NOTES AND CORRESPONDENCE

On the Interpretation of Antarctic Temperature Trends

MICHIEL R. VAN DEN BROEKE

Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, Netherlands

9 August 1999 and 3 April 2000

ABSTRACT

Determining the rate of atmospheric warming in Antarctica is hampered by the brevity of the temperature records (<50 years), which still contain signals of decadal circulation variability in the Southern Hemisphere. In this note it is demonstrated that Antarctic warming trends have been regionally modified by slow circulation changes and associated changes in sea-ice cover: decadal weakening of the semiannual oscillation since the mid-1970s has limited the meridional heat exchange between Antarctica and its surroundings, so that warming trends have leveled out since then. In contrast, northerly circulation anomalies in combination with decreased sea-ice cover have regionally enhanced low-level warming, for instance in the region of the Antarctic Peninsula. Based on this knowledge, the authors propose a background Antarctic warming trend of 1.30 $\pm$ 0.38°C (century)$^{-1}$, representative of the period 1957–95.

1. Introduction

With an annual mean surface temperature of -30°C, Antarctica is the coldest continent on earth (Fortuin and Oerlemans 1990). The atmosphere above the ice cap is thin and dry, which strongly limits the amount of incoming longwave radiation at the surface. Moreover, only 10%–20% of the solar radiation reaching the surface is used to warm the snow pack: the rest is reflected back to space. Because the ice cap is such a strong heat sink, large vertical and horizontal temperature gradients are constantly present between the continent and its immediate surroundings. That is why near-surface temperatures in Antarctica are very sensitive to changes in the low-level atmospheric circulation.

Although at some Antarctic stations the records are somewhat longer (Jones 1990), meteorological observations in Antarctica start in earnest in 1957, the International Geophysical Year. This means that the influence of decadal changes in the atmospheric circulation must be taken into account if one wants to determine warming trends from the short temperature records. For instance, circulation anomalies and local sea-ice retreat play a major role in the strong warming of 2.5°C over the last 45 years in the northern Antarctic Peninsula (King and Harangozo 1998; Marshall and King 1998; Jacobs and Comiso 1997), which has likely caused the rapid retreat of the Wordie, Prins Gustav Channel, and Larsen-A ice shelves (Vaughan and Doake 1996).

The circulation system that has the largest impact on Antarctic temperatures is the semiannual oscillation (SAO) in the Southern Hemisphere (van Loon 1967; van den Broeke 1998a). In response to meridional temperature gradients resulting from differences in heat storage between Antarctica and the Southern Ocean (Walland and Simmonds 1999), baroclinicity and depression activity at high southern latitudes peak in the equinoctial months March and September. This results in the twice-yearly contraction/expansion of the circumpolar low pressure belt, a process commonly referred to as the SAO. Especially pronounced is the atmospheric reorganization from autumn to early winter (March–June), when the expansion of the low pressure belt, in conjunction with surface pressure rises over the three midlatitude continents, causes an amplification of the wavenumber-3 pattern of the circulation around Antarctica (Fig. 1b). The associated increase of meridional air exchange combined with the pronounced surface temperature gradients in this time of year, results in a strong reduction or even a reversal of the seasonal cooling in Antarctica (van Loon 1967).

Spectral analysis of 95 years of surface pressure data from Orcadas (the longest Antarctic meteorological record available) reveals significant oscillations in the amplitude of the SAO with periods of 12 and 35 yr (van den Broeke 1998b), and modeling studies suggest the existence of even slower oscillations (Simmonds and

Corresponding author address: Dr. Michiel R. van den Broeke, Institute for Marine and Atmospheric Research, Utrecht University, P.O. Box 80005, 3508 TA Utrecht, Netherlands.
E-mail: broeke@phys.uu.nl

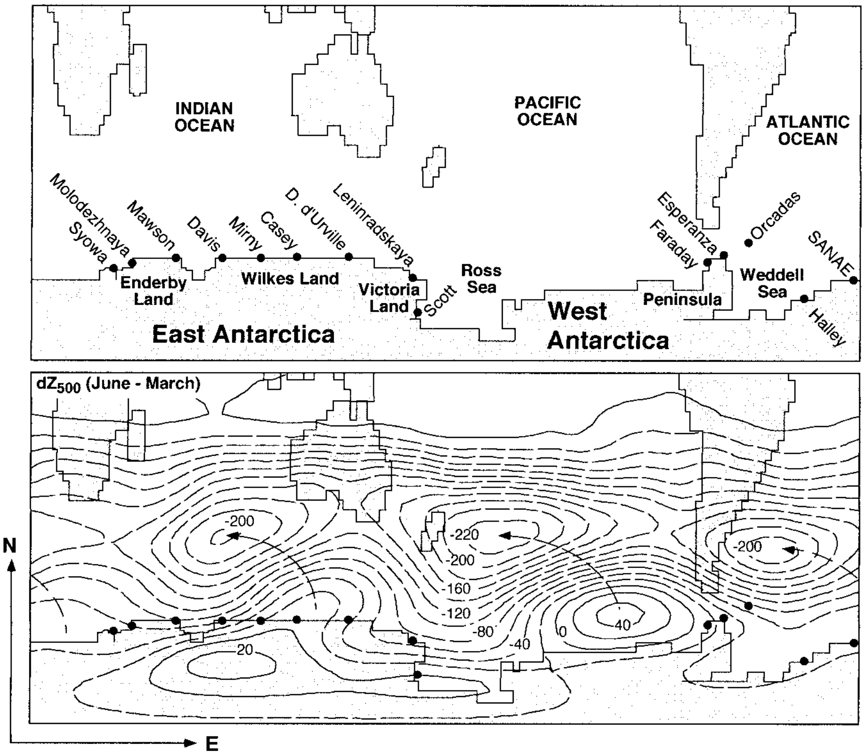

FIG. 1. (a) Location of stations and topographical features of the Southern Hemisphere. (b) Change of 500-hPa level geopotential height Z_{500hPa} in SAO expansion phase 2 from Mar to Jun. Contour interval 10 m, negative values are dashed. Arrows indicate approximate movement of the climatological low pressure areas in the circumpolar pressure belt. Derived from NCEP–NCAR reanalysis for 6 yr with well-developed SAO.

Walland 1998). As part of this variability, a rather dramatic weakening of the SAO has occurred since the mid-1970s (van Loon et al. 1993; Hurrel and van Loon 1994). The associated decrease of meridional air exchange has caused significant May–June cooling in coastal east Antarctica (van den Broeke 1998b), and is also able to explain changes in the annual cycle of temperature, wind speed, and precipitation events at some coastal Antarctic stations (van den Broeke 2000a, b, c).

2. Data analysis

We used data of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (NRA) project (Kalnay et al. 1996) to calculate Southern Hemisphere circulation and temperature anomalies associated with SAO weakening. NRA data have known deficiencies in the representation of precipitation over Antarctica (Cullather et al. 1998) as well as an unrealistic long-term pressure trend in the Southern Ocean (Hines et al. 2000). However, it is the only global gridded dataset that comprises the important early and mid-1970s, and van den Broeke (2000c) showed that from 1968 onward, the SAO is well represented in the pressure data.

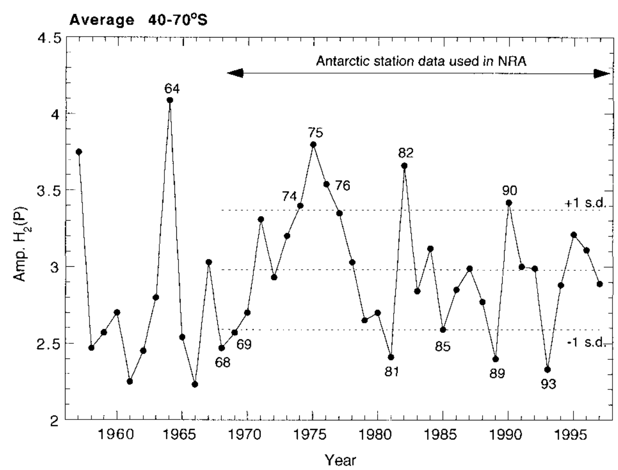

FIG. 2. SAO strength (1957–95), defined as the amplitude of the second harmonic in the annual cycle of surface pressure, $H_2(P)$, averaged over all longitudes and over the latitude band 40°–70°S. A total of 12 years that deviate more than 1σ from the mean is selected to represent the two extreme SAO states. Only years from 1968 onward are used, this being the period in which Antarctic station data are used for the reanalysis. An exception was made for the high-amplitude year 1964, because it is well represented in the observations (van den Broeke 2000c).

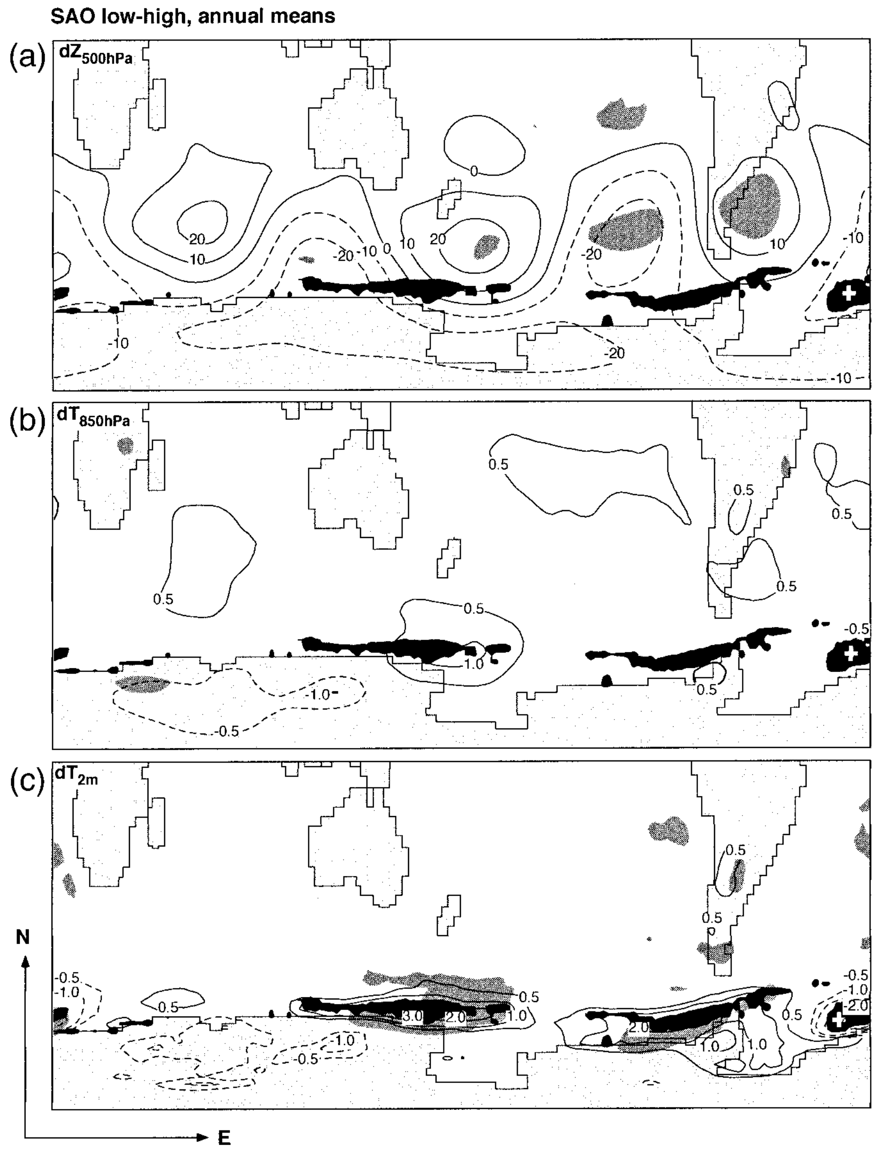

FIG. 3. "SAO weak–strong" annual mean anomaly fields of (a) 500-hPa height dZ_{500hPa}, (b) 850-hPa temperature dT_{850hPa} (K), and (c) 2-m temperature dT_{2m} (K). Areas where difference exceeds the 95% confidence level are shaded. Black areas denote negative sea-ice anomalies in excess of 10%; the white "+" denotes a positive anomaly of the same magnitude, indicating the formation of the Weddell Polynya in years with a strong SAO.

SAO strength (1957–95) is defined here as the amplitude of the second harmonic in the annual cycle of surface pressure, $H_2(P)$, averaged over all longitudes and over the latitude band 40°–70°S. A total of 12 years that deviate more than 1σ from the mean is selected to represent the two extreme SAO states (Fig. 2). These are stacked to obtain averaged fields, which are then subtracted to obtain anomaly fields of the 500-hPa level height dZ_{500hPa} (Fig. 3a), 850-hPa temperature dT_{850hPa} (Fig. 3b), and 2-m temperature dT_{2m} (Fig. 3c) for weak minus strong SAO conditions.

3. Results and discussion

The wavenumber-3 pattern of 500-hPa height anomalies in Fig. 3a reflects the failure of the circumpolar pressure belt to move north- and westward during the SAO expansion phases (October–January and March–June, compare with Fig. 1b). The associated reduction of meridional air exchange in the early winter dominates the annual temperature response, which results in a weak (0.26 K) near-surface cooling averaged over the continent (Fig. 3c). SAO weakening thus moderates Ant-

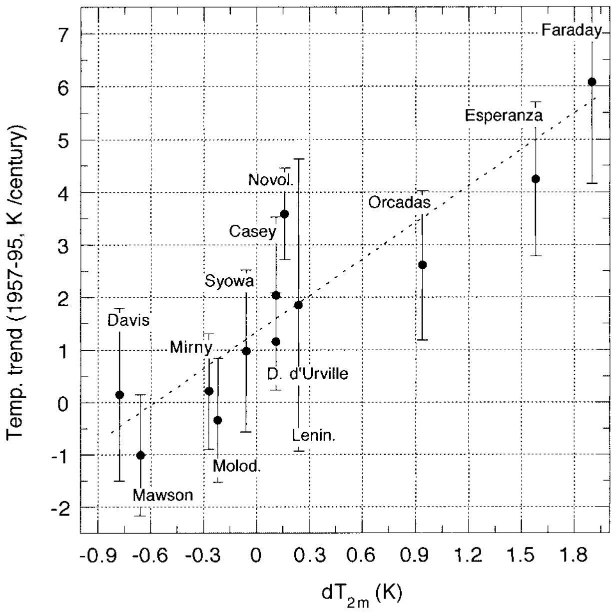

FIG. 4. The 2-m temperature trends (1957–95) at 12 coastal Antarctic stations as a function of dT_{2m}, derived from Fig. 3c. Error bars indicate one standard error, (a function of interannual variability and record length). Offset (''background warming'') and slope of the weighed regression are both significantly different from zero at the 99% confidence level.

arctic warming, which agrees qualitatively with the decreased warming rates observed since the mid-1970s, as reported in Raper et al. (1983) and Jones (1995).

The circulation anomalies displayed in Fig. 3a introduce zonal patterns in the temperature response. Locally enhanced advection of air from the ice cap interior causes stronger cooling in Enderby Land and western Wilkes Land, both at the 850-hPa and 2-m level (Figs. 3b,c). In contrast to this, the circulation attains a northerly component in the longitudinal sections of eastern Wilkes Land and the Antarctic Peninsula. This limits the northward migration of the sea-ice edge in winter (Harangozo 1997) so that annual mean sea-ice cover is reduced.[1] Where this happens, near-surface temperature anomalies (Fig. 3c) deviate strongly from the values found above the boundary layer at 850 hPa (Fig. 3b). In combination with the circulation anomalies, advection of the warm air causes low-level warming over continental Antarctica in a small strip of coastal Victoria Land/eastern Wilkes Land and in the northern part of the Antarctic Peninsula. Note that the pronounced south–north orientation of the Antarctic Peninsula makes it more sensitive to circulation changes with a zonal component than other sections of the Antarctic coast.

There exists a significant correlation of the above described near-surface temperature response with observed temperature trends at Antarctic coastal stations over the period 1957–95 (confidence level >99%, Fig. 4). This implies that temperature trends at Antarctic stations still carry the fingerprint of SAO weakening since the mid-1970s. The zonal dependency introduced by these circulation changes is offset by a value of 1.30 $\pm$ 0.38°C (century)$^{-1}$ (abscissa of the weighed linear fit in Fig. 4, significantly different from zero at 99% confidence level). This trend can be interpreted as a ''background'' Antarctic warming, that is, a temperature trend over 1957–95 that would be measured at a fictitious station where temperature is not sensitive to changes in the SAO.

We have excluded ice shelf stations SANAE, Halley, and Scott from the correlation; ice shelves are not well represented in the coarse NRA grid, and this can lead to opposite behavior of temperature trends when changes in the SAO are considered (van den Broeke 2000c). However, including these stations in the correlation does not change the results: 1.31 $\pm$ 0.35°C (century)$^{-1}$. The same result is also obtained when a rank correlation is used that takes into account the obvious nonnormal distribution of dT_{2m} in Fig. 4.

The background Antarctic warming found from Fig. 4 is not significantly different from the simple mean of all individual station trends (1957–95, using one composite value for Faraday, Esperanza, and Orcadas): 1.31 $\pm$ 0.37°C (century)$^{-1}$. In a similar way, Jacka and Budd (1998) found an Antarctic warming of 1.2°C (century)$^{-1}$ over 1959–96 and Jones (1995) a value of 1.54°C (century)$^{-1}$ over 1957–94 (not stacking the peninsula stations). According to our analysis, the fact that these numbers are not significantly different from the trend derived from Fig. 4 is a coincidence: Antarctic temperature time series now include roughly one complete 35-yr cycle of the SAO, so that a net effect of SAO changes is averaged out.

Further evidence of SAO influence on Antarctic temperature trends is found in changed annual temperature cycles at selected stations (van den Broeke 2000c). For the combined records of the winter months June and July (representative of the second expanded phase of the SAO), he found a background warming trend of 4.62 $\pm$ 1.02°C (century)$^{-1}$, three and one-half times the annual value found here. Apparently Antarctic warming for a large part derives from the winter months, when the vertical and horizontal temperature gradients are largest. This is similar to what is found for the continental polar regions of the Northern Hemisphere (Weller 1998).

4. Conclusions

Circulation changes associated with decadal variability of the semiannual oscillation (SAO) in the Southern Hemisphere influenced temperature trends at coastal

[1] An interesting feature is the positive sea-ice anomaly in the eastern Weddell Sea; it represents the presence of the Weddell Polynya in years with a strong SAO. This will be reported on elsewhere.

Antarctic stations. The signal stems largely from the winter months, when vertical and horizontal temperature gradients are largest, and Antarctic near-surface temperature most sensitive to circulation changes. When corrected for this, an Antarctic background warming of $1.30 \pm 0.38°C$ (century)$^{-1}$ can be derived.

Acknowledgments. We gratefully acknowledge the use of NCEP–NCAR reanalysis data for this work. Station temperature data were provided by the British Antarctic Survey, the Australian Bureau of Meteorology, and Paul Pettré from Météo France.

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