Antarctic Science 10 (2): 184–191 (1998)

The semi-annual oscillation and Antarctic climate. Part 2: recent changes

MICHIEL R. VAN DEN BROEKE*

Norwegian Polar Institute, PO Box 5072 Majorstua, N–0301 Oslo, Norway
**Present address: IMAU (Institute for Marine and Atmospheric Research), PO Box 80.005, 3508TA Utrecht, Netherlands*
E-mail: broeke@fys.ruu.nl

Abstract: Following a weakening of the semi-annual oscillation (SAO) since the mid-1970s, the half-yearly pressure wave in the Southern Hemisphere has become less significant. As a result, May/June temperatures have decreased in East Antarctica, which has moderated Antarctic warming. Spectral analysis of 87 years of pressure data at Orcadas suggest that the recent weakening of the SAO is part of the natural variability of the Southern Hemisphere circulation on decadal timescales. We interpret the time series of composite Antarctic temperature in terms of the historical strengthening and weakening of the SAO. If the dominant oscillations that occurred in the past prove to be persistent, an accelerated East Antarctic warming trend is expected for the coming decades. There are indications that the strength of the SAO is linked to the Southern Oscillation, in the sense that warm phases of the Southern Oscillation coincide with strong westerlies, a weakly developed SAO and below-average temperatures in East Antarctica. Temperatures on the west coast of the Antarctic Peninsula show strongly deviant patterns, which can not be explained by the same mechanism that applies to East Antarctica.

Received 11 September 1996, accepted 23 December 1997

Key words: Antarctic climate, Southern Hemisphere circulation

Introduction

In part 1 of this paper we showed how the semi-annual oscillation (SAO) influences East Antarctic coastal temperatures (van den Broeke 1998). It was found that circulation changes that are associated with the expanding phase of the SAO in autumn and spring (Fig. 1) increase the transport of air from lower latitudes towards continental Antarctica (van Loon 1967). This directly couples half-yearly waves of pressure and temperature. A detailed description of the spatial characteristics of the SAO can be found in Schwerdtfeger & Prohaska (1956) and van Loon (1972a).

Recent work has revealed a significant weakening of the SAO from the mid to late 1970s well into the 1980s. Van Loon & Rogers (1984) discussed the interannual variations of the SAO with respect to the zonally averaged geostrophic winds, but did not find trends. Van Loon *et al.* (1993) used zonal averages to describe the weakening of the SAO from 1977 onwards. The largest changes occurred in the South Pacific Ocean, where the second harmonic in mid-latitudes disappeared in the early 1980s. In the Indian and Atlantic Ocean the SAO weakened but recovered partly afterwards. The changes in the SAO were induced by an average northward movement of the trough, in association with pressure falls in the months of extreme northward extent.

Time series of the amplitude of the half-yearly pressure wave suggest that the recent changes are larger than the typical variations in the past 40–60 years (Hurrell & van Loon 1994). The latter authors also showed that the failure of the trough to expand northward in October/November resulted in a continued strong polar vortex into late spring during the 1980s, which could point towards a delay in spring warming owing to low stratospheric ozone concentrations. The absence of cooling at the 50 hPa level at Casey station, however, rather seemed to point in the direction of circulation changes in the troposphere.

In this paper we will only briefly discuss possible reasons for the SAO decline, and focus on how it affected Antarctic near-surface temperatures. We will discuss the historical significance of the recent changes, and how the results can be of help for the interpretation of Antarctic temperature time series.

Data

Table I lists the stations, their position and the number of years with available data. The location of the stations is presented in Fig. 1. Monthly mean pressure and temperatures for the period 1957–88, compiled by Jones & Limbert (1987) and updated by Smith & Stearns (1993), form the basis of this study. Where possible, data were updated to 1996. The most important sources for recent data are the Australian Antarctic Division (CRC/AAD) and the British Antarctic Survey (BAS) databases, both accessible via internet. Excellent data coverage and availability exists for the (current and former) British Antarctic stations (denoted by BAS in Table I). For many other stations, unfortunately, records are not so complete; especially pressure data lack from 1990 onwards. In line with the timing of the reported changes, time series were divided in two periods, 1957–79 and 1980–96. We decided to use all available monthly means to construct average annual cycles of temperature and pressure, which were then subjected to a harmonic analysis.

Composite Antarctic temperature anomalies for years after 1983 were calculated by correlation of a simple weighed mean of all stations (excluding Byrd) with the anomalies presented by Raper *et al.* (1984). For the overlapping period of 21 years (1963–83) a good correlation was found between the two methods (slope 1.01, $r = 0.95$), which we then used to extrapolate the timeseries of Raper *et al.* (1984) to 1993. East Antarctic temperature anomalies were calculated in a similar way using data from stations 1, 2, 4–13 in Table I.

Station pressure changes

We calculated pressure differences between three pairs of coastal Antarctic stations and mid-latitude islands. Station pairs were chosen such that they are situated in or close to

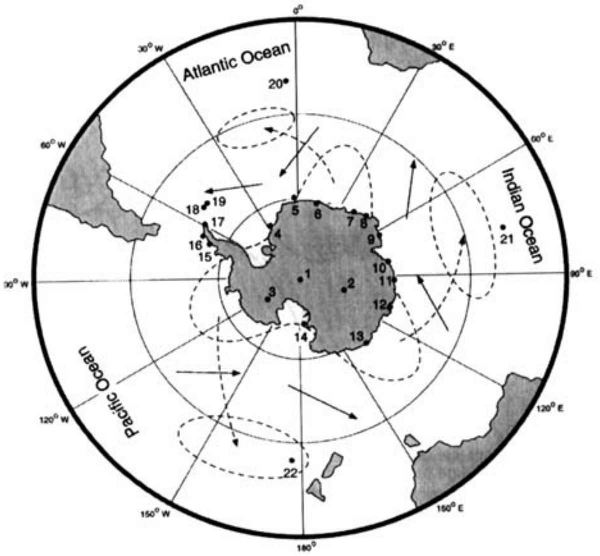

Fig. 1. Location of stations used in this study (numbers correspond to station numbers in Table I) and schematic outline of pressure and circulation changes from March to June. Dotted arrows connect locations of largest pressure changes (the approximate movement of climatological low pressure areas), solid arrows indicate associated mean circulation changes. Light grey areas denote ice shelves.

Table I. Location, elevation, number of years with observations (T: temperature; P: pressure) and main data source of 22 stations that were used in this study.

	Station	Location	Elevation (m a.s.l.)	# yrs T 57–79	# yrs T 80–96	# yrs P 57–79	# yrs P 80–96	Source
Plateau								
1.	South Pole	90.0°S	2835	23	17	23	10	S. & S. '93
2.	Vostok	78.5°S, 106.9°E	3488	21	15	21	6	S. & S. '93
3.	Byrd	80.0°S, 119.5°W	1515	15	12	15	13	S. & S. '93
Coastal East Antarctica								
4.	Halley	75.5°S, 26.7°W	32	23	17	23	17	BAS
5.	Sanae	70.3°S, 2.4°W	52	22	12	23	13	S. & S. '93
6.	Novolazarevskaya	70.8°S, 11.8°E	99	19	17	18	14	S. & S. '93
7.	Syowa	69.0°S, 39.6°E	21	18	16	19	12	S. & S. '93
8.	Molodezhnaya	67.7°S, 45.9°E	40	17	17	17	7	S. & S. '93
9.	Mawson	67.6°S, 62.9°E	16	23	17	23	12	S. & S. '93
10.	Davis	68.6°S, 78.0°E	13	19	17	19	12	S. & S. '93
11.	Mirny	66.6°S, 93.0°E	30	23	17	23	7	S. & S. '93
12.	Casey	66.3°S, 110.5°E	15	23	17	23	12	S. & S. '93
13.	Dumont d'Urville	66.7°S, 140.0°E	43	23	17	23	8	S. & S. '93
Ross Ice Shelf								
14.	Scott	77.9°S, 166.8°E	16	23	17	23	15	S. & S. '93
Antarctic Peninsula								
15.	Rothera	67.8°S, 68.1°W	15	20	17	20	17	BAS
16.	Faraday	65.3°S, 64.3°W	9	23	17	23	17	BAS
17.	Esperanza	63.4°S, 57.0°W	8	23	14	23	12	S. & S. '93
18.	Signy	60.7°S, 45.6°W	7	23	15	23	16	BAS
19.	Orcadas	60.7°S, 44.7°W	6	22	17	23	12	S. & S. '93
Mid-latitude islands								
20.	Gough	40.4°S, 9.9°W	54	-	-	23	12	CRC/AAD
21.	New Amsterdam	37.8°S, 77.5°E	29	-	-	23	9	CRC/AAD
22.	Chatham	44.0°S, 176.6°W	48	-	-	23	12	CRC/AAD

Abbreviations: S. & S. '93: Smith & Stearns (1993); CRC/AAD: Antarctic Cooperative Research Centre/Australian Antarctic Division internet page; BAS: British Antarctic Survey internet page.

https://doi.org/10.1017/S095410209800025X Published online by Cambridge University Press

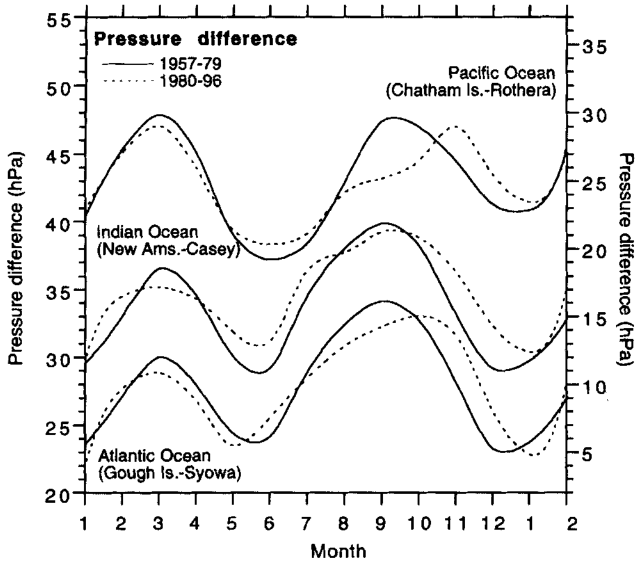

Fig. 2. Smoothed mean annual cycle of pressure differences between mid-latitude islands and Antarctic coastal stations, for 1957–79 (solid line) and 1980–96 (dashed line). Values for Chatham-Rothera on right axis, for the other two stations pairs on left axis.

areas of maximum pressure changes in the first expanding phase of the SAO (Fig. 1), i.e. they are situated north-west–south-east relative to each other. Figure 2 shows how the character of the SAO changed in the three ocean basins. Because the pressure generally decreases from middle latitudes southward, the north-westward expansion of the low pressure belt causes a decrease of the pressure difference. Before 1980, the SAO is represented by a clear half-yearly wave, showing the expansion phases from March–June and September–December and the contraction phases from December–March and June–September.

From 1980 onwards, the second expansion phase appears to be delayed by a month, which agrees with the analysis of Hurrel & van Loon (1994). The delay is most pronounced in the Pacific Ocean. During the first expansion phase, changes are somewhat less dramatic: the amplitude has decreased, mostly so in the Indian Ocean, and the phase has shifted in the opposite direction.

These changes have effectively decreased the contribution of the second harmonic $H_2(P)$ to the variation in the annual pressure cycle, as shown in Fig. 3. Again the changes have been most dramatic in the Pacific region of Antarctica; at Faraday station, for instance, the percentage of total variance explained by $H_2(P)$ decreased from 77% to 10%. Significant changes are also visible in the pressure records of East Antarctic stations: comparing mean annual pressure cycles of seven coastal stations with the longest pressure records, it was found that the amplitude of $H_2(P)$ has decreased on average from 2.9 hPa to 2.2 hPa (a change that is significant at the 99% confidence level), while the percentage of the total variance explained by $H_2(P)$ decreased from 61% to 38%. Similar reductions are found for stations on the East Antarctic plateau.

Station temperature changes

Figure 4 shows the annual and combined May/June temperature changes, 1980–96 minus 1957–79. On average, Antarctic temperatures have increased by about 0.5 K, but large variations are visible from place to place. The west coast of the Antarctic Peninsula shows the largest warming trends, which has caused the rapid disintegration of some of the northerly ice shelves (Vaughan & Doake 1996). In East

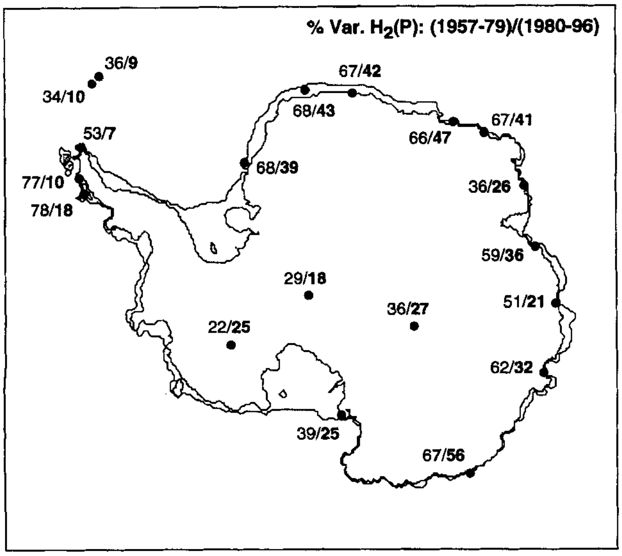

Fig. 3. Percentage of variance explained by the second harmonic of the mean annual pressure cycle $H_2(P)$ for 1957–79 (plain numbers) and 1980–96 (bold numbers).

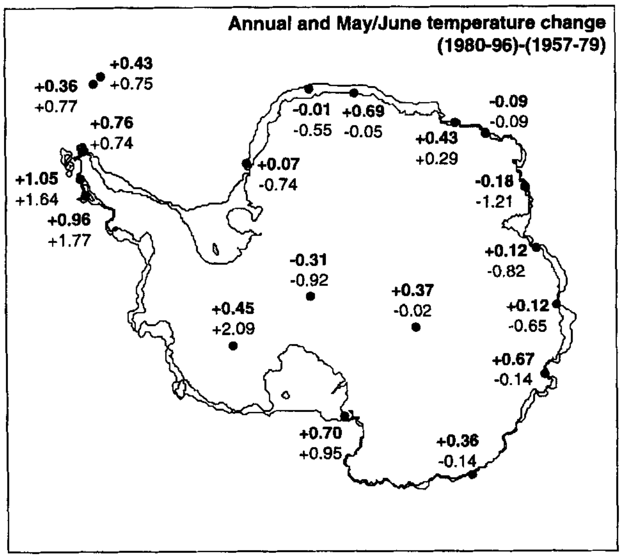

Fig. 4. Changes of mean annual temperature (bold numbers) and May/June temperatures (plain numbers), 1980–96 minus 1957–79.

https://doi.org/10.1017/S095410209800025X Published online by Cambridge University Press

Antarctica, warming has been more moderate, and at places even a cooling has occurred, for instance at South Pole and around Mawson stations. These remarkable differences in regional temperature trends are in general agreement with earlier studies, e.g. Jacka (1990) and Jones & Wigley (1988).

Upon closer inspection of the annual cycle, it appears that the largest differences between East and West Antarctica occur in the months May and June. Temperatures in these months have decreased at all East Antarctic stations, except for Syowa (Fig. 4). The opposite is true for stations in West Antarctica and the Peninsula, where May/June have contributed more than average to the annual temperature increase. We will therefore discuss both regions separately in the following.

East Antarctic stations

In part 1 of this paper we found a strong correlation between the SAO and the annual cycle of near-surface temperatures in coastal East Antarctica for the period 1957–79: stations with a relatively small amplitude of the semi-annual pressure wave experience a relatively strong half-yearly temperature wave and vice versa. This intuitively unexpected correlation stems from the large longitudinal (westward) displacement of the trough in the expansion phase, in addition to the meridional (northward) movement, as is schematically illustrated in Fig. 1.

To investigate whether and how the recent weakening of the SAO has impacted on East Antarctic temperatures, we selected nine coastal East Antarctic stations (those that have more than 15 years of temperature data in the period 1980–96) and correlated changes of monthly mean temperatures to the amplitude of $H_2(T)$ (1957–79) (Fig. 5a). The correlation curves shows two local minima, surrounding the months with extreme northward extent of the trough. The local minimum in the summer fails to reach significance, but significant negative correlations do exist for May, June and July (with confidence levels of 95%, 99% and 90%, respectively). To find that these months are most sensitive to the changes in the SAO, in spite of the less dramatic circulation changes (Fig. 2), is somewhat surprizing. The reason for this is the much larger meridional temperature gradient at the surface between Antarctica and its surroundings (van Loon 1972b), which makes that winter temperatures are sensitive to small changes in the circulation.

The correlations for the May/June/July temperature changes are presented in Fig. 5b. Two effects are visible: the suppressed meridional movement of the trough caused cooling in the former expansion phase (May) and warming in the former contracting phase (July). In between, the meridional position of the trough has not changed, resulting in a zonally averaged zero temperature difference for June. The suppressed longitudinal movement of the trough modifies this pattern, in the sense that warm/cool areas are situated directly east/west of the negative pressure anomaly, where the former values of $H_2(T)$ were relatively low/high. It is likely that this process also accounted for the May cooling/July warming at South Pole station (Dutton *et al.* 1991), which is sensitive to SAO signals from the Pacific Ocean (van Loon 1967).

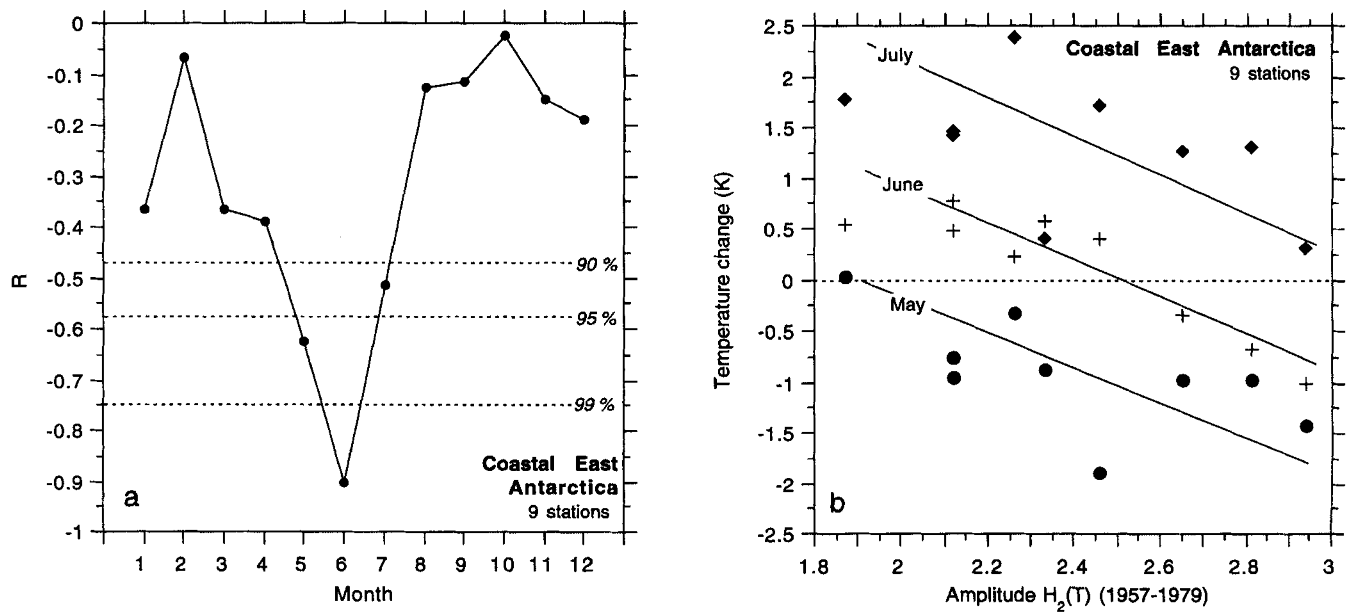

Fig. 5. a. Linear correlation R of monthly mean temperature changes (1980–96 minus 1957–79) with the amplitude of $H_2(T)$ at nine East Antarctic coastal stations. 90%, 95% and 99% confidence intervals are indicated by the dashed lines. **b.** Temperature changes for May, June and July (1980–96 minus 1957–79) vs. amplitude of $H_2(T)$ at nine East Antarctic coastal stations.

https://doi.org/10.1017/S095410209800025X Published online by Cambridge University Press

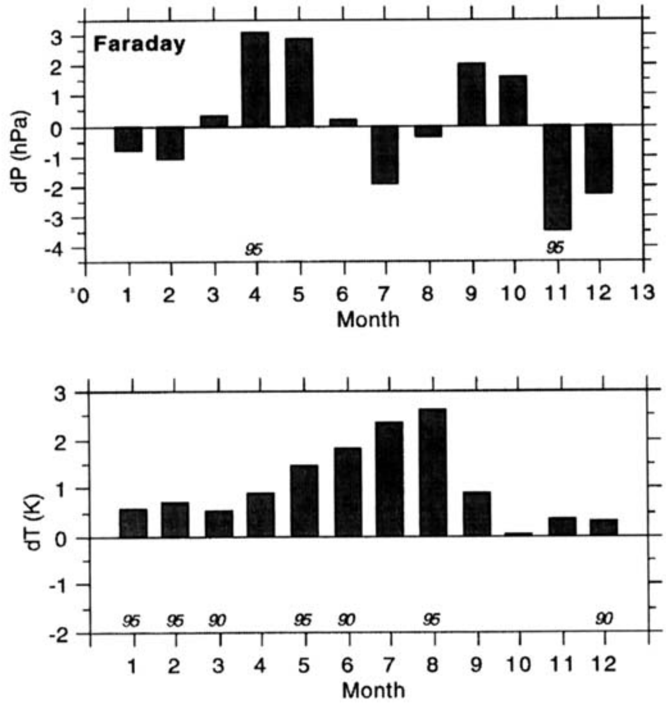

Fig. 6. Pressure changes (upper panel) and temperature changes (lower panel) at Faraday Station (1980–96 minus 1957–79). Numbers at bottom indicate confidence levels.

Antarctic Peninsula

In contrast to East Antarctica, May/June temperatures at the west coast of the Peninsula have shown a continuous increase. As an example, changes of monthly mean temperature and pressure at Faraday are presented in Fig. 6. Note that the temperature changes have been highly asymmetric, with stronger warming in autumn and winter than in spring. The significant pressure rise in April could denote an early expansion of the trough. Because pressure in these months rose even stronger at Orcadas, situated to the east, it is well possible that the new pressure distribution in spring initiated a northerly flow. In spring, when the trough expansion is delayed by one month, the meridional circulation is suppressed, which has clearly moderated warming in the months from September onwards.

It is not easy to explain why this region reacts so differently to the (changes in the) SAO, when compared to East Antarctica. It is likely that the steep, north–south directed topography and the cold climate in the Weddell Sea shields the west coast of the Peninsula from changes that occur eastwards, i.e. in the Atlantic cell of the SAO, and enhances meridional exchange of air masses. The analysis of Jacka (1990) showed that stations in South America (situated in the same longitudinal interval) experienced negative temperature trends during the last decades. This could point towards increased meridional air exchange in this section of Antarctica. King (1994) proved that temperatures at the Peninsula are sensitive to the meridional circulation; July temperatures, however, more strongly depend on local sea ice conditions. Clearly, the interaction between circulation and temperatures is very complex in this area, and more research is needed.

Historical significance and interpretation of composite Antarctic time series

Time series of the amplitude of $H_2(P)$ for some representative stations are presented in Fig. 7. To highlight long-term changes, calculations are based on 5 year running means of monthly mean pressure. Recent variations in the strength of the SAO occur simultaneously at all stations, in spite of the large distances in between (Orcadas & Mawson are almost 5000 km apart). The early Orcadas record suggests that large variations, similar to the ones that were observed recently, have occurred throughout this century. Thus, the recent weakening of the SAO is by no means exceptional. A spectral analysis of the Orcadas data (Fig. 8) shows major oscillations

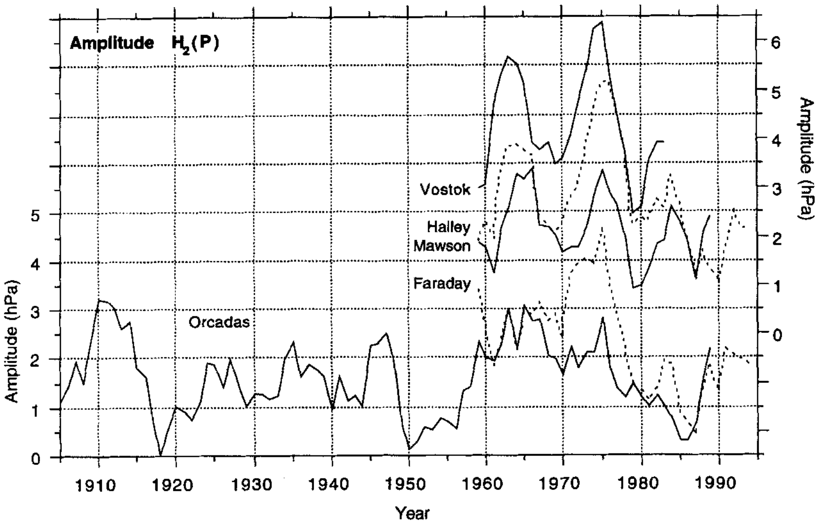

Fig. 7. Time series of the amplitude of $H_2(P)$ at Orcadas and Faraday (lower pair of lines, scale at left axis) and at Vostok, Halley and Mawson (upper three lines, scale at right axis). To highlight long-term variations, the harmonic analysis was performed on 5 year running means of monthly mean pressure.

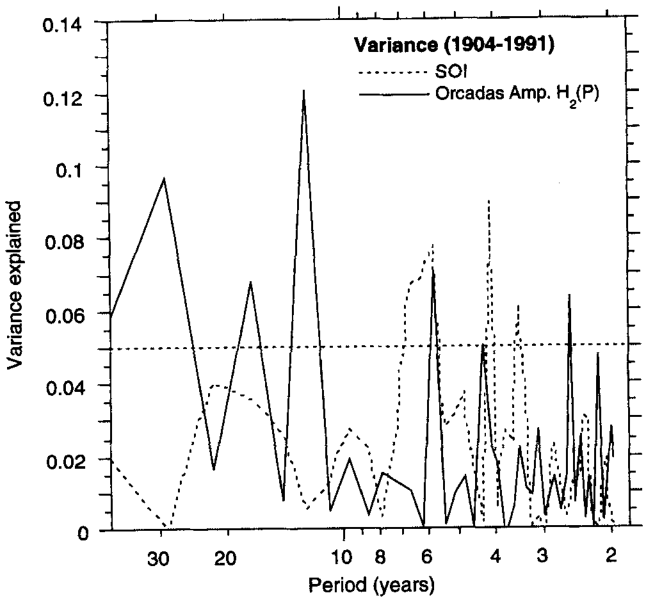

Fig. 8. Spectrum of the amplitude of $H_2(P)$ at Orcadas (solid lines) and yearly mean values of the SOI (dashed line), both based on 87 years of data (1904–91).

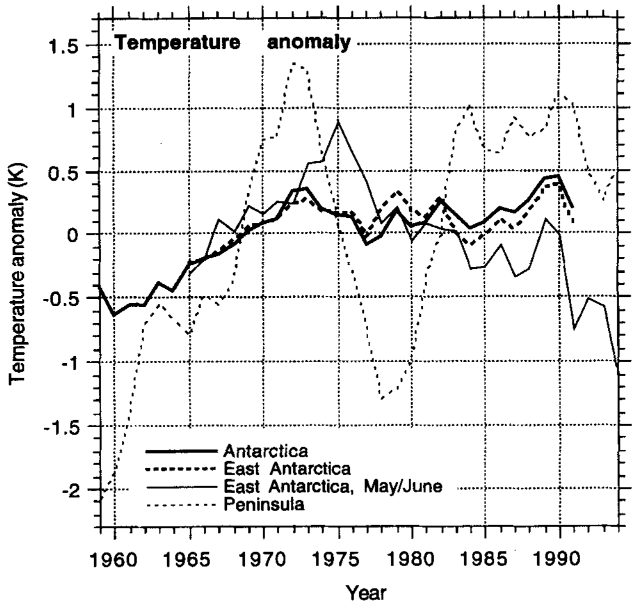

Fig. 9. Five year running means of temperature anomalies. The Peninsula region is represented by Faraday Station. For calculation methods, see section 'Data'.

with periods of 12 and 29 years, which are both clearly visible in Fig. 6, and smaller peaks at 2.5, 6 and 17 years. A 17 year periodicity was also apparent in time series of the amplitude of $H_2(P)$ for Chatham Island (Hurrel & van Loon 1994). The length of the Orcadas record (87 years) 'forces' the longest oscillation towards 29 years, but judging from Fig. 6 it is more likely that the real period of this oscillation is 30–35 years. Time series of the other stations are too short to reveal the 30–35 yr variations, but an oscillation with an approximate period of one decade is well developed.

Based on the results presented above, we make an attempt to interpret composite Antarctic temperature time series. First we extended the series presented by Raper *et al.* (1984) to 1993 (see section 2). Figure 9 shows 5-year running means of the Antarctic, East Antarctic and East Antarctic composite May/June temperature anomalies. Also included are the temperature anomalies at Faraday, as a representative station at the west coast of the Antarctic Peninsula. East Antarctic, Peninsula and composite Antarctic temperatures increased quickly from the late 1950s onwards to the beginning of the 1970s, rising by almost 1 K in 15 years. Following rapid temperature falls in the Peninsula area after 1973 and stabilizing East Antarctic temperatures, this trend levelled out.

Since the beginning of the 1980s, East Antarctic temperatures in general and May/June temperatures in particular contribute negatively to the composite Antarctic temperature anomaly (Fig. 9). We propose here that this is due to the weakening of the SAO since 1975, which has caused East Antarctic May/June temperatures to decrease. In the beginning of the 1990s, May/June temperatures in East Antarctica show very large negative anomalies, which, combined with lower temperatures in the Peninsula area, has caused a decline of composite Antarctic temperatures. If the 30–35 year oscillation that was found in the Orcadas record is real, and applies to entire East Antarctica (which Fig. 7 suggests), it is expected that the next decades will show a strengthening of the SAO, resulting in an East Antarctic warming trend that is similar to that before 1975. This would likely also cause an accelerated increase of composite Antarctic temperatures.

Discussion

Changes on decadal timescales are difficult to quantify, owing to the relative brevity of the Antarctic climate records. The similarity of the variations at Orcadas and other Antarctic stations in Fig. 7, however, suggests that the former record gives a fair representation of the strength of the SAO for the entire continent. This suggests that the recent changes in the SAO are part of natural variations of the Southern Hemisphere circulation, with possible teleconnections to lower latitudes. Climate connections between low and high southern latitudes are complex, and results of recent research are summarized by King & Turner (1997). Some general remarks on associations between the SAO and other characteristic features of the Southern Hemisphere circulation can be made, though.

Meehl (1991) mentioned possible interactions between the SAO and the Southern Oscillation (SO): interannual variations in sea surface temperatures (SST) at 50°S weaken or enhance the SAO, which on its turn influences the strength of the subtropical high and could thus trigger warm or cold events in the SO. Such slow oscillations in SST could for instance be forced by the recently discovered Antarctic circumpolar wave (White & Peterson 1996). The amplitude of $H_2(P)$ at Chatham Island is indeed negatively correlated with departures of the

https://doi.org/10.1017/S095410209800025X Published online by Cambridge University Press

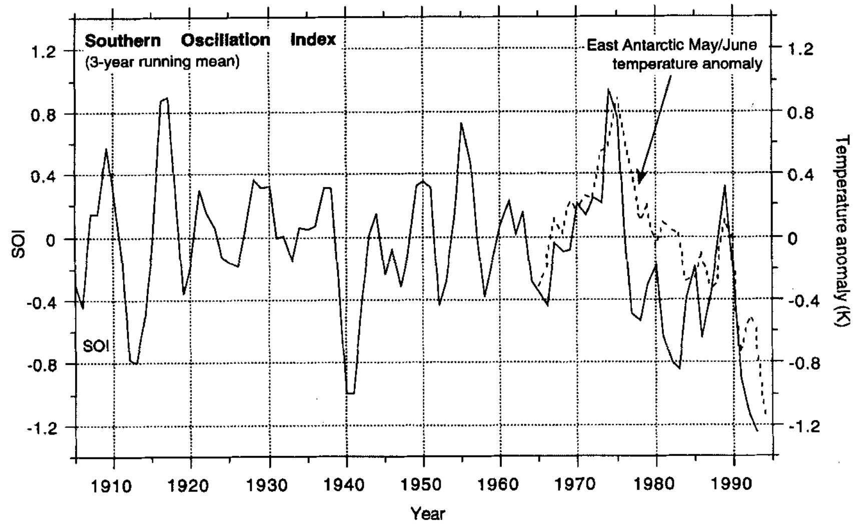

Fig. 10. Time series of the 3-year running mean Southern Oscillation Index (SOI, left axis) and East Antarctic temperature anomaly (5-year running mean, right axis).

tropical SST in the Pacific (Hurrell & van Loon 1994). This suggests that periods during which the SAO is weak are associated with warm events in the SO. A link between the SO and the SAO is supported by Fig. 10, in which 3 yr running means of the Southern Oscillation Index (SOI, the twice-normalized pressure difference between Tahiti and Darwin) are presented together with East Antarctic May/June temperature anomalies. The general increase of the SOI from 1972–76 (Swanson & Trenberth 1981) concurred with a strengthening of the SAO (Fig. 6) and rising May/June temperatures in East Antarctica. The decrease of the SOI since 1975, arising from several warm events and culminating in the 'extended' El Niño in the first half of the 1990s (Trenberth & Hoar 1996), is connected to the weakening of the SAO and lower May/June temperatures in East Antarctica.

There also appears to be an association between the strength of the westerlies and the SAO. With the availability of gridded analyses from 1972 onwards, the rapid changes in the zonal circulation that occurred during the 1970s were especially well documented. Trenberth (1979, 1980 and 1981) and Swanson & Trenberth (1981) discussed the strong increase in the early 1970s of geopotential height of the 500 hPa level over Antarctica and the concurrent decrease over the midlatitude continents, resulting in weakening westerlies and increased wave 2 and 3 circulation. Since then, the meridional gradients of geopotential heights have increased again (van Loon *et al.* 1993, Hurrell & van Loon 1994). These changes are in phase with long-term strengthening and weakening of the SAO. A link between the circumpolar westerlies to East Antarctic temperatures via the SAO is supported by the significant negative correlation that was found between the strength of the circumpolar westerlies and temperature at South Pole (Rogers & van Loon 1982) as well as composite Antarctic temperatures (Raper *et al.* 1984).

Although long-term variations seem to be well correlated, the connection between the SO and the SAO on the shorter time scales seems to be more complex. Van Loon (1984) and van Loon & Shea (1987) found that the year before a warm event was characterized by a suppressed amplification of the trough into the Pacific during May/June/July, forced by a stronger-than-normal ridge, and an enhanced amplification during the warm event one year later. Smith & Stearns (1993) calculated composite temperature and pressure anomalies over Antarctica for the 24 months surrounding a warm event; their results show that both before and after the warm event coastal East Antarctic temperatures are below normal, but that the temperature anomaly at the East Antarctic plateau changed sign from warm to cold. A link between warm events in the SOI and colder temperatures at South Pole one year later was also found by Savage *et al.* 1988. These results are not in disagreement with our findings that 'warm' events in the SO are associated with low temperatures in East Antarctica (Fig. 10).

Summary and conclusions

In part 1 of this paper we described the relation between the annual temperature cycle at East Antarctic stations and the semi-annual oscillation (SAO), i.e. the twice yearly expansion and contraction of the circumpolar trough. A well developed SAO tends to enhance the meridional exchange of air, thereby moderating early winter cooling in East Antarctica. Following a significant weakening of the SAO since the mid-1970s, East Antarctic May/June temperatures have decreased, which levelled out the Antarctic warming trend. Spectral analysis of 87 years of Orcadas pressure data suggest that the recent weakening of the SAO is part of a set of low-frequency variations in the SAO, with dominant periods of 12 and 30–35 years. If the process proves to be repetitive and valid for the entire continent, an accelerated East Antarctic warming should be expected in the coming decades, comparable to the trends observed before 1975 (i.e. 1 K per 15 years).

There are indications of links between the SAO and the Southern Oscillation, in the sense that warm phases of the SO

https://doi.org/10.1017/S095410209800025X Published online by Cambridge University Press

coincide with strong westerlies, a weakly developed SAO and below-average temperatures in east Antarctica and vice versa.

Acknowledgements

This is Norsk Polarinstitutt Contribution No. 330.

References

Dutton, E.G., Stone, R.S., Nelson, D.W. & Mendonca, B.G. 1991. Recent interannual variations in solar radiation, cloudiness and surface temperature at the South Pole. *Journal of Climate*, **4**, 848-858.

Hurrell, J.W. & van Loon, H. 1994. A modulation of the atmospheric annual cycle in the Southern Hemisphere. *Tellus*, **46A**, 325-338.

Jacka, T.H. 1990. Antarctic and Southern Ocean sea-ice and climate trends. *Annals of Glaciology*, **14**, 127-130.

Jones, P.D. & Limbert, D.W.S. 1987. A data bank of Antarctic surface temperature and pressure data. *US Department of Energy Technical Report*, TR038, 52 pp.

Jones, P.D. & Wigley, T.M.L. 1988. Antarctic gridded sea level pressure data: an analysis and reconstruction back to 1957. *Journal of Climate*, **1**, 1199-1220.

King, J.C. 1994. Recent climate variability in the vicinity of the Antarctic Peninsula. *International Journal of Climatology*, **14**, 357-369.

King, J.C. & Turner, J. 1997. *Antarctic meteorology and climatology*. Cambridge: Cambridge University Press, 409 pp.

Meehl, G.A. 1991. A reexamination of the mechanism of the semi-annual cycle in the Southern Hemisphere. *Journal of Climate*, **4**, 911-926.

Raper, S.C.B., Wigley, T.M.L., Mayes, P.R., Jones, P.D. & Salinger, M.J. 1984. Variations in surface air temperatures. Part 3. The Antarctic. 1957-1982. *Monthly Weather Review*, **112**, 1341-1353.

Rogers, J.C. & van Loon, H. 1982. Spatial variability of sea level pressure and 500 mb height anomalies over the Southern Hemisphere. *Monthly Weather Review*, **110**, 1375-1392.

Savage, M.L., Stearns, C.R. & Weidner, G.A. 1988. The Southern Oscillation signal in Antarctica. In preprint volume Second Conference on Polar Meteorology and Oceanography, AMS Boston, 141-144.

Schwerdtfeger, W. & Prohaska, F. 1956. The semi-annual pressure oscillation: cause and effects. *Journal of Meteorolgy*, **13**, 217-218.

Smith, S.R. & Stearns, C.R. 1993. Antarctic climate anomalies surrounding the minimum in the Southern Oscillation Index. *Antarctic Research Series*, **61**, 149-174.

Swanson, G.S. & Trenberth, K.E. 1981. Trends in the Southern Hemisphere circulation. *Monthly Weather Review*, **109**, 1879-1889.

Trenberth, K.E. 1979. Interannual variability of the 500 mb zonal mean flow in the Southern Hemisphere. *Monthly Weather Review*, **107**, 1515-1524.

Trenberth, K.E. 1980. Planetary waves at 500 mb in the Southern Hemisphere. *Monthly Weather Review*, **108**, 1378-1389.

Trenberth, K.E. 1981. Interannual variability of the Southern Hemisphere 500 mb flow: regional characteristics. *Monthly Weather Review*, **109**, 127-136.

Trenberth, K.E. & Hoar, T.J. 1996. The 1990-1995 El Niño-Southern Oscillation event: longest on record. *Geophysical Research Letters*, **23**, 57-60.

van den Broeke, M.R. 1998. The semi-annual oscillation and Antarctic climate, part 1: influence on near-surface temperatures. *Antarctic Science*, **10**, .

van Loon, H. 1967. The half-yearly oscillation in the middle and high southern latitudes and the coreless winter. *Journal of Atmospheric Sciences*, **24**, 472-486.

van Loon, H. 1972a. Pressure in the Southern Hemisphere. *In* Newton, C.W., *ed.* Meteorology of the Southern Hemisphere. *Meteorological Monographs*, **13**(35), 59-86.

van Loon, H. 1972b. Temperature in the Southern Hemisphere. *In* Newton, C.W., *ed.* Meteorology of the Southern Hemisphere. *Meteorological Monographs*, **13**(35), 25-58.

van Loon, H. 1984. The Southern Oscillation, part III: Associations with the trades and with the trough in the westerlies of the South Pacific Ocean. *Monthly Weather Review*, **112**, 947-954.

van Loon, H. & Rogers, J.C. 1984. Interannual variations in the half-yearly cycle of pressure gradients and zonal wind at sea level on the Southern Hemisphere. *Tellus*, **36A**, 76-86.

van Loon, H. &Shea, D.J. 1987. The Southern Oscillation, part VI: Anomalies of sea level pressure on the Southern Hemisphere and of Pacific sea surface temperature during the development of a Warm Event. *Monthly Weather Review*, **114**, 370-381.

van Loon, H., Kidson, J.W. & Mullan, A.B. 1993. Decadal variation of the annual cycle in the Australian dataset. *Journal of Climate*, **6**, 1227-1231.

Vaughan, D.G. & Doake, C.S.M. 1996. Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. *Nature*, **379**, 328-331.

White, W.B. & Peterson, R.G. 1996. An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. *Nature*, **380**, 699-702.