NOTES AND CORRESPONDENCE

Changes in Climate at High Southern Latitudes: A Unique Daily Record at Orcadas Spanning 1903–2008

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ABSTRACT

The climate observations at Orcadas represent the only southern high-latitude site where data span more than a century, and its daily measurements are presented for the first time in this paper. Although limited to a single station, the observed warming trends are among the largest found anywhere on the earth, facilitating the study of changes in extreme temperatures as well as averages. Factors that may influence Antarctic climate include natural variability; changes in greenhouse gases; and, since about the mid-1970s, the development of the ozone hole. The seasonality of observed warming and its temporal evolution during the century are both key for interpretations of Antarctic climate change. No statistically significant climate trends are observed at Orcadas from 1903 to 1950. However, statistically significant warming is evident at Orcadas throughout all four seasons of the year since 1950. Particularly in austral fall and winter, the warming of the cold extremes (coldest 5% and 10% of days) substantially exceeds the warming of the mean or of the warmest days, providing a key indicator for cold season Antarctic climate change studies. Trends in the summer season means and extremes since 1970 are approximately twice as large as those observed earlier, supporting suggestions of additional regional warming in that season because of the effects of ozone depletion on the circulation. Further, in the spring and summer seasons, significant mean warming also occurred prior to the development of the Antarctic ozone hole (i.e., 1950–70), supporting an important role for processes other than ozone depletion, such as greenhouse gas increases, for the climate changes.

1. Introduction

In the past several decades, some portions of West Antarctica have been subject to extremely large warming trends, whereas East Antarctica has exhibited cooling trends in some seasons (e.g., Turner et al. 2005; Marshall et al. 2006; Marshall 2007; Chapman and Walsh 2007; see Fig. 1). These contrasting trends have their origins in a strengthening of the westerly winds that encircle the south polar cap in recent decades, which in turn has been linked to stratospheric ozone depletion and greenhouse gas increases (Thompson and Solomon 2002; Gillett and Thompson 2003; Marshall et al. 2004; Arblaster and Meehl 2006; Cai and Cowan 2007). Key questions have been raised, however, regarding how often such changes in climate and circulation patterns may occur through natural internal variability (Jones and Widmann 2004; Fogt and Bromwich 2006) and the contribution of greenhouse gases, especially prior to the onset of the ozone hole (Steig et al. 2009). Schneider et al. (2006) and Monaghan et al. (2008) have also used ice-core data to examine changes in the Antarctic climate over long time scales (albeit only with annual resolution). Van den Broeke (1998) highlighted observed changes in

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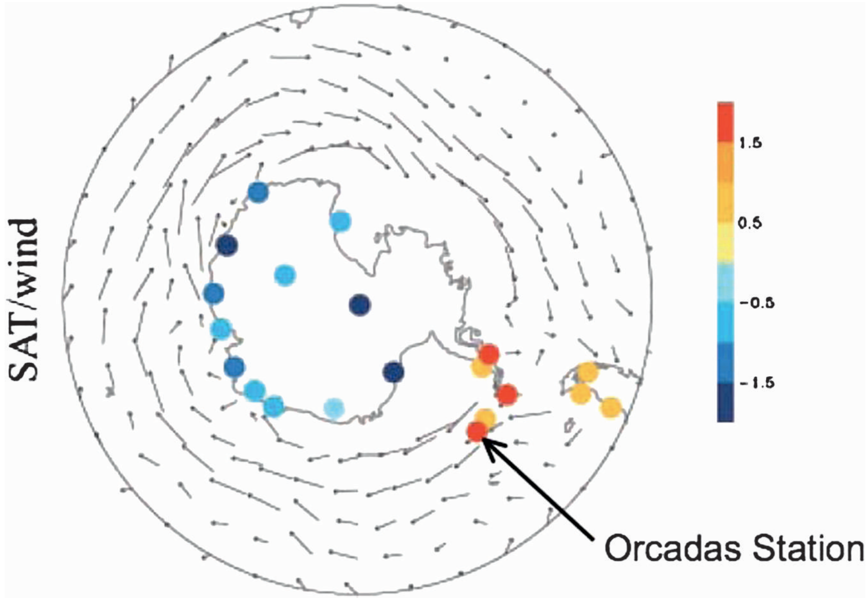

FIG. 1. Observations of Decemeber–May trends in surface air temperature for 1969–2000 (dots) and 925-mbar winds (1979–2000) over Antarctica; the longest wind vector denotes a trend of $\approx$4 m s^{-1}. Adapted from Thompson and Solomon (2002) and used with permission. The location of Orcadas is indicated.

the semiannual cycle in the Antarctic climate and possible links to anomalies in the atmospheric circulation (Van den Broeke 2000).

A number of Antarctic sites have reported daily and monthly instrumental climate observations since the International Geophysical Year (IGY) in 1958, and a few have records beginning in the 1940s, with variable consistency and confidence, but only one high-latitude southern station has an instrumental record of daily surface temperature covering the entire twentieth century—the Argentine station Orcadas at 60°44′S, 44°44′W. Although only a single such long-term site is available, and it does not fully represent the average across Antarctica (Raper et al. 1984), the station lies within the region displaying strong December–May warming in recent decades, as shown in Fig. 1. The observed changes are correlated to circulation changes linked to the southern annular mode (e.g., Marshall et al. 2004; Visbeck 2009). Seasonally and monthly averaged trends for this station have been previously reported (e.g., Turner et al. 2005) and are in broad agreement with observations gathered since the 1940s at other nearby sites (e.g., as shown in Fig. 2). No clear warming trends are seen prior to the 1950s, but the rapid summer warming observed in this region since about 1950 is evident and far exceeds observed long-term global trends. Here, we present daily data since the beginning of record keeping in 1903. The data were provided by the National Weather Service of Argentina in paper form (Servicio Meteorológico Nacional de la República Argentina 2007, personal communication) for the data prior to 1950. They have been digitized for this work and are available upon request from the National Weather Service of Argentina, but the following few years of daily data are missing: 1951–56 and 1975. Changes in the extremes of daily temperatures are of interest not only for physical climate science but also because they may influence a range of climate impacts, such as the retreat of glaciers, sea ice, and snow cover, as well as the ecological effects on polar flora and fauna (Vaughan et al. 2001, and references therein). In this paper, we explore this unique daily record of temporal and seasonal changes in averages and extremes of climate since the beginning of the twentieth century.

2. Data availability and the seasonal cycle in different periods

Beginning with the Scotia expedition in 1903, daily measurements of temperature are available from Orcadas (the earliest data are compared to other expeditionary records by Jones 1990). Prior to 1950, observations were reported hourly and the daily means represented the averages over 24 h; since 1950, the daily means are constructed from observations of the daily maximum plus minimum divided by 2. Note that most of the warming

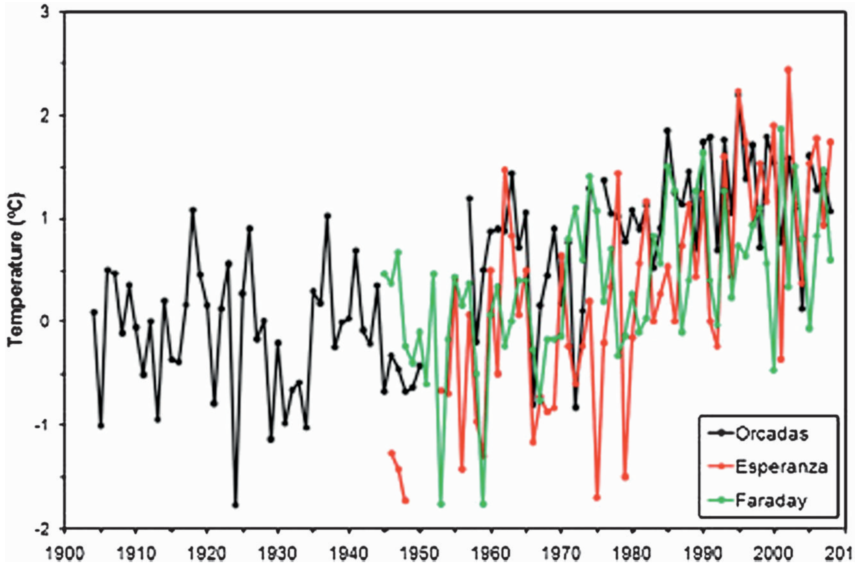

FIG. 2. DJF seasonal temperatures over the periods of record of observations at the following three Antarctic Peninsula region stations: Orcadas (60°45′S, 44°43′W), Esperanza (63°23′S, 56°59′W), and Faraday (65°15′S, 64°16′W).

discussed here occurred after 1960, when observations were taken exclusively using the latter method. Further, the comparability of these two approaches for temperature trend analyses has been shown in previous studies (Karl et al. 1986). For a few years, maximum, minimum, and limited diurnal temperature observations (roughly but not systematically 3 hourly) were also available at Orcadas. A comparison between such data for 1996 and 1997 reveals that the seasonally averaged differences between the two averaging approaches were not more than 0.2°C and were generally closer to 0.1°C or less, suggesting that the difference in daily averaging does not make a major contribution to the changes shown in this paper.

Figure 3 shows the seasonal cycle of daily temperatures observed at Orcadas for each of five 20-yr periods. Strong warming is evident at Orcadas from late spring through the early fall season, November–March,

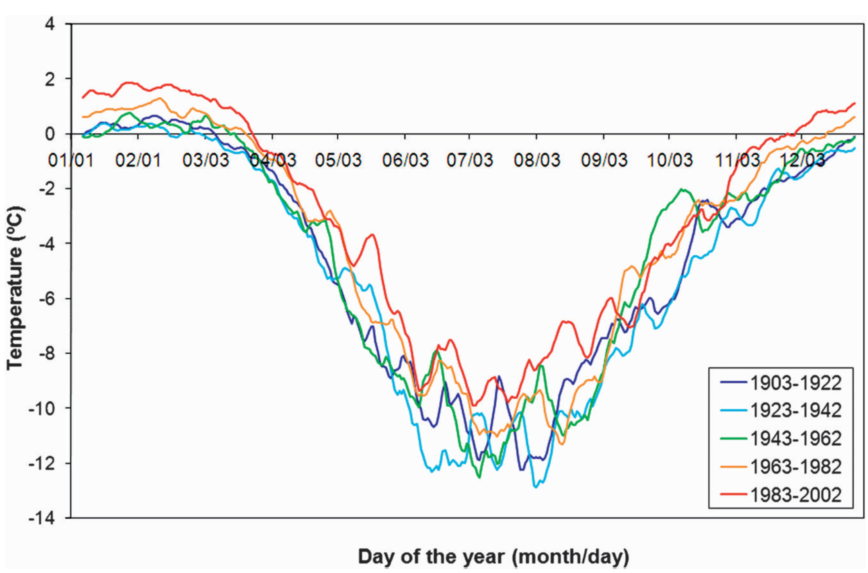

FIG. 3. Mean annual cycle of temperatures at Orcadas over 20-yr intervals beginning in 1903. A 10-day smoothing has been applied.

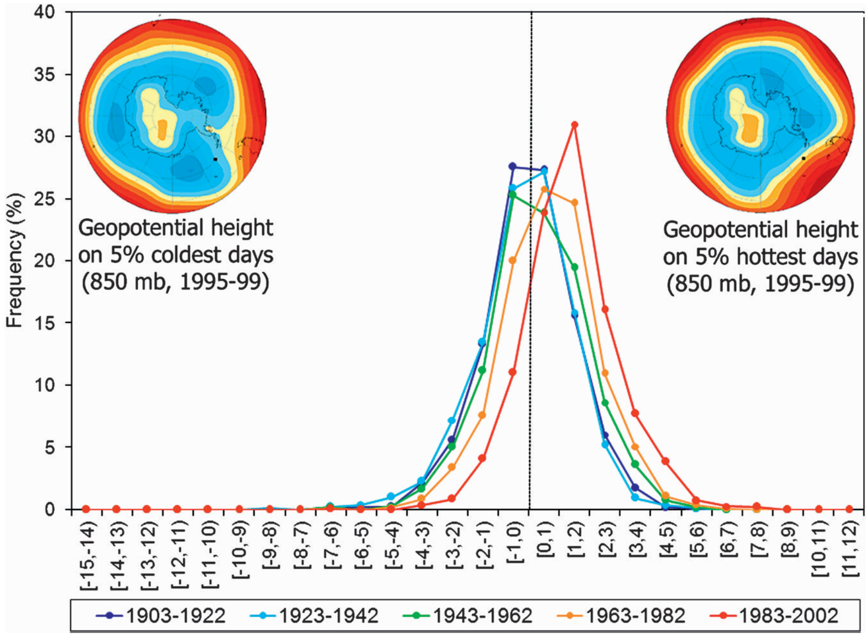

FIG. 4. Distribution of frequencies of observations of daily temperatures during DJF for each 20-yr period since 1903. One degree bins have been used as shown. The dashed line at zero highlights the increase in days of ice melt. Average geopotential height fields obtained on the 5% coldest and 5% hottest summer days are also shown for 5 illustrative years (1995–99), showing the different circulation patterns characterizing these conditions. The location of Orcadas is indicated with a black square.

particularly since the 1980s. The length of the season over which atmospheric temperatures exceed 0°C is important for ice melt and has substantially increased. Variability is greater relative to the trends in colder seasons; however, the period since 1982 appears to be warmest throughout nearly the entire year, including the late fall and winter season of April–August (see Table 1).

3. Results: Changes in the distribution of temperatures in various seasons

Figure 4 presents the probability distribution functions (PDFs) for daily summer [December–February (DJF)] temperatures at Orcadas over each 20-yr period since 1903/04. The zero-degree line is marked in the figure to highlight the large observed increase in the number of days of ice melt. Although the shape of the distribution has been nearly constant in this season, the mean temperatures have systematically shifted in recent decades, producing a large change in the frequency of occurrence of cold and warm extremes. For example, the figure shows that temperatures warmer than 4°C are now observed with increasing regularity but were obtained only extremely rarely prior to the 1980s. Figure 4 also shows geopotential height patterns at 850 mbar from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) for the 5% of hottest and 5% of coldest summer days for five illustrative years (1995–99; qualitatively similar patterns are obtained in other years). The warmest 5% of summer days at Orcadas are distinguished by stronger westerly and northwesterly flow (maritime conditions) compared to the average. The coldest 5% of summer days display a more disturbed pattern, allowing more southerly flow from the cold continent (discussed further later in this study). The large warming and limited variability in the summer season at Orcadas make the changes particularly easy to identify compared with many other locations and are a motivating factor for the present analysis.

The changes of warm and cool extremes at Orcadas in summer are probed further in Fig. 5, where we show the systematic progression of changes in the frequency of occurrence of temperatures exceeding specific warm and cool extremes (these selected temperature groupings were chosen by inspection of the PDFs shown in Fig. 3) over 5-yr intervals. It is evident that there has been a pronounced increase in the frequency of the occurrence of summer temperatures warmer than 2°C in the past few decades, whereas the occurrence of summer extremes cooler than −2°C has virtually ceased over the same time period. Previous studies have highlighted observed

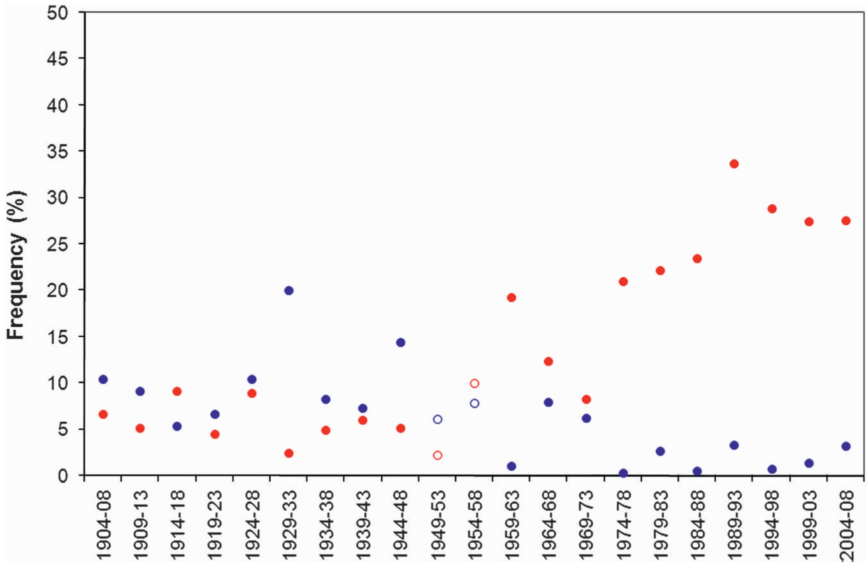

FIG. 5. Changes in the percentages of relatively warm days (temperatures >2°C) and cold days (temperatures <−2°C) for 5-yr periods for DJF. Open circles indicate periods with 2 rather than 5 yr of available measurements (in the periods 1949–53 and 1954–58).

strengthening of the westerlies in southern high-latitude summer (e.g., Thompson and Solomon 2002; Marshall et al. 2004; Marshall 2007). Analysis of the 850-mbar geopotential heights for consecutive 5-yr periods, as in Fig. 4, reveals changes in circulation (not shown) that have rendered extreme days in this region increasingly dominated by warmer maritime conditions and less influenced by cold air from Antarctica. This is broadly consistent with summer season circulation changes that have been linked to the effects of ozone depletion; however, other influences cannot be ruled out.

Figure 5 shows that there is a brief period, around 1958–62, that exhibits unusually high frequencies of warm extremes and whose character is qualitatively similar to that obtained since 1980 (see Marshall et al. 2004). However, the long record at Orcadas shows that it is of quite a limited duration and it is not apparent in the corresponding 20-yr PDF shown in Fig. 4. Thus, Figures 4 and 5 indicate that although some summer warming occurred prior to 1970 for a few years, the sustained shift in Antarctic summer climate of the past several decades is unprecedented in the instrumental record since 1903, not only in terms of the mean changes (Turner et al. 2005) but also in the changes in both hot and cold extremes.

Figure 6 presents PDFs of the temperature data for the other three seasons, September–November (SON), March–May (MAM), and June–August (JJA). The figure shows that there has been an increase in hot extremes at Orcadas in all seasons since 1980, similar to but generally smaller than DJF. In contrast to the summer season, the winter season temperature distribution is strongly skewed. The long tail of cold winter extremes is linked to flow from the cold continent, whereas the sharp cutoff of warm extremes is linked to the thermal stability of sub-Antarctic maritime temperatures close to the freezing point. Figure 6 also shows decreases in cold extremes in fall (MAM) and winter (JJA), with a systematic decline in the frequency of occurrence of the coldest winter season extremes below, for example, −15°C.

4. Discussion and summary

Table 1 summarizes the results by season, showing decadal-averaged trends in the seasonal means throughout the year, as well as in the warmest and coolest 5% and 10% of the daily data (where P95 and P90 denote the 5% and 10% warmest days, respectively, whereas P5 and P10 denote the corresponding coldest days; a 2-σ statistical significance is indicated by an asterisk). These trends are among the strongest seen anywhere on the earth over the course of the twentieth century. The total warming since 1903 is about 2°C for the seasonal averages (comparable to values in previous studies such as Turner et al. 2005) and up to 5°C in the coldest winter and fall extremes. Trends significant at 95% confidence (2σ) are obtained for mean temperatures in all seasons of the year over the full period of 1903–2007. Statistically significant trends are also obtained for the twentieth century in both the 5% and 10% warmest and coolest portions of the temperature distributions over much of the year, with the exception of the coolest temperatures

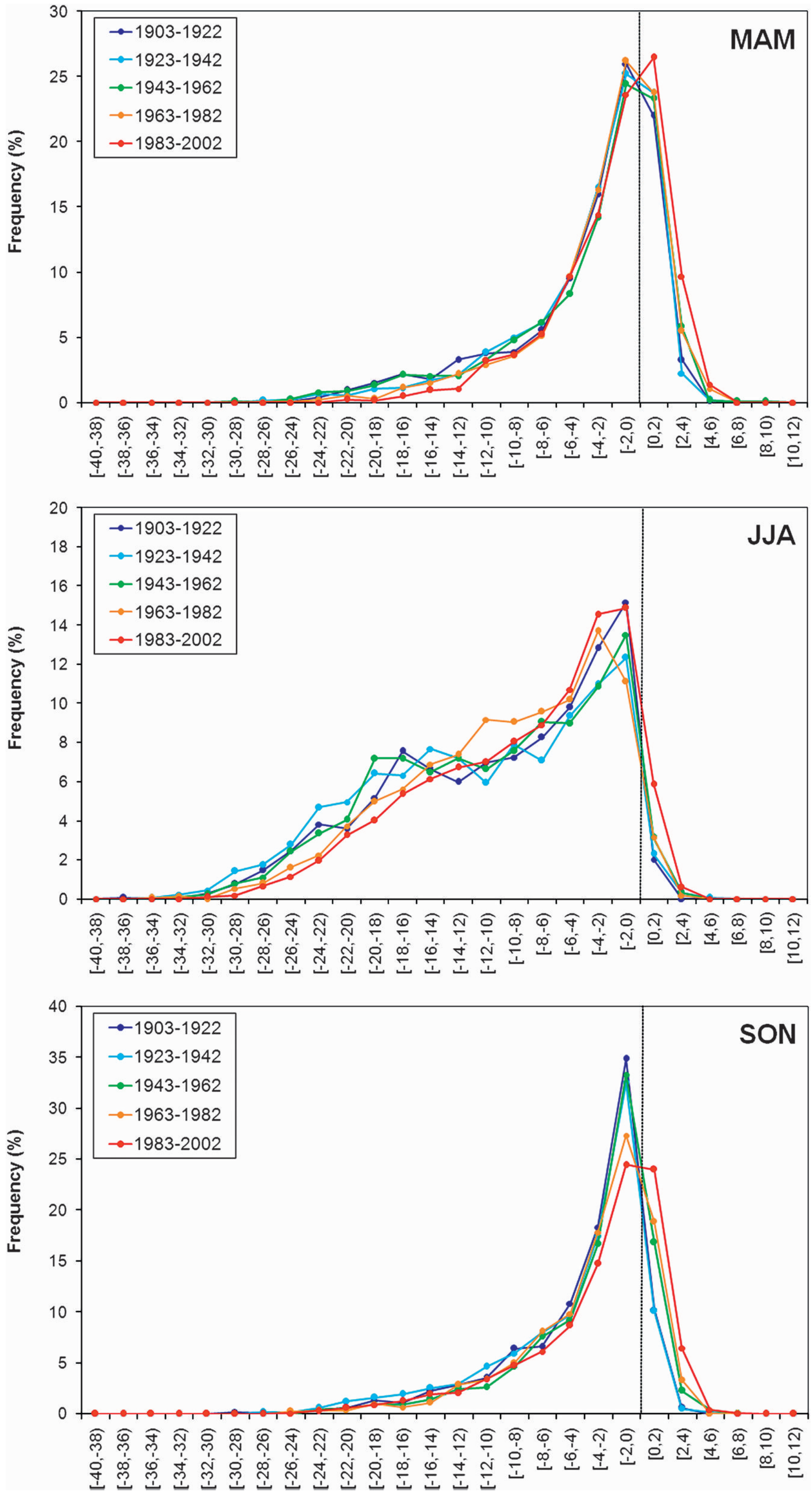

FIG. 6. Distribution of frequencies of observations of daily temperatures during MMA, JJA, and SON seasons, for each 20-yr period since 1903. Two degree bins have been used as shown.

TABLE 1. Trends (°C decade^{-1}) in temperature observed at Orcadas for various seasons and periods, where 2-σ uncertainties are indicated. P95 and P90 denote the 5% and 10% warmest days, whereas P5 and P10 denote the corresponding coldest days.

		1903–2007	2-σ	1957–2007	2-σ	1903–70	2-σ
DJF	mean	0.18*	0.04	0.20*	0.11	0.10*	0.08
	P95	0.21*	0.05	0.25*	0.13	0.11*	0.09
	P90	0.19*	0.04	0.23*	0.11	0.11*	0.08
	P10	0.19*	0.05	0.21*	0.15	0.12*	0.10
	P5	0.21*	0.06	0.23*	0.18	0.13*	0.12
MAM	mean	0.22*	0.10	0.29*	0.29	0.12	0.22
	P95	0.13*	0.05	0.15	0.16	0.07	0.08
	P90	0.12*	0.04	0.15*	0.15	0.07	0.08
	P10	0.47*	0.26	0.53	0.66	0.29	0.55
	P5	0.53*	0.28	0.47	0.74	0.39	0.59
JJA	mean	0.23*	0.15	0.35	0.39	0.14	0.32
	P95	0.09*	0.05	0.19*	0.16	0.05	0.11
	P90	0.09*	0.07	0.22*	0.17	0.03	0.14
	P10	0.36*	0.19	0.15	0.55	0.41*	0.38
	P5	0.33*	0.20	0.14	0.61	0.41*	0.36
SON	mean	0.17*	0.09	−0.01	0.26	0.24*	0.18
	P95	0.20*	0.04	0.05	0.13	0.21*	0.08
	P90	0.18*	0.04	0.07	0.13	0.17*	0.07
	P10	0.22	0.22	−0.26	0.59	0.47	0.47
	P5	0.23	0.25	−0.35	0.67	0.49	0.52

* Trend significant at the 2-σ level.

in spring (SON). The winter warming is particularly pronounced in the cold extremes, whereas the summer season changes represent a shift rather than a change in shape of the distribution, underscoring differences in the character of the climatic changes with each season.

Some recent studies using ice-core data (which do not provide seasonal information) suggest that there was no statistically significant long-term trend in Antarctic temperatures prior to 1950, which is an important point of comparison for global warming studies because climate models do suggest a trend (Monaghan et al. 2008; Schneider et al. 2006). Schneider and Steig (2008) suggest a warming trend prior to 1950 from ice cores in West Antarctica. If only the period from 1903 to 1950 is considered, there is no trend at Orcadas; however, consideration of the seasonal data for the period from 1903 to 1970 provides additional information not possible with annual ice cores. Significant trends are obtained in cold extremes in winter (see Fig. 5 and Table 1) for 1903–70 and for both warm extremes and means in summer and fall. The change in winter cold extremes is marked and provides important support for significant trends in the Antarctic climate, occurring too early in the year and too early in the twentieth century to be attributable to ozone depletion. Although internal variability cannot be ruled out as a cause of some of these changes (particularly on a seasonal basis), the long record at Orcadas shows that the recent climate at this site (see Figs. 3 and 6 and Table 1) is distinctly different from that obtained in any previous 20-yr period—not only in summer but in all seasons—suggesting a contribution resulting from greenhouse gas increases. The ozone hole emerged in the late 1970s and is expected to exert its greatest effect on Antarctic circulation patterns and surface climate in the summer season (i.e., displaying a several-month lag relative to the stratosphere). The summer warming at Orcadas strengthened after about the mid-1970s. A new result of this study is the quantification of the marked increase in the summertime frequency of warm extremes and the decrease in cold extremes that also occurred around this time (Fig. 4) and is likely linked to ozone depletion. Thus, the unique Antarctic record at Orcadas is helpful to elucidate changes in the south polar climate over more than a century, their seasonal changes, changes in extremes, and possible causes.

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