variability in the seasonal temperatures, which in turn results in smaller regression coefficients with the SAM, as is the case with summer.

The long-term stability of the relationship between the SAM and Antarctic temperatures was examined at three stations, located on the Antarctic Plateau (Amundsen-Scott), coastal East Antarctica (Mawson) and northern Antarctic Peninsula (Esperanza). The main conclusion from this analysis, based on running 20-year periods, is that there has not been any significant long-term change in the strength of the relationship over the near half-century examined. This finding suggests that interpreting appropriate chemical variability in ice cores in terms of long-term changes in the SAM by using transfer functions based upon recent relationships may be valid (e.g. Goodwin *et al.*, 2004). There are however 20-year periods when correlations between temperatures and the SAM are reduced at Amundsen-Scott and Esperanza but these can be traced to one or two individual years when the normal SAM-temperature relationship is weakened or sometimes reversed in sign. Such anomalous years do not appear to occur at Mawson. Thus, we may also conclude that on an inter-annual basis, the relationship between the SAM and near-surface temperatures appears more stable in coastal East Antarctica than elsewhere on the continent.

There have been a number of papers proposing physical mechanisms linking the changes in the SAM to observed trends in Antarctic temperatures: Marshall *et al.* (2006) explain the marked summer warming in the north-east Peninsula in terms of the increased westerlies associated with a more positive SAM while Gillet and Thompson (2003) state that cooling within the region of enhanced westerlies is consistent with adiabatic changes in temperature driven by thermally indirect rising motion there. Gillet and Thompson (2003) advocated anthropogenically-induced ozone depletion above Antarctica in austral spring as a major driver of the changes in the SAM. As this process did not become significant until ~1980, the present study suggests that it has not affected significantly the relationship between the strength of the SAM and the magnitude of response of Antarctic temperatures. It might prove instructive to utilise General Circulation Models (GCMs) to examine the future stability of the relationship in a climate with increased greenhouse gases, which modelling studies have linked to a more positive SAM (e.g. Fyfe *et al.*, 1999; Kushner *et al.*, 2001; Marshall *et al.*, 2004; Shindell and Schmidt, 2004).

References

Bromwich DH, Fogt RL. 2004. Strong trends in the skill of the ERA-40 and NCEP-NCAR reanalyses in the high and midlatitudes of the Southern Hemisphere, 1958-2001. *Journal of Climate* **17**: 4603–4619.

Fogt RL, Marshall GJ. Submitted. Some observations on defining the Southern Hemisphere Annular Mode. *International Journal of Climatology.*

Fyfe JC, Lorenz DJ. 2005. Characterizing midlatitude jet variability: lessons from a simple GCM. *Journal of Climate* **18**: 3400–3404.

Fyfe JC, Boer GJ, Flato GM. 1999. The Arctic and Antarctic oscillations and their projected changes under global warming. *Geophysical Research Letters* **26**: 1601–1604.

Gillet NP, Thompson DWJ. 2003. Simulation of recent Southern Hemisphere climate change. *Science* **302**: 273–275.

Gong D, Wang S. 1999. Definition of Antarctic oscillation index. *Geophysical Research Letters* **26**: 459–462.

Goodwin ID, van Ommen TD, Curran MAJ, Mayewski PA. 2004. Mid latitude winter climate variability in the South Indian and southwest Pacific regions since 1300 AD. *Climate Dynamics* **22**: 783–794.

King JC, Turner J, Marshall GJ, Connolley WM, Lachlan-Cope TA. 2003. Antarctic Peninsula climate variability and its causes as revealed by instrumental records. *Antarctic Peninsula Climate Variability,* Domack E, Leventer A, Burnett A, Bindschadler R, Convey P, Kirby M, Eds., Antarctic Research Series, Vol. 79, Amer. Geophys. Union, 17–30.

Kushner PJ, Held IM, Delworth TL. 2001. Southern Hemisphere atmospheric circulation response to global warming. *Journal of Climate* **14**: 2238-2249.

Kwok R, Comiso J. 2002. Spatial patterns of variability in Antarctic surface temperature: Connections to the Southern Hemisphere Annular Mode and the Southern Oscillation. *Geophysical Research Letters* **29**: 1705, DOI:10.1029/2002GL015415.

Liu J, Curry JA, Martinson DG. 2004. Interpretation of recent Antarctic sea ice variability. *Geophysical Research Letters* **31,** L02205, DOI:10.1029/2003GL018732.

Marshall GJ. 2003. Trends in the Southern Annular Mode from observations and reanalyses. *Journal of Climate* **16**: 4134–4143.

Marshall GJ, Stott PA, Turner J, Connolley WM, King JC, Lachlan-Cope TA. 2004. Causes of exceptional atmospheric circulation changes in the Southern Hemisphere. *Geophysical Research Letters* **31**: L14205, DOI:10.1029/2004GL019952.

Marshall GJ, Orr A, van Lipzig NPM, King JC. 2006. The impact of a changing Southern Hemisphere Annular Mode on Antarctic Peninsula summer temperatures. *Journal of Climate* in press.

Schneider DP, Steig EJ, Comiso JC, 2004. Recent climate variability in Antarctica from satellite-derived temperature data. *Journal of Climate* **17**, 1569–1583.

Shindell DT, Schmidt GA. 2004. Southern Hemisphere climate response to ozone changes and greenhouse gas increases. *Geophysical Research Letters* **31:** L18209, DOI:10.1029/2004GL020724.

Thompson DWJ, Solomon S. 2002. Interpretation of recent Southern Hemisphere climate change. *Science* **296**: 895–899.

Thompson DWJ, Wallace JM, Hergerl GC. 2000. Annular modes in the extratropical circulation. Part II: Trends. *Journal of Climate* **13**: 1018–1036.

Turner J, Colwell SR, Marshall GJ, Lachlan-Cope TA, Carleton AM, Jones PD, Lagun V, Reid PA, Jagovkina, J. 2004. The SCAR READER project: towards a high-quality data base of mean Antarctic meteorological observations. *Journal of Climate* **17:** 2890–2898.

Figure Captions

Figure 1. Location map of the Antarctic stations used in this study.

Figure 2. The magnitude and significance of correlations between the SAM and Antarctic near-surface temperatures for 1957-2004: (a) autumn; (b) winter; (c) spring; and (d) summer.

Figure 3. The estimated change in Antarctic near-surface temperatures for 1957-2004 caused by trends in the SAM: (a) autumn; (b) winter; (c) spring; and (d) summer.

Figure 4. Temporal changes in the magnitude and significance in the correlation between the SAM and near-surface temperatures using a running 20-year window: (a) Amundsen-Scott; (b) Mawson; and (c) Esperanza. Winter data are the solid line and filled circles, summer data the dotted line and open circles.

Table captions

Table 1. Annual and seasonal trends in the SAM from 1965-2000. Units are decade^{-1}. Significant trends are shown by the asterisks; *** <1%; ** <5%; and * <10%.

AUT (MAM)	WIN (JJA)	SPR (SON)	SUM (DJF)
+0.45 ± 0.27***	+0.21 ± 0.38	0.00 ± 0.35	+0.45 ± 0.39**

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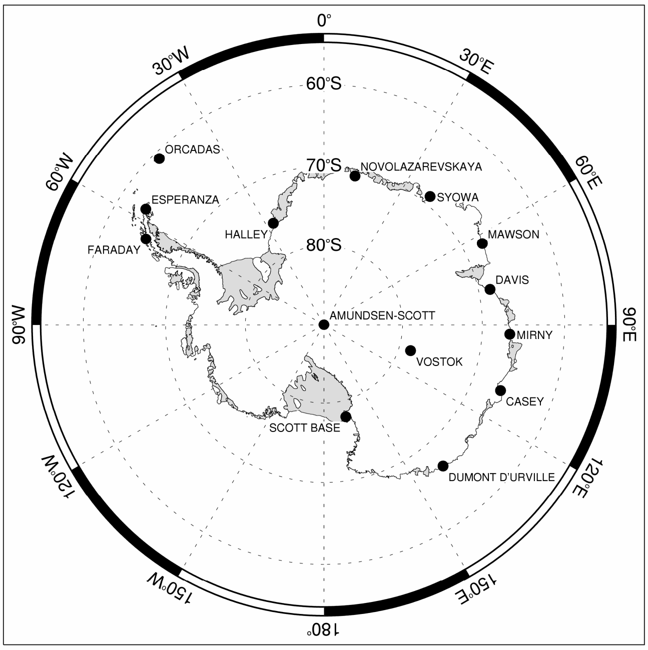

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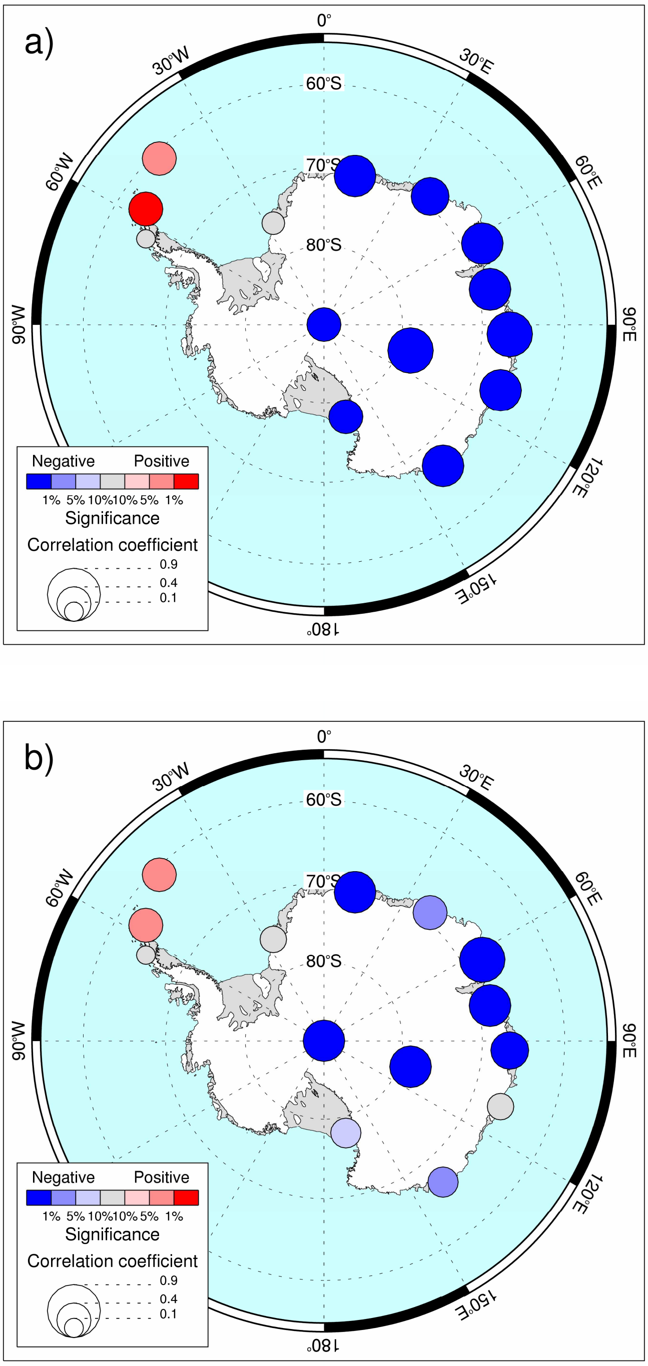
a)
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30°E
60°E
90°E
120°E
150°E
180°
30°W
60°W
90°W
60°S
70°S
80°S
Negative
Positive
1% 5% 10% 10% 5% 1%
Significance
Correlation coefficient
0.9
0.4
0.1
b)
0°
30°E
60°E
90°E
120°E
150°E
180°
30°W
60°W
90°W
60°S
70°S
80°S
Negative
Positive
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Significance
Correlation coefficient
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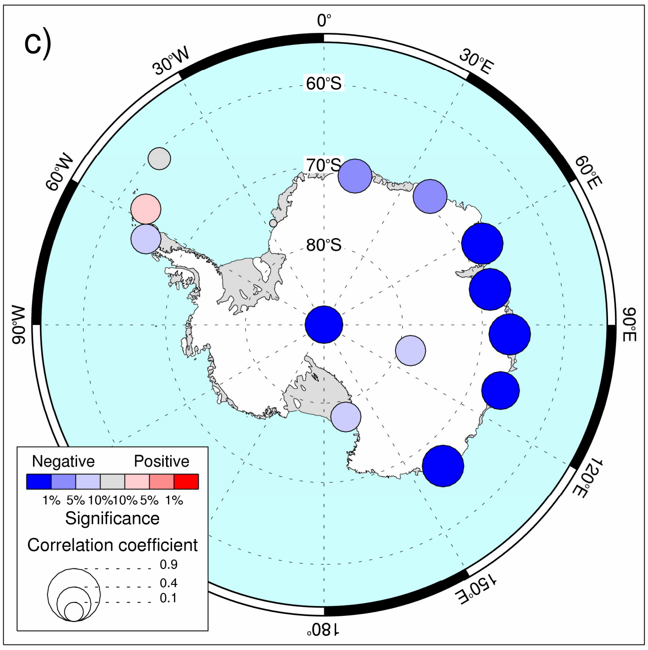


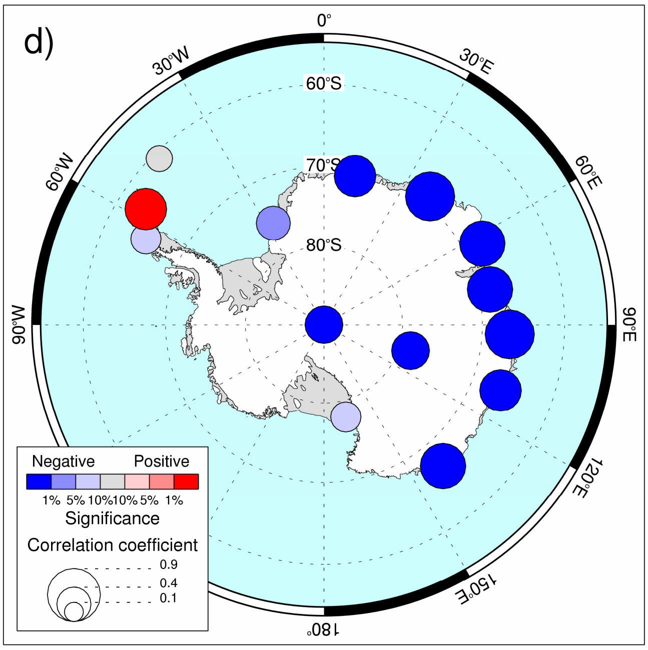
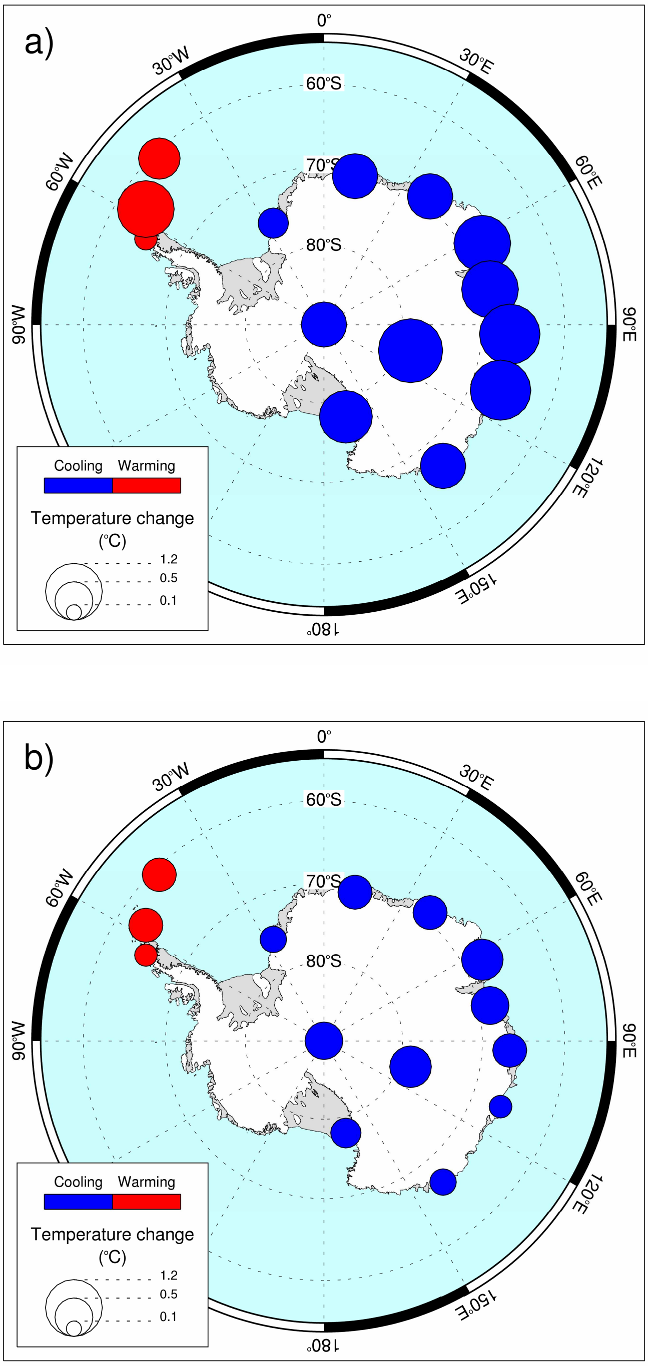


Figure 2. The magnitude and significance of correlations between the SAM and Antarctic near-surface temperatures for 1957-2004: (a) autumn; (b) winter; (c) spring; and (d) summer.


a)
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0°
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Cooling
Warming
Temperature change
(°C)
1.2
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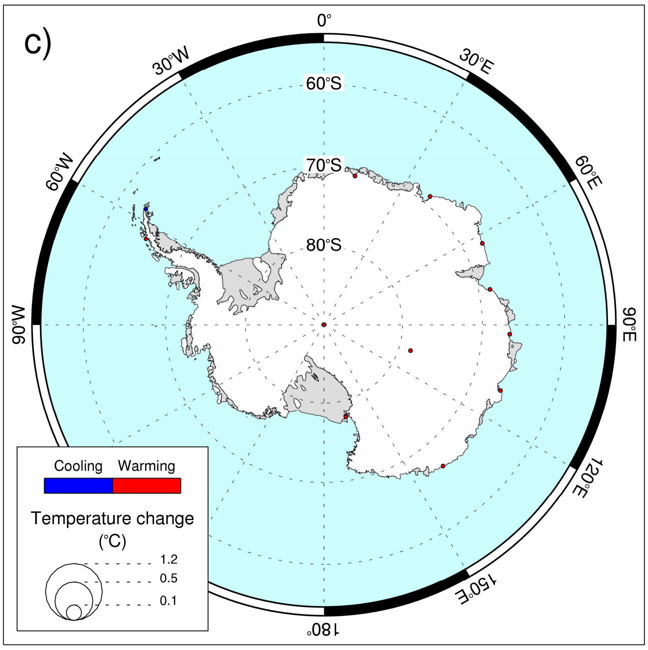

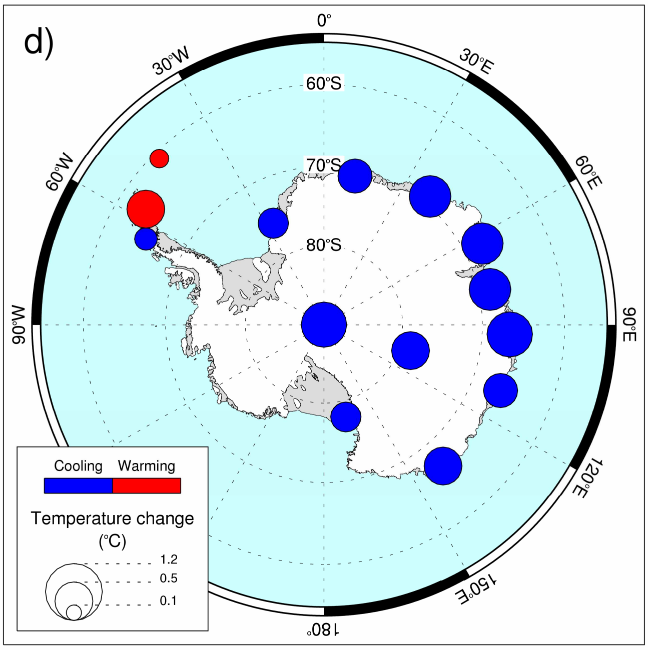

Figure 3. The estimated change in Antarctic near-surface temperatures for 1957-2004 caused by trends in the SAM: (a) autumn; (b) winter; (c) spring; and (d) summer.

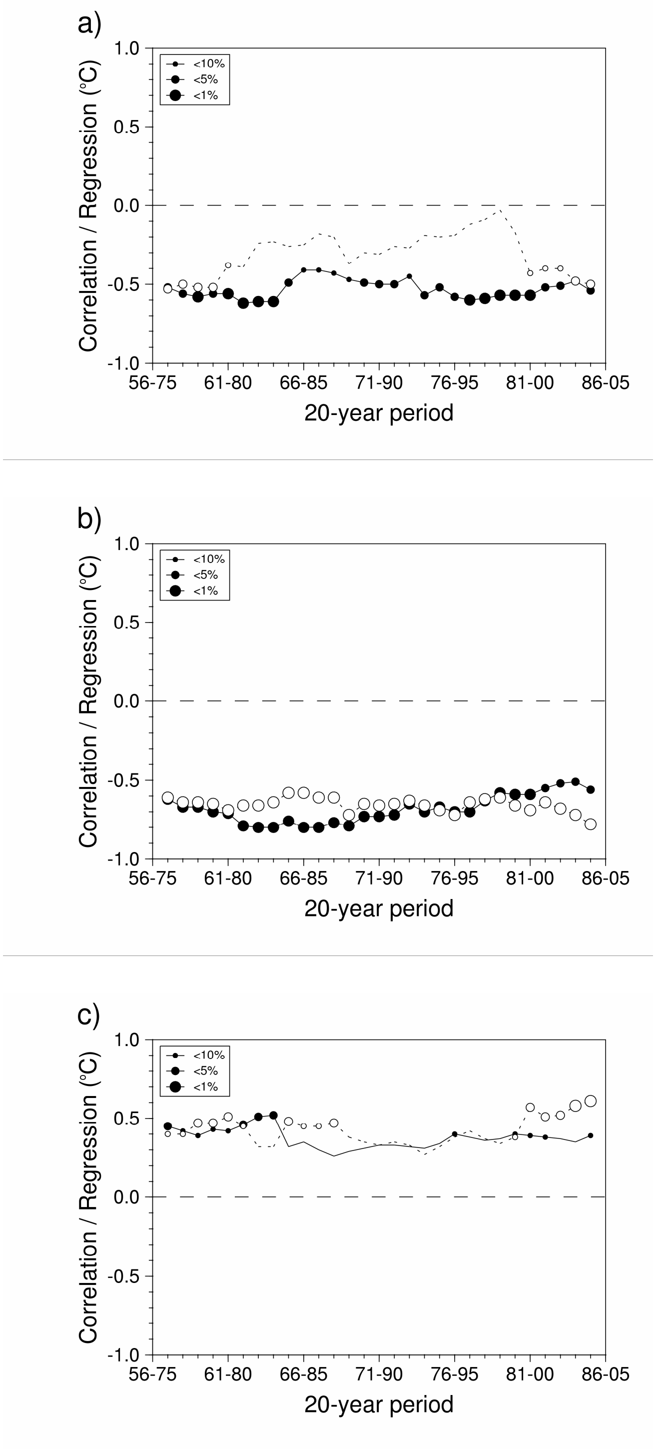

Figure 4. Temporal changes in the magnitude and significance in the correlation between the SAM and near-surface temperatures using a running 20-year window: (a) Amundsen-Scott; (b) Mawson; and (c) Esperanza. Winter data are the solid line and filled circles, summer data the dotted line and open circles.