Antarctic Science 24(1), 59–76 (2012) © Antarctic Science Ltd 2011 doi:10.1017/S095410201100054X

Influence of the Antarctic Oscillation, the Pacific–South American modes and the El Niño–Southern Oscillation on the Antarctic surface temperature and pressure variations

LEJIANG YU[1,2], ZHANHAI ZHANG[2], MINGYU ZHOU[2], SHARON ZHONG[3], DONALD LENSCHOW[4], HSIAOMING HSU[4], HUIDING WU[2] and BO SUN[2]

[1]*Applied Hydrometeorological Research Institute, Nanjing University of information Science & Technology, Nanjing 210044, China*
[2]*Polar Research Institute of China, Shanghai 200136, China*
[3]*Michigan State University, East Lansing, MI 48824, USA*
[4]*National Center for Atmospheric Research, Boulder, CO 80307, USA*
yulejiang@pric.gov.cn

Abstract: In this study, the impacts of the Antarctic Oscillation (AAO), the Pacific–South American teleconnection (PSA) and the El Niño–Southern Oscillation (ENSO) on Antarctic sea level pressure and surface temperature are investigated using surface observational data, European Centre for Medium-Range Weather Forecasts (ECMWF) 40 Year Re-analysis (ERA-40) and the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) re-analysis data from 1958–2001. There is the most significant correlation between PSA and Antarctic sea level pressure and surface temperature in the northern Antarctic Peninsula during four seasons. But the correlation between Southern Oscillation Index and surface temperature and sea level pressure is significant at some stations only in spring. The three indices can explain a large portion of the trends found in sea level pressure and temperature at some stations, but not at all stations. Among the three indices the most important contribution to the trends in the two surface variables comes from AAO, followed by PSA, and finally by ENSO. The two re-analysis datasets show great similarity for the trends in surface temperature and sea level pressure in April–May and October–November, but not December–February. In summer the trends in surface temperature and sea level pressure in East Antarctica for ERA-40 re-analysis are opposite to those of NCEP re-analysis.

Received 31 August 2010, accepted 23 May 2011, first published online 23 September 2011

Key words: Antarctica, re-analysis data, sea level pressure

Introduction

In recent decades, observational data from Antarctica have shown that both temperature and pressure from surface to upper levels have changed significantly in the Antarctic continent. Turner *et al*. (2005) found a strong warming over the Antarctic Peninsula and slight cooling over the Antarctic continental interior in recent decades. By analysing Antarctic radiosonde data, Turner *et al*. (2006) reported that regional mid-tropospheric temperature had increased at a statistically significant rate of 0.5–0.7°C per decade over the past 30 years. Recently, Steig *et al*. (2009) reported that the significant warming has extended beyond the Antarctic Peninsula to cover most of West Antarctica with a trend of 0.1°C per decade in winter and spring over the past 50 years.

Previous studies have linked these observed changes in temperature and pressure over Antarctica to various global and regional-scale factors. Thompson & Solomon (2002) suggested that the patterns of temperature change are related to an increase in circumpolar westerlies resulting from changes

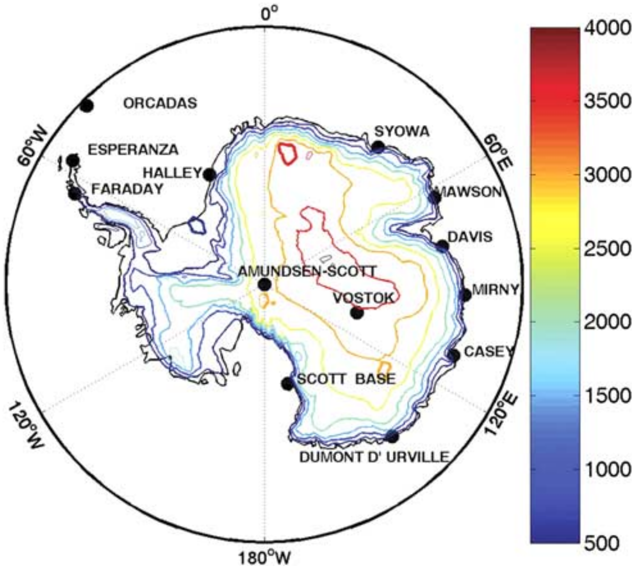

Fig. 1. Location map of the Antarctic stations used in this study and the Antarctic topography.

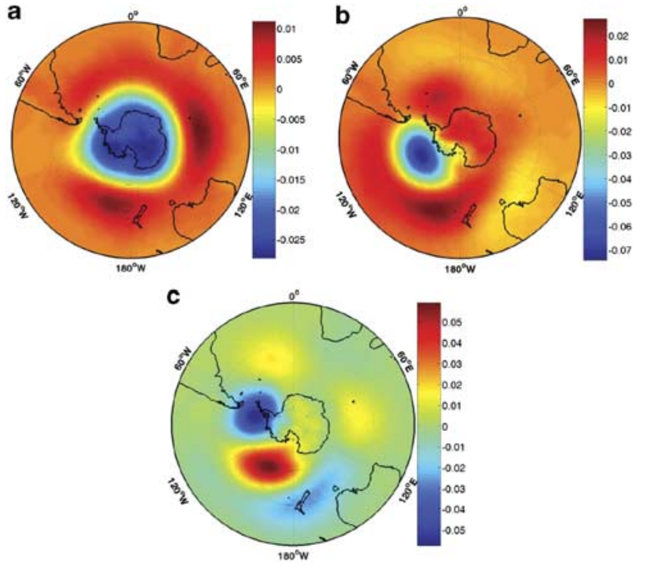

Fig. 2. Spatial distributions of the leading three EOF modes of mean sea level pressure (southward of 20°S). **a.**, **b.**, **& c.** indicate the first, second, and third modes, respectively.

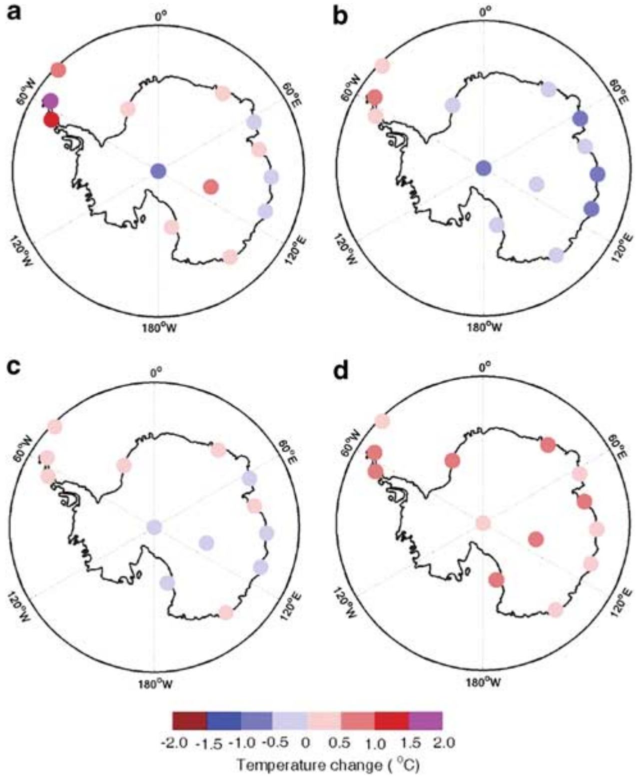

Fig. 3. The estimated trends in Antarctic surface temperature for 1958–2001 in summer (December–February) for observational data. **a.** Total trend, **b.** trend congruent with AAO, **c.** trend congruent with PSA2, and **d.** residual trend.

in stratospheric polar vortex and ozone. Steig *et al.* (2009) attributed the enhanced warming in West Antarctica to regional changes in atmospheric circulation. Turner *et al.* (2005) found that there is a correlation between the fall of sea level pressure over the Antarctic continent and high Antarctic Oscillation (AAO) index. The AAO, also called the Southern Annular Mode (SAM), is the leading mode of low frequency variability poleward of 20°S with a see-saw of atmospheric pressure between the Antarctic region and the Southern Hemispheric mid latitudes (Thompson & Wallace 2000a). During the positive phase of the AAO, anomalous low (high) pressure exists over Antarctica (the southern mid latitudes). There has been a significant trend of AAO index towards the positive phase in recent decades (Jones & Widmann 2004), which can be induced by external forcing such as stratospheric ozone depletion and increased atmospheric greenhouse gas (Thompson & Solomon 2002, Arblaster & Meehl 2006).

In addition to AAO, the changes in Antarctic climate have also been linked to the Pacific–South American (PSA) mode (Liu *et al.* 2004). Mo & Ghil (1986) found a wave train from the central Pacific to Argentina with large amplitudes in the Pacific–South American (PSA) sector, and called it the PSA mode (hereafter referred to as the PSA1 mode). Szeredi & Karoly (1987a, 1987b) found another wave train pattern with a 90° zonal phase lead by PSA1 (referred to here as the PSA2 pattern). Pacific–South American modes occurred in many empirical orthogonal function (EOF) analyses and teleconnection analyses at different timescales (Lau *et al.* 1994, Kidson 1999). The PSA1 mode has been identified as the Southern Hemisphere response to El Niño–Southern Oscillation (ENSO) (Karoly 1989, Mo & Paegle 2001). The PSA2 pattern has been linked to the quasi-biennial (QB) oscillation in the tropics (Mo 2000). Liu *et al.* (2004) found the ice changes associated with the AAO and ENSO could not explain the trends of Antarctic sea ice, and thought the PSA might be the reason for the trends.

Studies have shown that the AAO and PSA patterns are leading modes of EOF analysis of different pressures

Table I. 44 year (1958–2001) linear trends for the AAO, PSA1, PSA2 and SOI indices (SD 44 yr^{-1}). Trends that exceed the 90% threshold are in bold.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AAO	**0.95**	**1.04**	0.38	**1.20**	**1.10**	0.47	0.60	0.47	-0.47	**0.94**	0.36	**1.25**
PSA1	0.85	0.41	0.37	**1.14**	0.43	0.31	-0.08	-0.06	0.42	0.37	**1.59**	0.53
PSA2	**1.28**	0.85	0.70	0.64	-0.02	0.45	0.65	0.65	-0.06	0.57	0.72	**1.21**
SOI	0.13	-0.01	-0.72	-0.82	-0.64	-0.55	-0.02	-0.81	-0.26	-0.25	0.05	-0.43

Table II. The estimated change in Antarctic surface temperature for 1958–2001 caused by total trends, trends in the AAO, PSA1 and PSA2 and residual trends. Units: °C.

	Summer (Dec–Feb)				Autumn (Apr–May)				Spring (Oct–Nov)			
	total	AAO	PSA2	residual	total	AAO	PSA1	residual	total	AAO	PSA1	residual
Amundsen–Scott	-0.69	-0.61	-0.32	0.24	-1.54	-0.70	0.10	-0.84	0.07	-0.72	-0.11	0.90
Casey	-0.29	-0.51	-0.01	0.23	-1.02	-1.14	-0.19	0.31	-0.16	-0.39	0.15	0.08
Davis	0.24	-0.42	0.05	0.61	-0.64	-1.21	0.23	0.34	0.49	-0.40	0.36	0.53
Dumont d'Urville	0.11	-0.43	0.17	0.37	-1.85	-0.76	-0.08	-1.01	0.56	-0.20	0.23	0.53
Esperanza	1.67	0.67	0.40	0.6	4.09	2.4	0.63	1.06	0.23	0.44	0.33	-0.54
Faraday	1.17	0.11	0.32	0.74	3.88	1.17	0.97	1.74	1.25	-0.11	0.88	0.48
Halley	0.36	-0.36	0.11	0.61	-3.29	-0.46	0.18	-3.01	0.21	-0.00	0.33	-0.12
Mawson	-0.31	-0.57	-0.11	0.37	-1.91	-1.53	0.01	-0.39	-0.08	-0.33	0.23	0.02
Mirny	-0.44	-0.72	-0.05	0.33	-0.78	-1.18	0.05	0.35	-0.00	-0.43	0.27	0.16
Orcadas	0.94	0.20	0.34	0.40	1.97	1.11	0.47	0.39	0.11	0.16	0.53	-0.58
Scott Base	0.12	-0.44	-0.02	0.58	1.02	-0.82	0.82	1.02	2.58	-0.26	0.76	2.08
Syowa	0.29	-0.31	0.08	0.52	-0.14	-0.36	-0.18	0.40	-0.39	-0.13	0.25	-0.51
Vostok	0.69	-0.20	-0.05	0.94	-1.37	-1.16	-0.00	-0.21	0.35	-0.26	0.22	0.39
Average	0.56	0.43	0.16	0.50	1.81	1.08	0.30	0.85	0.50	0.29	0.36	0.53

(Mo 2000). In this study, we examine how the changes of AAO and PSA contribute to the trends in surface air temperature and sea level pressure. We also investigate the impact of the ENSO on the surface temperature and pressure over Antarctica.

Data and method

Data

The data used in this study are monthly surface observations from 13 Antarctic stations (see Fig. 1) obtained from the

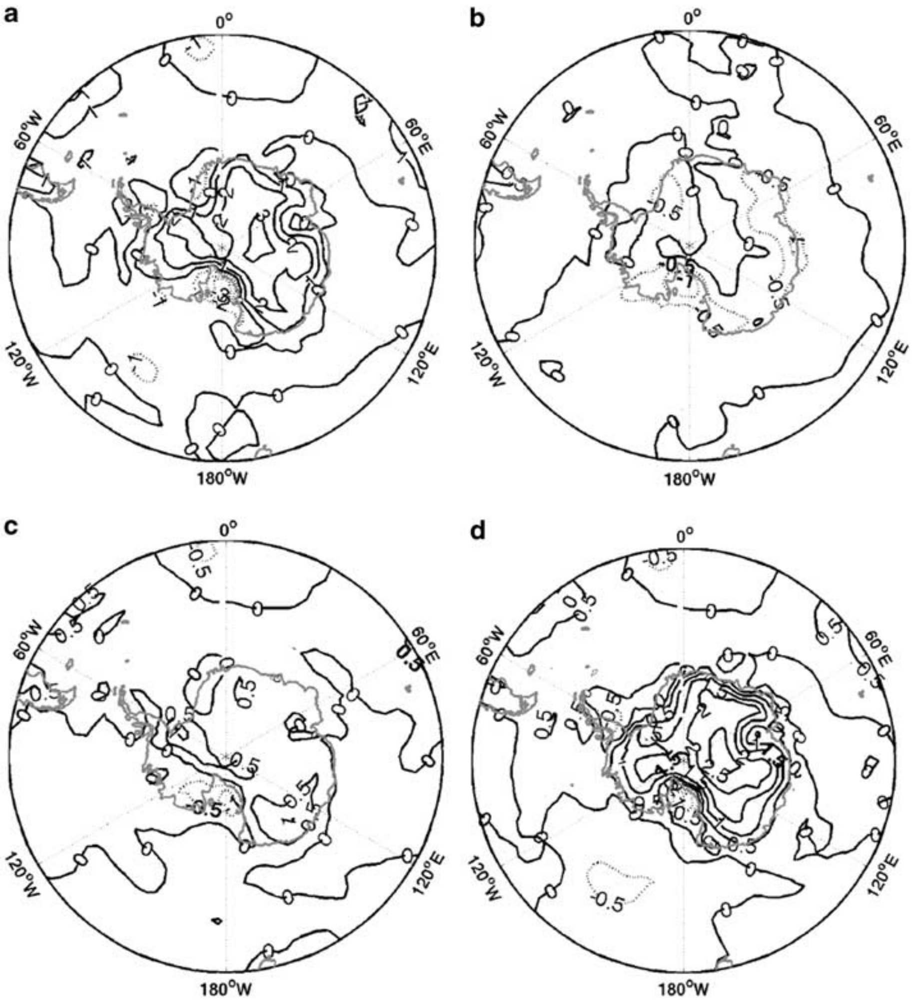

Fig. 4. 44 yr (1958–2001) linear December–February trends in surface air temperature for ERA-40 re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA2, and **d.** residual trends. Units are °C for surface air temperature.

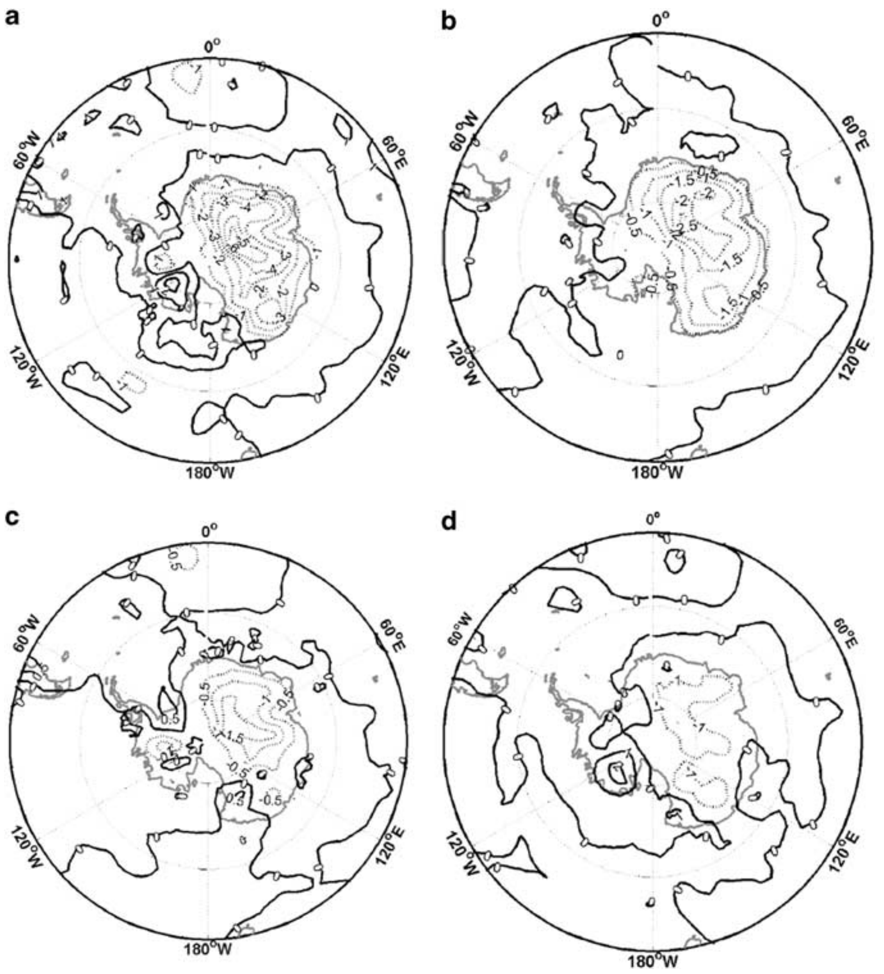

Fig. 5. 44 yr (1958–2001) linear December–February trends in surface air temperature for NCEP re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA2, and **d.** residual trends. Units are °C for surface air temperature.

Antarctic READER (Reference Antarctic Data for Environmental Research) Project (Turner *et al.* 2004) (http://www.antarctic.ac.uk/met/READER/data.html, accessed August 2010). This study uses two global datasets: the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) re-analysis NCEP-NCAR global re-analysis and the European Centre for Medium-Range Weather Forecasts (ECMWF) 40 Year Re-analysis ERA-40 re-analysis. The NCEP-NCAR global re-analysis is based on the NCEP operational Eta model of 10 January 1995 with a reduced horizontal resolution of T42 (209 km) and 28 vertical levels. Its temporal coverage is four times per day for NCEP I from 1 January 1948 to the present. Detailed descriptions of the NCEP-NCAR global re-analysis are given by Kalnay *et al.* (1996) and Kistler *et al.* (2001). The ERA-40 re-analysis contains the data from September 1957–August 2002 with a horizontal resolution of T159 (125 km) and 60 vertical levels (23 standard pressure levels). More descriptions about ERA-40 can be found in the work of Uppala *et al.* (2005). The two re-analysis datasets are on a 2.5°×2.5° latitude-longitude grid. The primary atmospheric variables include mean sea level pressure and 2 m air temperature for the period from 1958–2001. Although Bromwich & Fogt (2004) found a low level of skill in ERA-40 data before 1978, ERA-40 re-analysis data are also compared and validated (Uppala *et al.* 2005). Justino *et al.* (2010) found the seasonal cycle of the temperature 2 m above ground level over Antarctica may be biased in ERA-40. Yu *et al.* (2010) also compared two re-analysis from 1979–2001 with observational data and found at the interannual timescale, atmospheric pressures at different height levels in ERA-40 are in better agreement with the observed pressure than that in the NCEP-NCAR re-analysis. The ERA-40 re-analysis also outperforms NCEP-NCAR re-analysis in atmospheric temperature except the surface layer atmosphere where the biases are somewhat larger. Phillpot (1991) and Schwerdtfeger (1984) found that for stations located at high elevation, the reduction to sea level is ambiguous. Because of high elevation of Amundsen–Scott (2800 m) and Vostok (3488 m), surface pressure at these two stations is used to calculated trends and correlation coefficients, but at the other 11 stations sea level pressure is used.

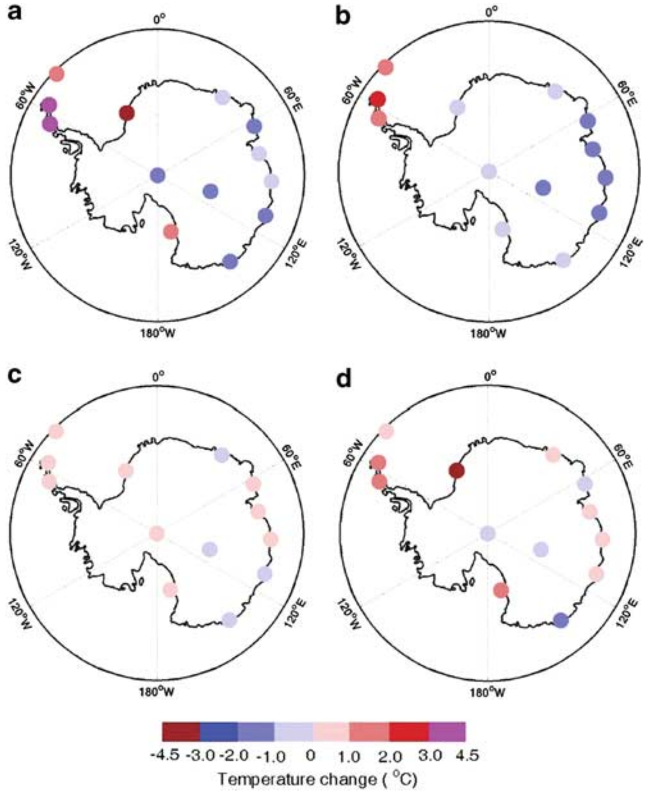

Fig. 6. The estimated trends in Antarctic surface temperature for 1958–2001 in autumn (April–May) for observational data. **a.** Total trend, **b.** trend congruent with AAO, **c.** trend congruent with PSA1, and **d.** residual trend.

In addition, the Southern Oscillation Index (SOI) was derived from http://www.cgd.ucar.edu/cas/catalog/climind/soiAnnual.html, accessed August 2009.

Analysis method

The AAO, PSA1 and PSA2 indices are defined as the standardized leading three time series of EOF analysis of ERA-40 monthly sea level pressure poleward of 20°S. Total linear trends are obtained as the slope of a straight line by least-square fit at each grid point for specific periods. The trends that are linearly congruent with the monthly AAO, PSA1 and PSA2 indices can be obtained following the method of Thompson & Wallace (2000b): a) regressing monthly values of the time series of the grid point onto the AAO index, b) multiplying the resulting regression coefficients by the linear trend in the AAO index, c) the trends that are linearly congruent with the monthly PSA indices are estimated by means of similar method to the AAO index. The residual trend is defined as the trend attained by subtracting the trends in the AAO and PSA1 (PSA2) indices from total trend.

Seasonal correlation between the PSA and surface air temperature are derived from the period 1958–2001 with 42 degrees of freedom. Significance of the correlations is tested by applying Student's *t*-test. Normally the four seasons are defined: summer (December–February), autumn (March–May), winter (June–August), and spring (September–November). To ease the comparison of the different contributions from three different indices at significant levels, autumn (April–May) and spring (October–November) are defined.

The pattern and trends of AAO and PSA

We performed EOF analysis of monthly mean sea level pressure poleward of 20°S from 1958–2001. Three leading patterns are presented in Fig. 2. The first mode (the AAO pattern) explains about 41.6% of the total variance. It is a zonally symmetric pattern with a phase reversal between high and mid latitudes. The pattern of the PSA1 (PSA2) corresponds to that of mode2 (mode3). The two PSA modes explain 8.0% and 6.6% of the total variance, respectively. These two patterns are similar to the EOF patterns obtained by Kidson (1988) using ECMWF operational analyses on interannual time scales. These two PSA patterns exhibit the following structures: a zonal wave with wave number three in mid to high latitudes and a meridional wave with wave number one between 70°S and the tropics, and a one quarter phase difference between these two PSA patterns. When grid boxes above 1000 m is moved, the result of EOF analysis is similar to those without moving 1000 m (not shown). Our primary interest is the time series of leading three modes (the AAO, PSA1, and PSA2 indices).

44 yr (1958–2001) linear trends of the AAO, PSA1, PSA2, and SOI indices are calculated and the results are shown in Table I. The trends exceed 90% significance level in six months (January, February, April, May, October, and December) for the AAO index, only two months (April and November) for PSA1, and two months (January and December) for PSA2. The significant trends for the AAO index are similar to the results of Thompson & Wallace (2000b). The trends of three indices are above 90% significance level in following seasons: for AAO, spring (October–November) with 0.85 SD 44 yr^{-1}, summer (December–February) with 1.52 SD 44 yr^{-1}, and autumn (April–May) with 1.41 SD 44 yr^{-1}; for PSA1, spring (October–November) with 1.18 SD 44 yr^{-1} and autumn (April–May) with 0.91 SD 44 yr^{-1}; for PSA2, austral summer (December–February) with 1.76 SD 44 yr^{-1}. Thus in summer (December–February) only the contributions from the AAO and PSA2 are considered when analysing the trend of any variable; in autumn (April–May) and spring (October–November) the contributions from the AAO and PSA1 are taken into account. For SOI, their trends in 12 months cannot exceed 95% confidence level.

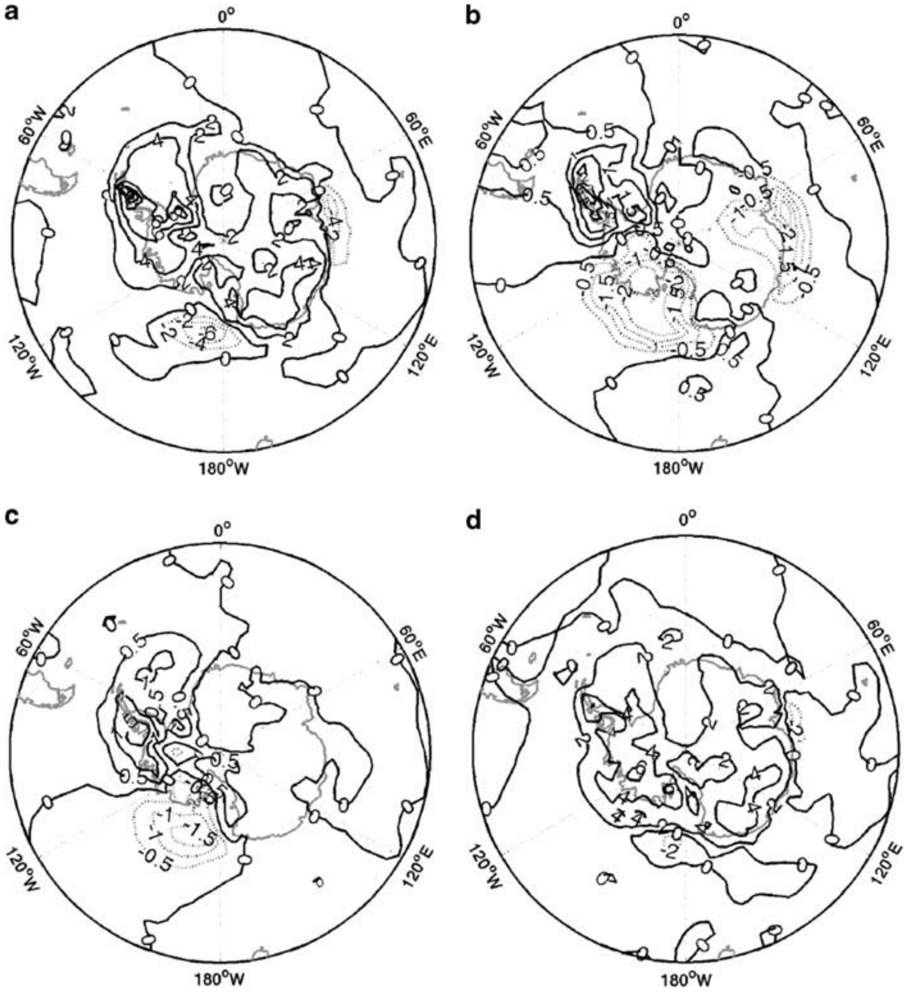

Fig. 7. 44 yr (1958–2001) linear April–May trends in surface air temperature for ERA-40 re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA1, and **d.** residual trends. Units are °C for surface air temperature.

Surface air temperature

Relationship to PSA

The seasonal relationship between the AAO index and surface air temperature has been discussed previously by Marshall (2007) using similar observational data. Therefore, we will focus only on the relationship between PSAs (PSA1 and PSA2) indices and surface air temperature.

The correlation between the PSA and Antarctic surface air temperatures are done for each of the four seasons during the 44 yr (1958–2001) period. In general, the strength and location of the low and high pressure centres associated with the PSA1 and PSA2 indices vary with seasons (Lau *et al*. 1994), and the strength and location of corresponding meridional wind also change, which together lead to significant seasonal variations of surface air temperature. The Antarctic Peninsula, Bellingshausen Sea, Amundsen Sea, Ross Sea and Weddell Sea are mainly areas influenced by the PSA during the entire year. There are, however, seasonal differences in the influence area coverage and significance of the relationship between the PSA and temperature.

In summer there are significant positive correlations (at a significance level of > 98%) between the PSA1 and temperature at the stations over the Ross Sea (Scott Base) and the Weddell Sea (Halley). At Amundsen–Scott, Davis and Faraday stations the positive correlations are significant at a significance level of > 90%. At Mawson, Esperanza, Orcadas, Syowa, and Vostok stations the correlation is positive but not statistically significant. At the other three stations (Casey, Dumont d'Urville, and Mirny) the negative relationship is weak and not significant. During the same season the PSA2 has a remarkable effect on the surface temperature in the northern Peninsula (Orcadas, Esperanza and Faraday) with high positive correlation coefficients, particularly at Orcadas where the relationship is significant at > 99% level. On the contrary the correlations between PSA2 index and temperature at other Antarctic stations are not significant.

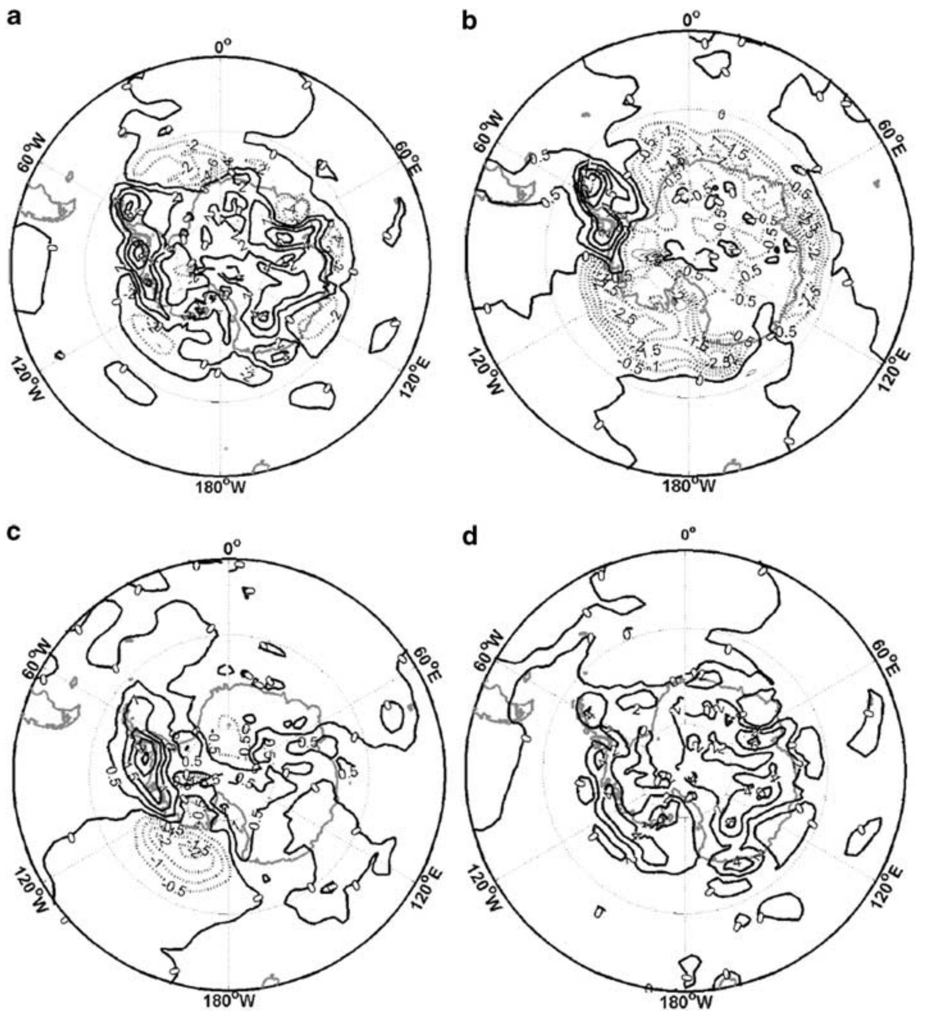

Fig. 8. 44 yr (1958–2001) linear April–May trends in surface air temperature for NCEP re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA1, and **d.** residual trends. Units are °C for surface air temperature.

The spatial pattern of the PSA-temperature correlations is similar in autumn to that in summer, and only the differences will be discussed here. The correlation between the PSA1 index and surface temperature strengthens in the northern Antarctic Peninsula with an increase in the correlation coefficient from 0.29–0.51 (at > 99.9% level) at Faraday, from 0.18–0.32 (at > 95% level) at Orcadas, and from 0.02–0.23 at Esperanza. On the contrary, the influence over the eastern Weddell Sea weakens with a decrease in correlation from 0.38 at > 98% level to 0.24 at < 90% level at Halley. The relationship between the PSA1 index and temperature at Scott Base remains unchangeable. The correlation between PSA2 index and temperature varies with station locations. The correlation at Scott Base increases from -0.01 to -0.32 at > 95% level, but a decrease occurs in the northern Antarctic Peninsula, especially for Esperanza and Faraday where the relation is less significant.

In winter the correlations between the PSA1 index and temperature at stations in the northern Peninsula are the most significant at > 99.9% level, but the correlation is much lower at other stations. Similarly, for PSA2, there is only one station (Dumont d'Urville) where the correlation between PSA2 index and surface temperature is significant at > 99% level and two other stations in East Antarctica and one station in the northern Peninsula where the correlation is found to be significant at > 90% significance level.

The spatial coverage of the significant correlation between PSA1 index and temperature is the largest in spring with seven stations at > 90% significance level. Only in spring are temperatures at Davis, Vostok, and Mirny significantly correlated with PSA1 index. The correlation between PSA1 index and Faraday temperatures is strongest in spring with a magnitude of 0.69 and a significance level > 99.9%. The physical mechanisms for the strong relationship involve the poleward advection of warm air across the northern Peninsula to the east coast where Faraday is located (not shown). At Orcadas, north of Faraday, the correlation coefficient is lower, 0.32 with > 95% level, but at Esperanza near Faraday, the correlation is not significant. These differences among the three stations in northern Peninsula may be related to the local circulation

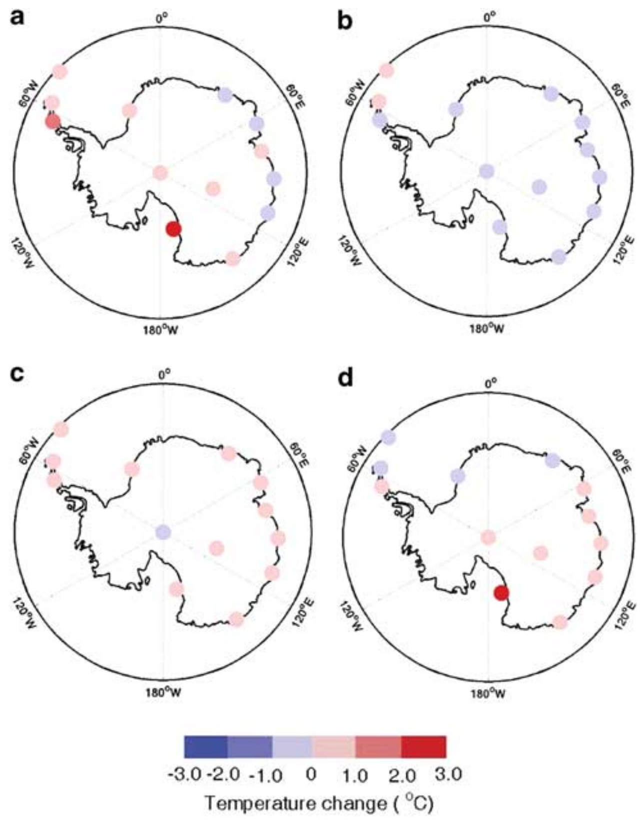

Fig. 9. The estimated trends in Antarctic surface temperature for 1958–2001 in spring (October–November) for observational data. **a.** Total trend, **b.** trend congruent with AAO, **c.** trend congruent with PSA1, and **d.** residual trend.

induced by topography. The correlations between PSA1 index and temperature at all 13 stations are positive. The strongest correlation between PSA1 index and Scott Base temperature also appears in spring, with correlation coefficient 0.48 at $>$ 99% level. The region influenced by the PSA2 in spring is the Weddell Sea (Halley, Esperanza and Orcadas), particular at Orcadas where the strongest correlation among the four seasons is found (0.56 at $>$ 99.9% level).

In summary, stations in the Ross Sea and the Weddell Sea, which are subject to a strong influence of Rossby wave train (Fig. 2b & c), exhibit high correlation between PSA and surface temperature, with the highest correlation found in the northern Antarctic Peninsula where northerly winds prevail.

Trend analysis

Figure 3 and Table II display the estimated summertime trends in surface temperature from 1958–2001 that include total trend, trend congruent with AAO, trend congruent with PSA2 and residual trend. Total trends in surface temperature are generally positive except at Amundsen–Scott, Mawson, Mirny, and Casey where a cooling trend exceeds 0.5°C. The strongest warming trend occurs in the northern Peninsula with a slope of 1.67°C 44 yr^{-1} at Esperanza. The significant warming trend in the northern Antarctic Peninsula was also found by Turner *et al.* (2005). 44 yr (1958–2001) summertime (December–February) linear trends in surface air temperature using ERA-40 re-analysis data are also computed and the results are shown in Fig. 4a. A positive trend occurs over the Antarctic continent with maximum values as high as 3°C 44 yr^{-1}. The gridded ERA-40 re-analysis data show variation of trend with topography, which is not captured by data from the surface stations that are located mostly over coastal area. For NCEP re-analysis there is a negative linear December–February trend in surface air temperature in East Antarctica with the minimum value of -6°C 44 yr^{-1}, which is opposite to the result of ERA-40 re-analysis and a positive trend occurs in East Antarctica in Fig. 5a.

Antarctic Oscillation contributes to warming over the northern Antarctic Peninsula (Esperanza, Faraday, and Orcadas) related to increasing westerly, but caused significant cooling at the rest of the ten surface station locations (Fig. 3b) (Thompson & Wallace 2000a, Van den Broeke & Van Lipzig 2004, Justino & Peltier 2008). Similar result was also found by Marshall (2007). Van den Broeke & Van Lipzig (2004) explained that during strong vortex (positive AAO) East Antarctic cooling has two components: suppressed meridional air exchange, and additional cooling near the surface in areas where a weakening of near-surface winds has intensified the surface temperature inversion. The warming in the Antarctic Peninsula may result from stronger northerly wind. Orr *et al.* (2004, 2008) found the warming over the Antarctic Peninsula involving northerly wind and adiabatical warming induced by strong down-slope wind. The regresses of zonal and meridional wind on summer AAO show positive AAO index corresponds to increasing north-westerly wind over the northern Antarctic Peninsula (not shown). The largest AAO related warming (0.67°C) is at Esperanza and the largest cooling (-0.72°C) occurs at Mirny. The proportion of total temperature change in autumn that is attributed to AAO varies significantly across Antarctica. At Faraday the AAO related warming is one tenth of what is actually observed. At Amundsen–Scott AAO explains majority of the total cooling trend. At some stations the temperature changes congruent with AAO is opposite to the total trend.

Positive trends caused by PSA2 lie at coastal stations from 60°E westwards to 120°W except for Davis and Dumont d'Urville. Negative trends are found at other six stations in East Antarctica (Fig. 3c). At most stations PSA2 related temperature changes (with maximum change of 0.4°C) are less than those associated with AAO. The trends in surface air temperature associated with PSA2 correspond to the wind direction of atmospheric circulation induced by PSA2 (Fig. 3b). In other words, the region with southerly (northerly) prevailing wind has a cooling (warming) trend.

The residual trends in summer are positive at all stations, with the largest positive trend of 0.94°C 44 yr^{-1} at Vostok

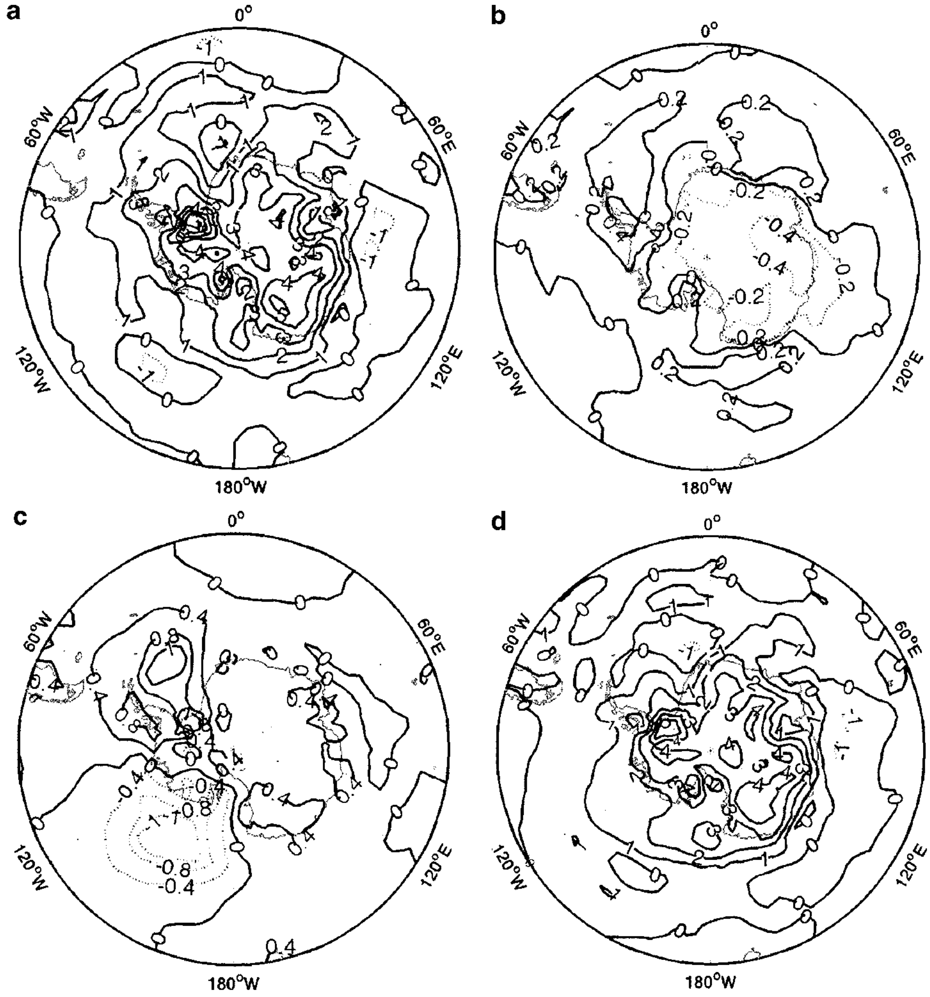

Fig. 10. 44 yr (1958–2001) linear October–November trends in surface air temperature for ERA-40 re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA1, and **d.** residual trends. Units are °C for surface air temperature.

(Fig. 3d). In contrast, the warming in East Antarctica determined from the ERA-40 re-analysis data (Fig. 4d) are > 2.5°C 44 yr^{-1}. There is a cooling trend in surface temperature over the Ross Sea, which is absent from the Scott Base (Fig. 3d). In summer significant differences in the surface temperature trends between ERA-40 and the surface stations occur in East Antarctica, where the residual trend reaches a maximum value. However, for the NCEP re-analysis the trends related to AAO and PSA2 explain a large part of total trends especially in East Antarctica, the magnitude of residual trends is smaller than that of ERA-40 (Fig. 5b–d).

In autumn (April–May, Fig. 6a) positive trends in surface temperature are at Orcadas, Esperanza, Faraday and Scott Base, particularly at Esperanza where the warming trend is 4.09°C 44 yr^{-1}. The warming trend over the northern Antarctic Peninsula is consistent with the result of Steig *et al.* (2009). The other nine stations show negative trends, with the most cooling of -3.39°C at Halley. The trends determined using ERA-40 re-analysis data are positive everywhere in Antarctica and the rate of warming at Esperanza nearly doubles that from the station data (Fig. 7a). For NCEP re-analysis the spatial pattern of the trend in Antarctica are similar to that of ERA-40 except for the Weddell Sea (Fig. 8a). It indicates that ERA-40 and NCEP re-analysis data are not accurate in describing the total trend in autumn surface air temperature.

The influence of AAO on surface temperature is stronger in autumn than in summer although the spatial pattern is similar between the two seasons (Figs 3b & 6b). The largest AAO related warming (2.4°C 44 yr^{-1}) is found at Esperanza while the strongest cooling (-1.53°C 44 yr^{-1}) occurs at Mawson. PSA1 contributes to warming at most stations except for Casey, Dumont d'Urville, Syowa, and Vostok, and the warming rate is < 1°C. The trends associated with AAO and PSA1 determined using ERA-40 and NCEP re-analyses are consistent with those derived from surface station data. Strong zonal westerlies induced by the strengthening of AAO and anomalous northerly winds associated with high PSA1 contribute to warming over the Antarctic Peninsula and West Antarctica (Fig. 6b & c). Similar to summer season, the trend attributable to AAO is more than to PSA2.

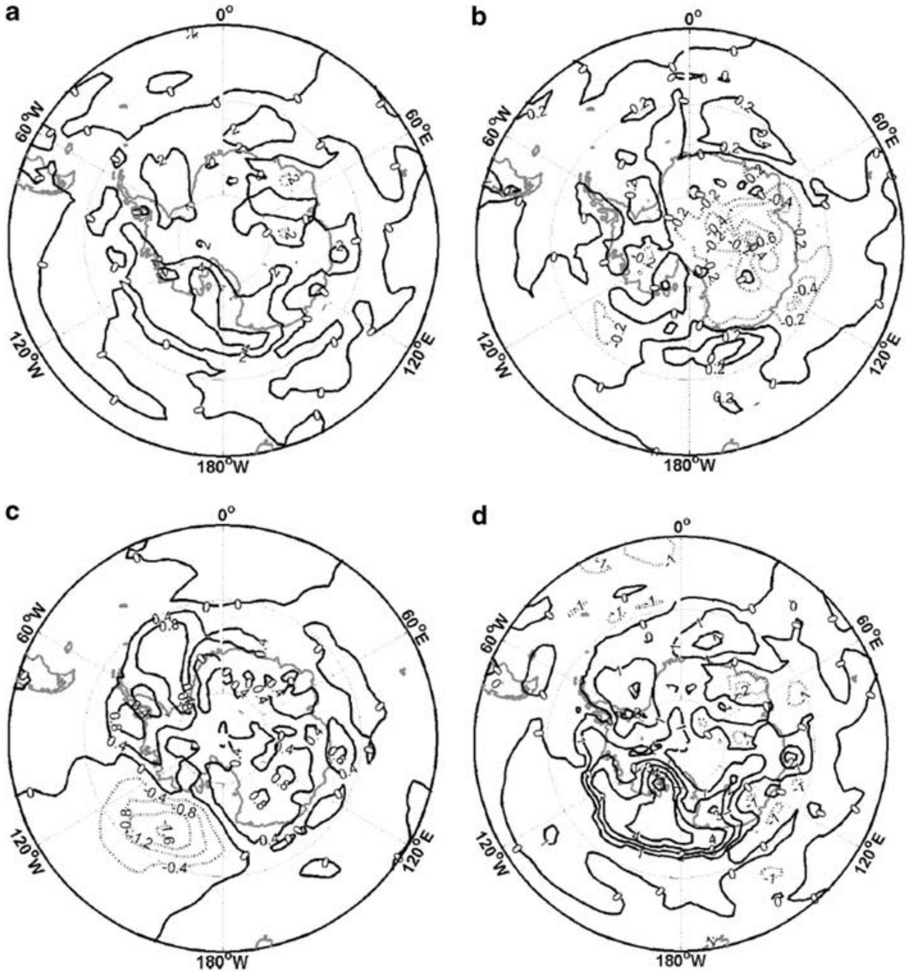

Fig. 11. 44 yr (1958–2001) linear October–November trends in surface air temperature for NCEP re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA1, and **d.** residual trends. Units are °C for surface air temperature.

The station residual trends in autumn (Fig. 6d) are not always positive as seen in the ERA-40 residual trends (Fig. 7d). The similar case also occurs in the NCEP residual trends (Fig. 8d). The residual trends are negative at five stations and the largest cooling rate of -3°C 44 yr^{-1} is found at Halley which is nearly equal to the total trend. This indicates that forces other than AAO and PSA1 are responsible for the surface temperature changes at Halley and other stations.

In spring (Fig. 9a, Table II) positive trends are found at most stations except for four coastal stations in East Antarctica (Syowa, Mawson, Mirny and Casey). The strongest warming of 2.58°C 44 yr^{-1} occurs at Scott Base. The ERA-40 re-analysis data (Fig. 10a) indicate a strong warming trend distributed across the Antarctic continent with the maximum value of $>$ 6°C 44 yr^{-1} in the Weddell Sea. The large differences between the ERA-40 trends and the station trends suggest that the surface air temperature in ERA-40 re-analysis data is unreliable in the spring season. Although an increasing trend exists in most of the Antarctic continent for the NCEP re-analysis, the magnitude is smaller than that of ERA-40 (Fig. 11a). The increase in surface temperature caused by AAO recedes northwards with AAO related warming occurring at only two stations. But the warming caused by PSA1 covers almost the entire Antarctic continent except for the South Pole. Like for summer and autumn, ERA-40 and NECP re-analyses show a high skill in describing the influence of AAO and PSA1 on springtime temperature. The springtime residual trends exhibit a positive spatial pattern except for four stations (Orcadas, Esperanza, Halley, and Syowa; Fig. 9d). The increasing trend of 2.08°C 44 yr^{-1} at Scott Base needs other explanation. Like for summer and autumn, the ERA-40 residual trends in spring (Fig. 10d) shows a strong warming over the entire Antarctic. The NCEP residual trends in spring also perform an increasing trend, but the centre of positive values lie over the Ross Sea (Fig. 11d).

The relative magnitudes of the trends are compared by averaging over the 13 stations for each of the three seasons and the results are shown in Table II. The change in surface air temperature is the largest in autumn (April–May), even surpassing the sum of the changes in summer (December–February) and spring (October–November), while the smallest is in spring. The same applies to the

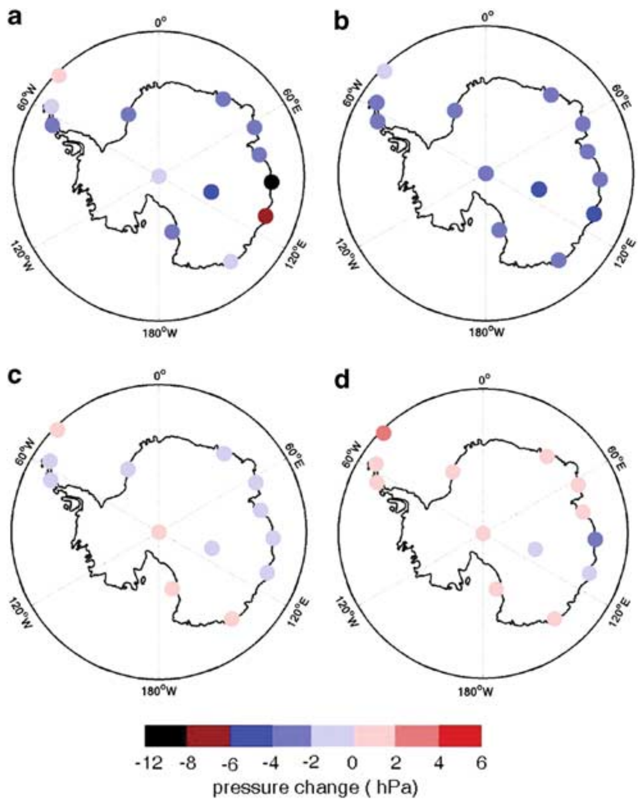

Fig. 12. The estimated trends in Antarctic sea level pressure for 1958–2001 in summer (December–February) for observational data. **a.** Total trend, **b.** trend congruent with AAO, **c.** trend congruent with PSA2, and **d.** residual trend. For Amundsen–Scott and Vostok stations, station surface pressure is used.

trends related to AAO. Besides the large trend in AAO, the more southward position of circumpolar trough in autumn is also the reason for the largest change connected with AAO. The change associated with PSA (PSA1 or PSA2) is most evident in spring and least in summer. Although the residual trend is the largest in autumn, the ratio of the temperature change explained by AAO and PSA to the total change is also the largest. In all three seasons, AAO appears to exert larger effect on surface temperature than that by PSA. The strong negative trend (-3.01°C 44 yr^{-1}) found at Halley does not appear to be connected to AAO and PSA. Other factors, e.g. katabatic wind may be responsible for the temperature trend at Halley in autumn and at other stations in different seasons (e.g. Vostok in summer and Scott Base in spring). Hence from Table II we can consider that under most circumstances during three seasons the AAO exert a larger effect on surface temperature than that of the PSA.

The comparison with ERA-40 re-analysis shows that the magnitude of temperature change in ERA-40 is larger than that of the station observations, especially in the total trends and the residual trends. The apparent strong ERA-40 warming trends in all three seasons in the entire Antarctic continent are not supported by the station data used in this study. Similar conclusions are also drawn by Johanson & Fu (2007). The summertime total and residual trends for NCEP re-analysis in East Antarctica are opposite to those of ERA-40 re-analysis. In October–November and April–May, the two re-analysis datasets show great similarity. However, the trends associated with the AAO and PSA determined based on ERA-40 and NCEP re-analyses data are mostly consistent with those determined from the station data.

Sea level pressure

The above analyses are repeated for sea level pressure and the results are presented in this section.

Relationship to PSA

In summer a positive correlation between sea level pressure and PSA1 at $>$ 90% significance level is only found at Dumont d'Urville. In autumn positive correlations exist at Faraday and Esperanza at $>$ 99% significance level, and over South Pole at $>$ 90% level. In winter the correlation in the northern Peninsula weakens, and negative correlations occur at Scott Base and Syowa at a level $>$ 95%. In spring the sea level pressure is positively correlated only with PSA1 at Amundsen–Scott. The regions under the influence of PSA1 vary with season. Compared to the temperature correlation patterns, the correlation for sea level pressure is more scattered.

PSA2 mainly changes the sea level pressure in the northern Peninsula with the strongest influence occurring in winter when three stations show negative correlation at 99% level. The main reason for these negative correlations is that the centre of the larger negative anomaly is situated in the northern Peninsula. In autumn the sea level pressure at three stations (Syowa, Mirny and Casey) in East Antarctica is correlated with PSA2 at $>$ 90% level, while in winter positive correlations occur at Scott Base and Vostok.

Trend analysis

The estimated changes in Antarctic sea level pressure for 1958–2001 associated with total trends, trends in AAO, PSA1 and PSA2, and residual trends during three seasons are shown in Figs 12–17 and Table III. Those trends in sea level pressure for NCEP are offered as supplemental material (http://dx.doi.org/10.1017/S095410201100054X) and are not shown in this paper.

In summer (Fig. 12a) all stations in the Antarctic continent experience a decrease in sea level pressure, with the most remarkable fall of -8 hPa happening at Mirny. Only in South Orkney Islands (Orcadas station) does a positive trend of 1.44 hPa 44 yr^{-1} exist. The ERA-40 sea level pressure trends in summer (Fig. 13a) also are negative

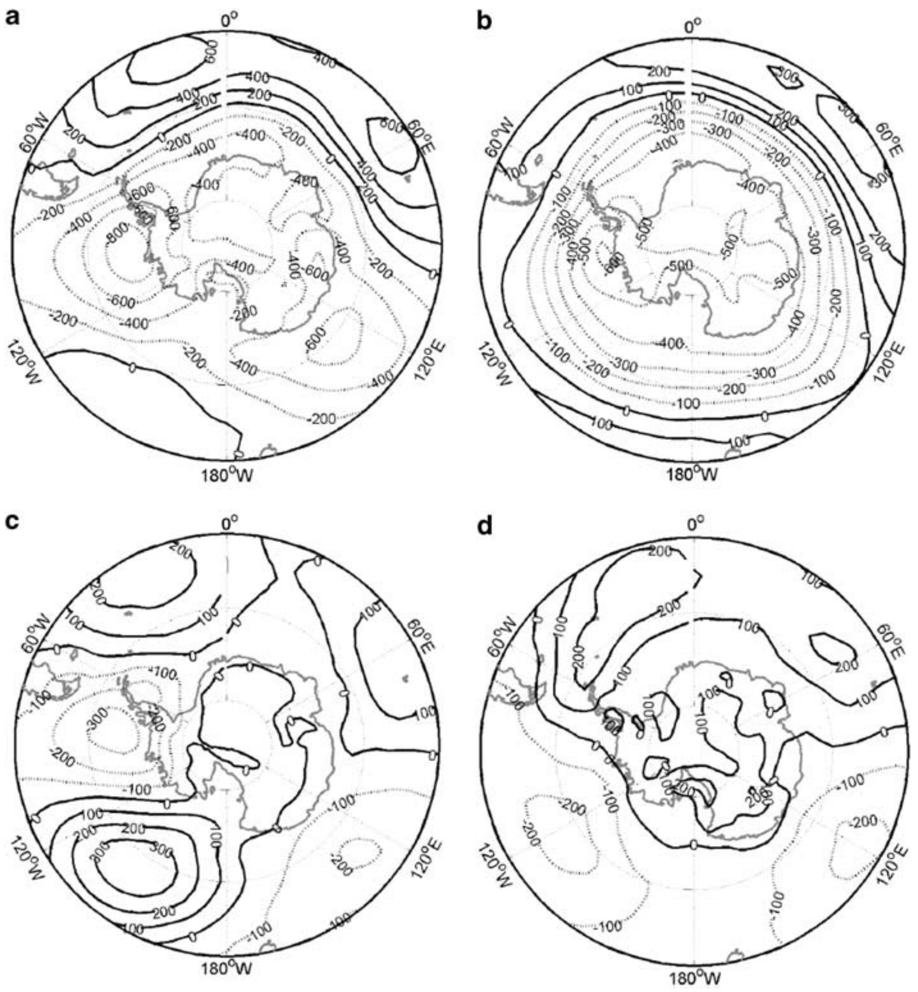

Fig. 13. 44 yr (1958–2001) linear December–February trends in sea level pressure for ERA-40 re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA2, and **d.** residual trends. Units are Pascal for sea level pressure.

60°S, but the pressure trend at the location near Mirny station is larger than the observed. The NCEP trends in sea level pressure in East Antarctica continent interior are positive and opposite to those of ERA-40. The similar case also occurs in trends in surface temperature. As a result of positive AAO index, all stations show a negative trend in

Table III. The estimated changes in Antarctic sea level pressure for 1958–2001 caused by total trends, trends in the AAO, PSA1 and PSA2 and residual trends. Units: Pascal.

	Summer (Dec–Feb)				Autumn (Apr–May)				Spring (Oct–Nov)			
	total	AAO	PSA2	residual	total	AAO	PSA1	residual	total	AAO	PSA1	residual
Amundsen–Scott*	-60.8	-340.3	85.2	194.3	-122.9	-417.4	71.4	223.1	194.9	-142.0	120.1	216.8
Casey	-631.7	-468.0	-77.0	-86.7	-792.8	-462.2	15.8	-346.4	-361.8	-164.6	6	-203.2
Davis	-306.2	-301.9	-13.5	9.2	-415.8	-372.7	-12.9	-30.2	-224.1	-147.0	0.5	-77.6
Dumont d'Urville	-114.5	-325.7	16.5	194.7	-300.3	-370.0	-27.6	97.3	-116.7	-171.4	50.6	4.1
Esperanza	-161.4	-261.7	-94.0	194.3	157.3	-155.6	146.0	166.9	-19.1	-152.8	-56.6	190.3
Faraday	-264.3	-285.1	-174.0	194.8	336.6	-173.5	92.8	417.3	-76.9	-129.4	-144.4	196.9
Halley	-279.2	-384.8	-19.9	125.5	-239.2	-399.5	28.0	132.3	-0.6	-204.4	-21.2	225.0
Mawson	-275.5	-306.7	-25.0	56.2	-365.3	-352.6	-29.9	17.2	-158.7	-152.4	4.4	-10.7
Mirny	-838.6	-368.8	-111.6	-358.2	-1102.8	-453.2	-36.5	-613.1	-670.8	-168.3	-41.0	-461.5
Orcadas	144.2	-151.2	51.7	243.7	488.3	-9.2	143.1	354.4	147.3	-71.4	52.5	166.2
Scott Base	-266.2	-391.6	4.2	121.2	-433.2	-417.4	-81.7	65.9	-231.9	-245.5	-12.1	25.7
Syowa	-258.7	-258.5	-25.4	25.2	-510.2	-405.7	1.8	-106.3	-4.4	-160.4	-36.5	192.5
Vostok*	-501.7	-444.7	-12.5	-44.5	-129.3	-257.6	9.6	118.7	164.7	-269.9	70.3	364.3
Average	315.6	329.9	54.7	142.2	414.9	326.7	53.6	206.9	182.5	167.7	47.4	179.6

*For Amundsen–Scott and Vostok stations station surface pressure is used.

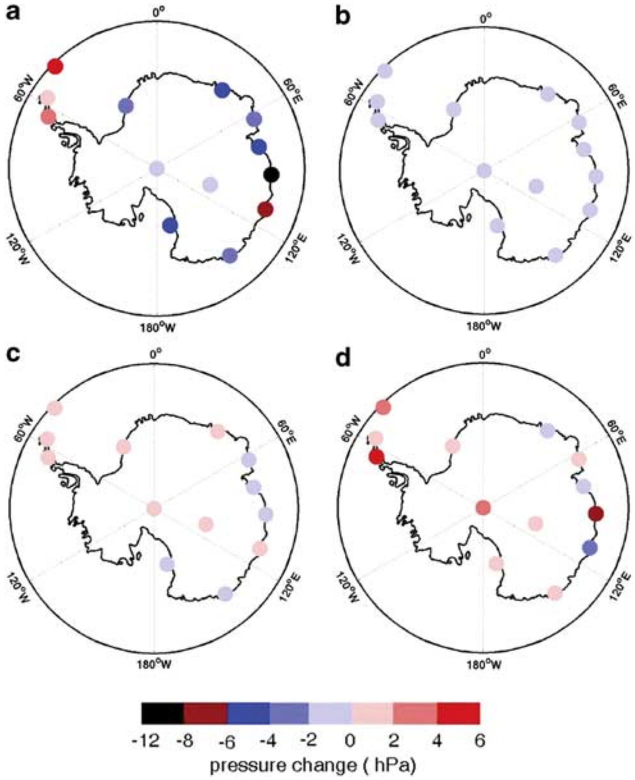

Fig. 14. The estimated trends in Antarctic sea level pressure for 1958–2001 in autumn (April–May) for observational data. **a.** Total trend, **b.** trend congruent with AAO, **c.** trend congruent with PSA1, and **d.** residual trend. For Amundsen–Scott and Vostok stations, station surface pressure is used.

sea level pressure (Fig. 12b). The decrease in pressure associated with positive PSA2 index occurs at all but four stations (Orcadas, Amundsen–Scott, Scott Base and Dumont d'Urville; Fig. 12c). The ERA-40 spatial patterns (Fig. 13b & c) are in agreement with observed data. Although the NCEP spatial patterns are similar to those of ERA-40 except for a small part of the Antarctic continent interior, the values of trends for NCEP is less than those of ERA-40 (not shown). The residual trend is an increasing trend except for three stations (Vostok, Casey and Mirny). For two re-analyses data a positive trend appears in the Antarctic continent, but the values in NCEP is larger than those in ERA-40 especially in East Antarctica. As shown in Table III, the changing values associated with PSA2 and the residual trend are further less than these caused by the AAO and the total trend. Hence the higher AAO index plays a crucial role in surface pressure variance (Thompson & Solomon 2002).

The total trend in autumn (Fig. 14a) is very similar to that in summer except for a strengthening of positive trend in the northern Peninsula. But the autumn trends in ERA-40 and NCEP re-analyses (Fig. 15a) are all negative in Antarctica including the Antarctic Peninsula. All stations manifest a decreased trend in sea level pressure (Fig. 14b). The pressure trend congruent with the PSA1 displays a positive trend except at five stations in East Antarctica. The residual trends at nine stations are positive trends with maximum value of 4.17 hPa, and the other four stations are negative with minimum value of -6.13 hPa. However, in Fig. 15d the trend in Antarctic continent shows positive except for the East Antarctic coastal zone. In contrast to ERA-40 re-analysis the area of positive trends in NCEP re-analysis is smaller (not shown).

In spring (Fig. 16a) ten stations display a negative trend with the strongest fall of surface pressure at Mirny. The opposite occurs at Antarctic Peninsula stations (Esperanza and Faraday) and island station (Orcadas). The total trends in ERA-40 and NCEP re-analyses is also negative in most of Antarctica (Fig. 17a). It seems that the total trends in ERA-40 and NCEP re-analysis data agrees with that of observations. Like the other two seasons the changes in sea level pressure corresponding AAO is negative, but the magnitude is somewhat less in spring. Except for Orcadas and South Pole, stations with positive trends are distributed

Table IV. The estimated changes in Antarctic surface temperature and sea level pressure for 1958–2001 caused by the SOI. Units are °C for surface air temperature and Pascal for sea level pressure.

	Temperature			Sea level pressure		
	Summer (Dec–Feb)	Autumn (Apr–May)	Spring (Oct–Nov)	Summer (Dec–Feb)	Autumn (Apr–May)	Spring (Oct–Nov)
Amundsen–Scott	-0.03	0.02	-0.01	1.5	-55.2	-1.6
Casey	0.01	0.14	-0.04	-12.2	-80.5	-5.0
Davis	-0.004	-0.37	-0.04	0.5	-21.3	2.5
Dumont d'Urville	0.02	0.03	-0.02	-3.9	-5.9	-7.3
Esperanza	0.01	-0.07	-0.06	-3.6	-0.2	-3.4
Faraday	-0.01	0.06	-0.07	-1.7	12.0	2.3
Halley	0.02	-0.47	0.001	-2.5	21.5	-0.1
Mawson	-0.004	-0.14	-0.02	0.1	5.4	2.2
Mirny	0.02	-0.14	-0.04	-7.2	-90.6	-0.9
Orcadas	-0.006	-0.08	-0.05	-4.8	1.8	-9.1
Scott Base	-0.01	-0.43	-0.005	1.6	23.2	-1.8
Syowa	0.007	0.45	-0.02	-0.7	-37.5	4.3
Vostok	0.009	0.05	-0.004	0.1	-8.2	-11.4

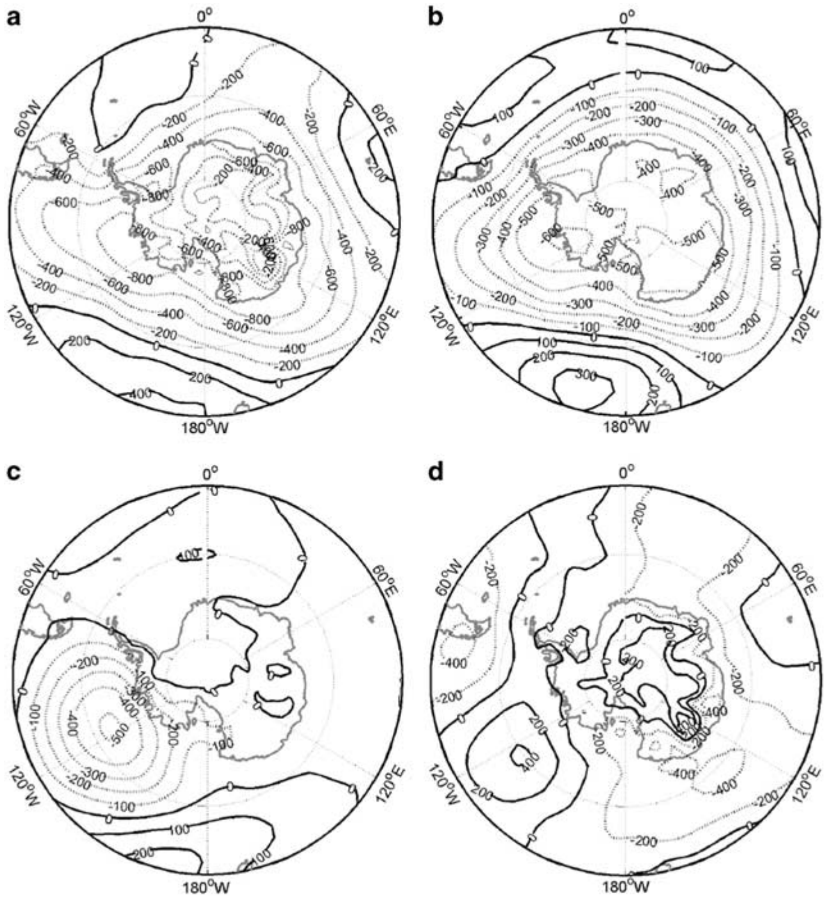

Fig. 15. 44 yr (1958–2001) linear April–May trends in sea level pressure for ERA-40 re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA1, and **d.** residual trends. Units are Pascal for sea level pressure.

in East Antarctica. Similar to the residual trend in autumn, only four stations in East Antarctica exhibit negative trends. There are some disagreements in trend between two re-analyses and observations for the residual trend.

In Antarctica sea level pressure has decreased in 44 yr, particularly at Mirny station where the falling trend is most pronounced in all three seasons. A large part of the pressure decrease is unlikely to be connected to either AAO or PSA. Like temperature, the magnitude of the pressure change averaged over the 13 stations is found to be the largest in autumn and the smallest in spring. The impact of AAO on sea level pressure varies with seasons with the least impact in spring. Among the three seasons AAO plays a more important role in explaining the summertime surface pressure change pattern. In most cases the influence from AAO exceeds that from PSA. The sea level pressure in ERA-40 and NCEP re-analyses appears to be in general more reliable than surface temperature.

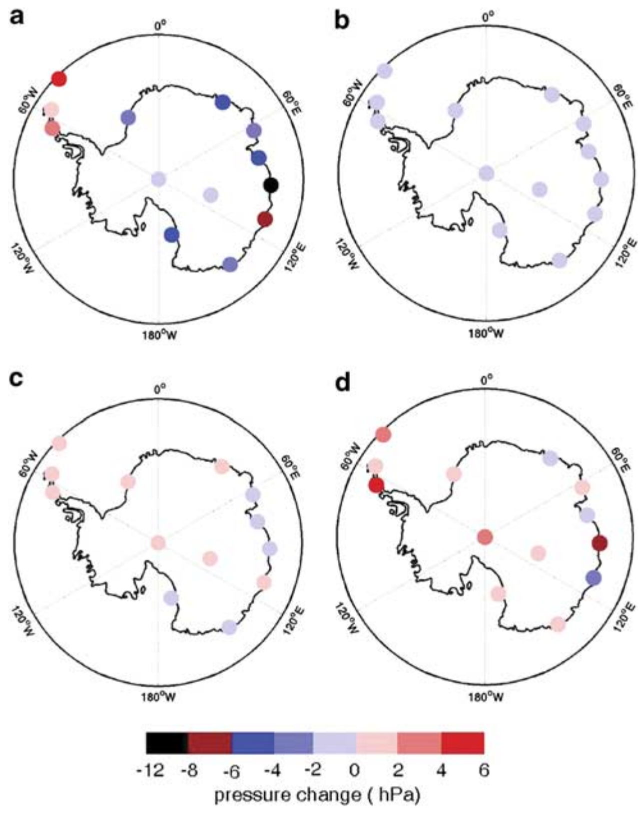

Fig. 16. The estimated trends in Antarctic sea level pressure for 1958–2001 in spring (October–November) for observational data. **a.** Total trend, **b.** trend congruent with AAO, **c.** trend congruent with PSA1, and **d.** residual trend. For Amundsen–Scott and Vostok stations, station surface pressure is used.

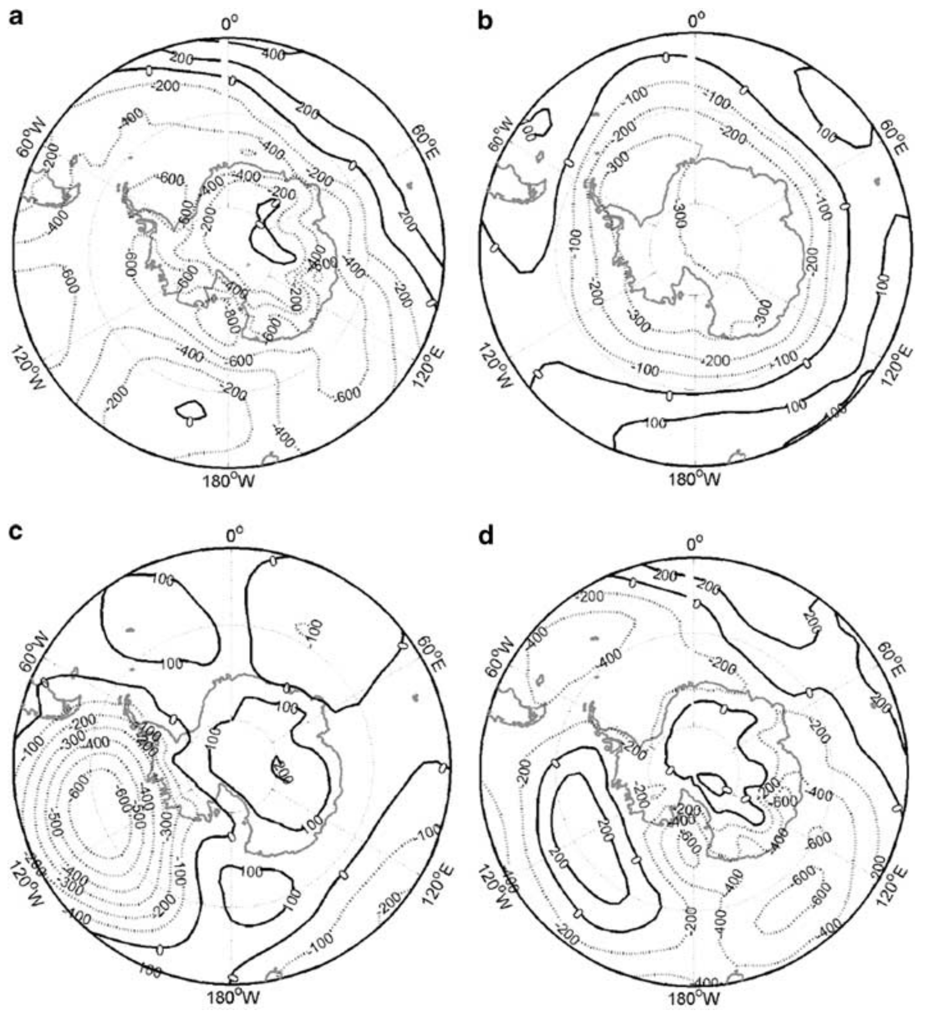

Fig. 17. 44 yr (1958–2001) linear October–November trends in sea level pressure for ERA-40 re-analysis data. **a.** Total trends, **b. & c.** the components of the trends that are linearly congruent with the monthly AAO, PSA1, and **d.** residual trends. Units are Pascal for sea level pressure.

Although AAO, PSA1 and PSA2 are main elements in EOF analysis of monthly mean sea level pressure, ENSO also influence strongly the Antarctic surface temperature and pressure leading to the Antarctic dipole (Yuan 2004). So the effect of the SOI on Antarctic surface temperature and pressure should be taken into consideration. Table I shows 44 yr (1958–2001) monthly linear trends of SOI. No monthly trend exceeds the 90% threshold. The trends for each of the four seasons in a year are also calculated. The trends in autumn (March–May), winter (June–August), spring (September–November) and summer (December–February) are -0.91, -0.51, -0.17 and -0.12, respectively. Only the trend in autumn is at 90% significance level.

Correlation analyses between SOI and surface temperature and pressure are performed and significant correlations are found only in springtime at several stations (not shown). The contributions of SOI to the Antarctic surface temperature and pressure in summer (December–February), autumn (April–May) and spring (October–November) are estimated and the results are shown in Fig. 18 and Table IV. The largest SOI related change occurs in autumn which is related to the largest trend of -0.86°C in autumn as compared to the trend of -0.12°C and -0.10°C in summer and spring. Although ENSO affects surface temperature and pressure over Antarctica differently in different seasons, the overall effect (with the largest value of < 0.5°C and 1 hPa in autumn), is smaller than that of AAO or PSA. The smaller contribution of ENSO to the Antarctic temperature and pressure trends may be a result of smaller change of SOI in the 44 years compared to the changes of AAO and PSA during the same periods.

Discussion

In this study, the contributions of the AAO, PSA and ENSO to the trends in sea level pressure and surface temperature were investigated using ERA-40 re-analysis, NCEP re-analysis and surface observational data from 1958–2001. Although the trends of AAO, PSA1 and PSA2, and ENSO are different in different seasons during this 44 yr period, overall, AAO is found to have the largest influence on the

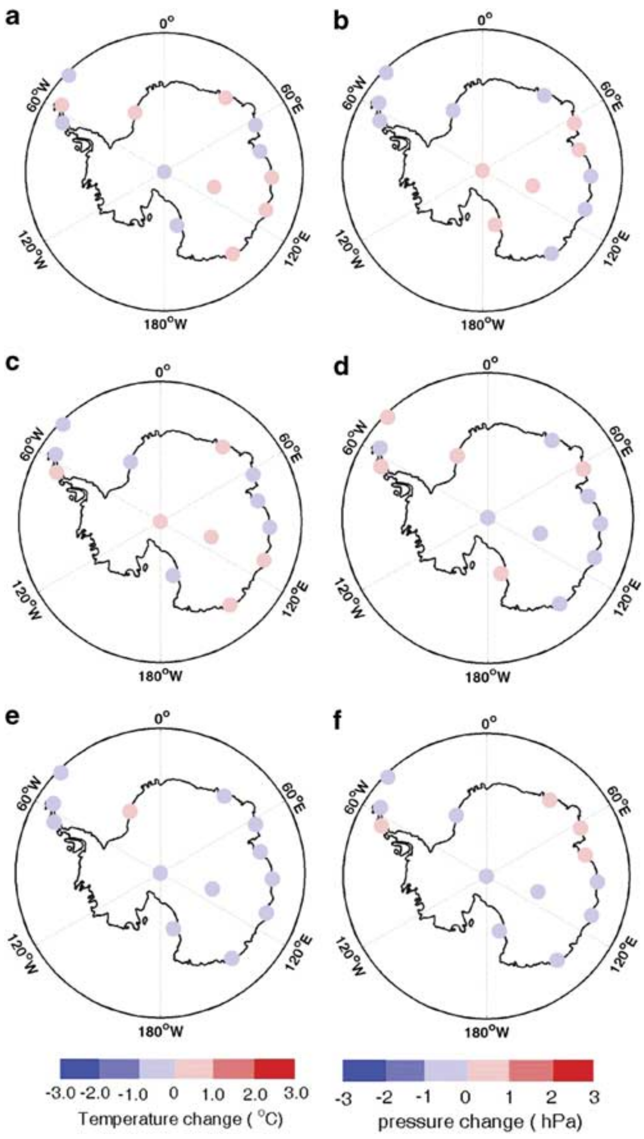

Fig. 18. The trends in Antarctic surface temperature (a., c. & e.), and sea level pressure (b., d. & f.), congruent with the SOI for 1958–2001. **a. & b.** In summer (December–February), **c. & d.** in autumn (April–May), and **e. & f.** in spring (October–November). For Amundsen–Scott and Vostok stations, station surface pressure is used.

Antarctic sea level pressure and surface temperature, followed by PSA, and finally ENSO.

The correlation analysis demonstrates that surface temperatures at three stations in the northern Antarctic Peninsula are positively correlated with PSA1 and PSA2, and surface pressures are negatively correlated with PSA2. The significance levels of the correlation vary with season. However, the correlation pattern between the observational pressure and the PSA1 is scattered, even though the surface pressures at Esperanza and Orcadas have significantly positive correlations in autumn (March–May).

During the three seasons, particularly in autumn, a consistent and significant warming trend occurs in the northern Antarctic Peninsula. The warming trend was also found in Steig *et al.* (2009) using reconstructed infrared satellite data. However, in East Antarctica the total trend in temperature varies considerably with season and in autumn a cooling trend is apparent across East Antarctica. For the 44 yr period, the average change across the 13 stations is the largest in autumn (April–May) and smallest in spring.

The sea level pressure shows a decreasing trend across the Antarctica except for Orcadas. This is consistent with the findings in Thompson & Solomon (2002) and Gillett & Thompson (2003). Similar to temperature, the pressure change averaged across the 13 stations is the largest in autumn and smallest in spring.

The temperature change related to the AAO is also the largest in autumn and smallest in spring. The spatial pattern of the trend associated with positive AAO exhibits a positive anomaly in the northern Antarctic Peninsula, and negative anomaly in other Antarctic region. A number of previous studies have proposed physical mechanisms linking the changes in the AAO to observed trends in Antarctic surface temperatures (Kwok & Comiso 2002, Gillett & Thompson 2003, Schneider *et al.* 2004, Marshall *et al.* 2006).

Among the three seasons the contribution of PSA to temperature change is found to be the largest in spring and smallest in summer. But on the whole the variance associated with PSA is less than that of AAO. The physical mechanism is that the meridional wind induced by the anomalous pressure leads to the change of surface air temperature.

The pressure change related to AAO is larger than PSA. The AAO plays most important role in accounting for the change of surface pressure in summer season. The impact of the PSA on surface pressure varies less with seasons.

The comparison with ERA-40 re-analysis shows that the magnitude of temperature change in ERA-40 is larger than that of observation, especially in total trends and residual trends. The apparent warming trends in all three seasons and in the entire Antarctic continent are not supported by the station data (Johanson & Fu 2007). However, the trends associated with AAO and PSA in ERA-40 re-analysis data are consistent with those in the observational data. The trend of surface pressure in ERA-40 re-analysis data is more reliable than that of surface temperature. Bromwich & Fogt (2004) suggested that the quality of ERA-40 re-analysis data has been significantly improved after 1979 due to the assimilation of considerably more satellite data. The trends in ERA-40 re-analysis are, thus, in better agreement with observations after 1979. It is unfortunate, however, that the trends in AAO, PSA, and ENSO are less significant after 1979 than from 1958–2001, and a 30 yr period is considered short for trend analysis. However, similar trends in surface air temperature and pressure are also made for the period 1979–2001 (not shown), the difference between two periods is large. Besides indices computed from ERA-40 is verified against station-based indices (Marshall 2003). The correlation coefficients between indices computed from ERA-40 and observational AAO are 0.84 in autumn (March–May), 0.8 in spring (September–November), 0.82 in summer (December–February), and 0.56 in winter (June–August).

Total summertime trends in surface air temperature and sea level pressure in East Antarctica for NCEP re-analysis are opposite to those for ERA-40 re-analysis. In West Antarctica and the Antarctic Peninsula two re-analyses data show similarity. The NCEP trends related to AAO and PSA2 explain a large part of total trends in summer. The case does not appear for ERA-40. The pattern of the April–May trends in surface air temperature for NCEP re-analysis is similar to that for ERA-40 re-analysis with the exception of the north-eastern Weddell Sea. Like ERA-40 re-analysis the residual trends in April–May for NCEP re-analysis are also positive in Antarctic continent. The negative April–May trends in sea level pressure for NCEP re-analysis exceed those for ERA-40 re-analysis, but the positive April–May trends in Antarctic continent for NCEP re-analysis are less than those for ERA-40 re-analysis. In contrast to the trends in December–February and April–May surface temperature and sea level pressure, those in October–November show larger similarity between two re-analyses data.

Few stations with long time series exist along the West Antarctic coast, an important region affected by the PSA. Therefore the effect of PSA on sea level pressure and surface temperature are not fully reflected in observational station data. The large residual trends in, for example, autumn surface temperature at Halley, spring surface temperature at Scott Base, and sea level pressure at Mirny suggest that other factors, such as local katabatic flow, may play an important role in the temperature and pressure variation. An improved understanding of what factors and how they affect the Antarctic sea level pressure and surface temperature will give us more insight into changes in Antarctic sea ice.

Acknowledgements

This research was funded by Chinese Polar Program Strategic Research Fund No. 20080218, the NNSFC (40233032) and MOST (2006BAB18B03 and 2006BAB18B05). The National Center for Atmospheric Research is sponsored by the National Science Foundation. The constructive comments of the reviewers are also gratefully acknowledged.

Supplemental material

Three supplemental figures will be found at http://dx.doi.org/10.1017/S095410201100054X.

References

Arblaster, J.M. & Meehl, G.A. 2006. Contributions of external forcings to Southern Annular Mode trends. *Journal of Climate*, **19**, 2896–2905.

Bromwich, D.H. & Fogt, R.L. 2004. Strong trends in the skill of the ERA-40 and NCEP-NCAR re-analyses in the high and midlatitudes of the Southern Hemisphere, 1958–2001. *Journal of Climate*, **17**, 4603–4619.

Gillett, N.P. & Thompson, D.W.J. 2003. Simulation of recent Southern Hemisphere climate change. *Science*, **302**, 273–275.

Johanson, C.M. & Fu, Q. 2007. Antarctic atmospheric temperature trend patterns from satellite observations. *Geophysical Research Letters*, **34**, 10.1029/2006GL029108.

Jones, J.M. & Widmann, M. 2004. Early peak in Antarctic Oscillation index. *Nature*, **432**, 290–291.

Justino, F. & Peltier, W.R. 2008. Climate anomalies induced by the Arctic and Antarctic Oscillation: glacial maximum and present-day perspectives. *Journal of Climate*, **21**, 459–474.

Justino, F., Setzer, A., Bracegirdle, T.J., Mendges, D., Grimm, A., Dechiche, G. & Schaefer, C.E.G. 2010. Harmonic analysis of climatological temperature over Antarctica: present-day and greenhouse warming perspectives. *International Journal of Climatology*, **31**, 514–530.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Leetmaa, A., Reynolds, R. & Jenne, R. 1996. The NCEP/NCAR 40-year re-analysis project. *Bulletin of the American Meteorological Society*, **77**, 437–471.

Karoly, D.J. 1989. Southern Hemisphere circulation features associated with El Niño–Southern Oscillation events. *Journal of Climate*, **2**, 1239–1251.

Kidson, J.W. 1988. Interannual variations in the Southern Hemisphere circulation. *Journal of Climate*, **1**, 1177–1198.

Kidson, J.W. 1999. Principal modes of Southern Hemisphere low frequency variability obtained from NCEP-NCAR re-analysis. *Journal of Climate*, **12**, 2808–2830.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van Den Dool, H., Jenne, R. & Fiorino, M. 2001. The NCEP-NCAR 50-year re-analysis: monthly means CD-ROM and documentation. *Bulletin of the American Meteorological Society*, **82**, 247–267.

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**, 10.1029/2002GL015415.

Lau, K.M., Sheu, P.J. & Kang, I.S. 1994. Multiscale low-frequency circulation modes in the global atmosphere. *Journal of the Atmospheric Sciences*, **51**, 1169–1193.

Liu, J., Curry, J.A. & Martinson, D.G. 2004. Interpretation of recent Antarctic sea ice variability. *Geophysical Research Letters*, **31**, 10.1029/2003GL018732.

Marshall, G.J. 2003. Trends in the Southern Annular Mode from observations and re-analyses. *Journal of Climate*, **16**, 4134–4143.

Marshall, G.J. 2007. Half-century seasonal relationships between the Southern Annular mode and Antarctic temperatures. *International Journal of Climatology*, **27**, 373–383.

Marshall, G.J., Orr, A., van Lipzig, N.P.M. & King, J.C. 2006. The impact of a changing Southern Hemisphere Annular Mode on Antarctic Peninsula summer temperatures. *Journal of Climate*, **19**, 5388–5404.

Mo, K.C. 2000. Relationships between interdecadal variability in the Southern Hemisphere and sea surface temperature anomalies. *Journal of Climate*, **13**, 3599–3610.

Mo, K.C. & Ghil, M. 1986. Statistical and dynamics of persistent anomalies. *Journal of the Atmospheric Sciences*, **44**, 877–901.

Mo, K.C. & Paegle, J.N. 2001. The Pacific-South American modes and their downstream effects. *International Journal of Climatology*, **21**, 1211–1229.

Orr, A., Cresswell, D., Marshall, G.J., Hunt, J.C.R., Sommeria, J., Wang, C.G. & Light, M. 2004. A 'low-level' explanation for the recent large warming trend over the western Antarctic Peninsula involving blocked winds and changes in zonal circulation. *Geophysical Research Letters*, **31**, 10.1029/2003GL019160.

Orr, A., Marshall, G.J., Hunt, J.C.R., Sommeria, J., Wang, C.G., van Lipzig, N.P.M., Cresswell, D. & King, J.C. 2008. Characteristics of summer airflow over the Antarctic Peninsula in response to recent strengthening of westerly circumpolar winds. *Journal of the Atmospheric Sciences*, **65**, 1396–1413.

Phillpot, H.R. 1991. The derivation of 500 hPa height from automatic weather station surface observations in the Antarctic continental interior. *Australian Meteorological Magazine*, **39**, 79–86.

Schneider, D.P., Steig, E.J. & Comiso, J.C. 2004. Recent climate variability in Antarctica from satellite-derived temperature data. *Journal of Climate*, **17**, 1569–1583.

Schwerdtfeger, W. 1984. *Weather and climate of the Antarctic*. New York: Elsevier Science, 261 pp.

Steig, E.J., Schneider, D.P., Rutherford, S.D., Mann, M.E., Comiso, J.C. & Shindell, D.T. 2009. Warming of the Antarctic ice sheet surface since the 1957 International Geophysical Year. *Nature*, **457**, 459–463.

Szeredi, I. & Karoly, D. 1987a. The vertical structure of monthly fluctuations of the Southern Hemisphere troposphere. *Australian Meteorological Magazine*, **35**, 19–30.

Szeredi, I. & Karoly, D. 1987b. The horizontal structure of monthly fluctuations of the Southern Hemisphere troposphere from station data. *Australian Meteorological Magazine*, **35**, 119–129.

Thompson, D.W.J. & Solomon, S. 2002. Interpretation of recent Southern Hemisphere climate change. *Science*, **296**, 895–899.

Thompson, D.W.J. & Wallace, J.M. 2000a. Annular modes in the extratropical circulation. Part I: Month-to-month variability. *Journal of Climate*, **13**, 1000–1016.

Thompson, D.W.J. & Wallace, J.M. 2000b. Annular modes in the extratropical circulation. Part II: Trends. *Journal of Climate*, **13**, 1018–1036.

Turner, J., Lachlan-Cope, T.A., Colwell, S., Marshall, G.J. & Connolley, W.M. 2006. Significant warming of the Antarctic winter troposphere. *Science*, **311**, 1914–1917.

Turner, J., Colwell, S.R., Marshall, G.J., Lachlan-Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A. & Iagovkina, S. 2004. The SCAR READER project: towards a high-quality database of mean Antarctic meteorological observations. *Journal of Climate*, **17**, 2890–2898.

Turner, J., Colwell, S.R., Marshall, G.J., Lachlan-Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A. & Iagovkina, S. 2005. Antarctic climate change during the last 50 years. *International Journal of Climatology*, **25**, 279–294.

Uppala, S.M., Kållberg, P.W. & Simmons, A.J. *et al*. 2005. The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, **131**, 2961–3012.

Van den Broeke, M.R. & van Lipzig, N.P.M. 2004. Changes in Antarctic temperature, wind and precipitation in response to the Antarctic Ocscillation. *Annals of Glaciology*, **39**, 119–126.

Yuan, X. 2004. ENSO related impacts on Antarctic sea ice: a synthesis of phenomenon mechanisms. *Antarctic Science*, **16**, 415–425.

Yu, L., Zhang, Z., Zhou, M., Zhong, S., Lenschow, D., Hsu, H., Wu, H. & Sun, B. 2010. Validation of ECMWF and NCEP–NCAR re-analysis data in Antarctica. *Advances in Atmospheric Sciences*, **27**, 1151–1168.