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An analysis of a 34-year air temperature record from Fossil Bluff (71°S, 68°W), Antarctica

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Abstract: An analysis of a long-term surface air temperature record for Fossil Bluff in the George VI Sound, West Antarctic Peninsula (WAP) documents in detail some important aspects of the climate of this area for the first time. The analysis identifies the close dependency of air temperatures on latitude in the WAP but reveals that the strength of this dependency is greatest in winter. This result along with others leads to the Fossil Bluff climate regime being characterized as 'continental' rather than 'maritime' as found further north. The WAP as a whole displays large interannual temperature variability but this is greatest in Marguerite Bay rather than the Fossil Bluff area. Evidence is also provided for secular climatic change appearing in summer throughout the WAP over the last few decades. The representativeness of existing Antarctic Peninsula annual air temperature climatologies, based mainly on snow temperature measurements, for the winter and summer periods is also noted.

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Key words: air temperature variations, Antarctic Peninsula, climate change

Introduction

Analyses of Antarctic surface air temperature records for the past few decades (Raper *et al.* 1984, Jones *et al.* 1986, Sansom 1989, Jones 1990, Jacka 1990, Weatherly *et al.* 1991, Chapman & Walsh 1993, King 1994) reveal varying long-term trends in different regions. Amongst these different regions the central and northern parts of the West Antarctic Peninsula, hereafter WAP, appear to be distinct as they exhibit a more pronounced warming trend than other parts of the continent. As yet, however, it remains to be seen whether such a trend appears elsewhere in the WAP and, in particular, in the southern part.

In this paper a detailed analysis is made of a surface air temperature record compiled for Fossil Bluff (71°S 68°W, 55 m), Alexander Island situated adjacent to the ice shelf in George VI Sound (Fig. 1). This record spans a period of over 30 years although it is unfortunately broken at various times and, in particular, outside of the main summer months (December–February). Using some additional winter (June–August) data available from a nearby automatic weather station (AWS) since 1986, summer and winter climatological statistics are presented for Fossil Bluff (FB) and compared to those of other WAP stations at Faraday (65°S 64°W, 11 m) (FAR) and "Marguerite Bay" (MGB). The MGB record is a composite that, for the period covered by the FB record, is derived from spatially proximate observations made at Adelaide Island (68°S 69°W, 30 m) from 1962–75 and Rothera (68°S 68°W, 16 m) from 1976 onward (Jones & Limbert 1987). Derived winter and summer latitudinal temperature gradients for the WAP are used to assess the homogeneity of the climate of the region and also compared to results of studies for the Antarctic Peninsula as a whole that are mainly reliant on snow temperature measurements. These analyses provide the background to the final part of the study in which interannual and, in the case of summer, long-term temperature variations are described and discussed.

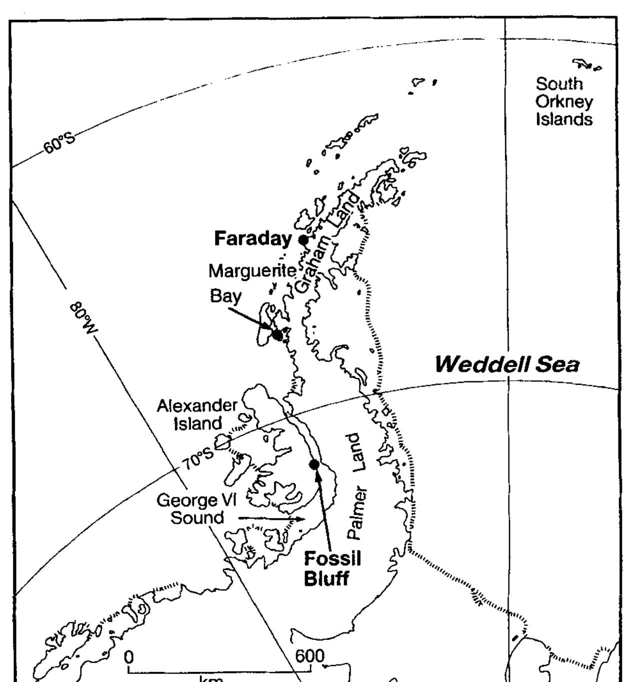

Fig. 1. Location of the BAS meteorological observing stations in the West Antarctic Peninsula referred to in this study.

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The Fossil Bluff surface air temperature record

Sources of data

Mostly routine daily synoptic observations have been made at the British Antarctic Survey base at FB since it opened in 1961 (Appendix A). These data are available for both the summer (December–February) and winter (June–August) seasons up to 1975 but only for summer after this (Appendix A) when FB became a summer-only base. In general synoptic observations have been made at both 00h00 and 12h00 UTC but only 17h00 UTC data exist for 1974 and 1975. In 1971 and 1972 only thermogram records exist for winter. These have gaps mainly lasting 1–2 days that may be due to the freezing up of instruments. If periods without data are in fact generally cold this would introduce a warm bias in winter monthly and seasonal temperature estimates but, as noted below, only those months with mostly complete data have been retained for analysis. Any remaining warm bias in monthly and, in particular, seasonal thermogram-based average temperatures retained for analysis ought to be to 1°C. Overall, station temperature data for FB is sufficiently complete for analysis for 17 summer seasons and eight winters.

Use of AWS data to augment the FB winter record

As no winter temperature measurements were taken at FB after 1975 an attempt has been made to augment the winter record using data from a nearby AWS. The AWS is located on Uranus Glacier (71°S 69°W, 780 m) south-west of FB and has been jointly run by the University of Wisconsin and BAS since early 1986, hereafter referred to as UWAWS. Up to 1992 these data have been supplied by the University of Wisconsin (1987–93) but as from February 1993 they have been collected directly from the Global Telecommunications System (GTS). In contrast to FB station data, the UWAWS logs at 3-hourly intervals and data are available on more than 25 days in most months with the exception of two extended periods from December 1990–January 1992 and from February–November 1994. The GTS-collected data are also less complete owing to transmission problems. A standard method for deriving month and season averages from both FB and UWAWS daily data is noted below.

The AWS equipment at Uranus Glacier is the same as that deployed generally throughout Antarctica by the US and air temperature measurements from this source have certain limitations in this kind of environment (Stearns *et al.* 1993). These include changes in the elevation of sensors above the snow surface during winter and radiation errors resulting from a lack of proper ventilation at low wind speeds. The latter leads to lower temperatures in winter and raised temperatures in summer. It should be noted, however, that each of these problems may also affect conventional surface station data in Antarctica. Regardless of the equipment-based limitations, however, the main difficulty of incorporating AWS air temperature data into long-term Antarctic climatological studies stems from differences in station elevation and exposure. Ordinarily, adjustments for altitude are made using a standard lapse rate but this is not possible in Antarctica during most of the year when inversion rather than lapse conditions obtain. Thus, use of UWAWS data to augment the winter FB record is hindered by the 725 m elevation difference between the sites and, in particular, the presence of a climatological inversion in the area at this time of year as noted below.

In order to establish if UWAWS data can be used to extend the FB winter temperature record additional data have been obtained from another AWS, ECPAWS (EC Project Automatic Weather Station), that operated at the lower reach of Uranus Glacier in 1993 as part of a European Community funded project (Robb 1994). The elevation of ECPAWS (13 m) is similar to that of FB and the two sites are 5 km apart. In Fig. 2 daily temperatures for UWAWS and ECPAWS based on 00h00 and 12h00 UTC data are plotted for February 1993–January 1994 and derived monthly averages are shown in Table I for the same period (except February 1993 when insufficient ECPAWS data exist for averaging). In the summer months of December 1993 and January 1994 surface temperature-based lapse rates vary between 3.4 and 4.8°C km^{-1}. Different conditions obtain at other times with reduced lapse

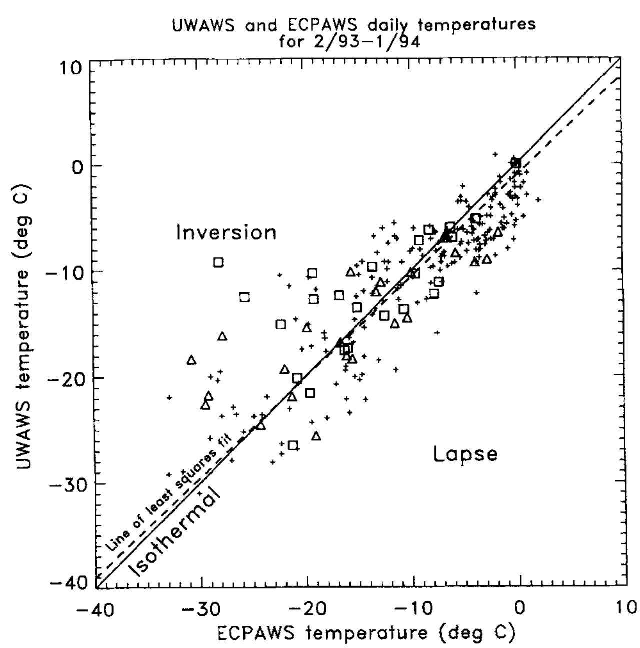

Fig. 2. Scatter plot of daily average temperatures (°C) for UWAWS and ECPAWS (see text) for the eleven month period February 1993–January 1994 shown by crosses except for July that is indicated by squares and August by triangles. Points that fall to the left of the diagonal line indicate colder conditions at ECPAWS, the lower of the two sites. Note that the outlier immediately under the label 'inversion' was excluded from the analysis.

Table I. Monthly mean (AVG) and standard deviation (s d) of temperature (°C), temperature difference (DIFF), number of days (*n*) with concurrent twice daily (00h00 and 12h00 UTC) observations and derived lapse rate for each month in the period March 1993–January 1994 based on data for Uranus Glacier AWS sites maintained by the University of Wisconsin (UWAWS) and British Antarctic Survey (ECPAWS). The elevation of the UWAWS is 780 m and ECPAWS is at 13 m. A negative value of DIFF indicates colder conditions at ECPAWS. 'INV' in the lapse rate column denotes an average inversion. The April–August average for the two sites is calculated from all daily observations to overcome the problem of varying numbers of observations in individual months.

Month	UW mean (°C)	EC mean (°C)	UW s d (°C)	EC s d (°C)	DIFF (°C)	*n* (days)	Lapse rate (°C/km^{-1})
Mar.	-10.6	-8.3	5.8	5.6	2.3	22	3.0
Apr.	-8.1	-9.3	3.2	4.4	-1.2	13	INV
May	-15.8	-16.7	7.7	8.4	-0.9	23	INV
June	-16.2	-17.7	8.7	10.0	-1.5	26	INV
July	-12.9	-14.0	5.4	6.2	-1.1	22	INV
Aug.	-14.6	-15.2	6.0	8.8	-0.6	25	INV
Sept.	-15.0	-14.8	6.9	6.3	0.2	21	0.26
Oct.	-11.2	-9.0	5.4	5.9	2.2	23	2.87
Nov.	-4.6	-4.3	2.7	4.4	0.3	21	0.39
Dec.	-5.9	-3.3	2.2	1.9	2.6	20	3.39
Jan. (1994)	-4.6	-0.9	2.1	1.7	3.7	19	4.82
Apr-Aug mean	-14.1	-15.2	-	-	-1.1	-	inversion 1.42°C/km^{-1}

rates in autumn and, in particular, spring months and, most noticeably, an average inversion of 1.4°C km^{-1} over the period April–August 1993. Thus it appears that lapse conditions in the vicinity of FB are temporally modulated and, on average, stable conditions characterize the main winter period. No independent information exists to verify the wintertime thermodynamic structure in the area of interest but using 10 m snow temperature information Morris & Vaughan (1994) have demonstrated the presence of an annual average inversion on the colder Weddell Sea side of the Antarctic Peninsula. Moreover, they show that stable conditions are most pronounced below 700 m and also ascribe this to surface-based inversions. As ECPAWS and UWAWS can also be regarded as low-elevation stations and, as shown below, the climate of Fossil Bluff area is colder than that of the more northern parts of the WAP, it does seem that inversions are a real and important feature of the winter climatology of this area.

Further scrutiny of Table I reveals the magnitude of the winter inversion does not systematically adjust with the monthly average air temperature, e.g. in July 1993 the ECPAWS is 1.2°C colder than UWAWS compared to 0.6°C in August although August is the colder month at both sites. In addition, it is also evident in Fig. 2 that the frequency of days with inversions is similar in both months. The lack of dependence of surface air temperature on surface inversion strength is not unexpected as such inversion development is closely tied to wind speed in Antarctica. Unfortunately, AWSs in Antarctica do not provide generally reliable wind speed (and direction) data during winter due to the periodic riming of wind vanes (University of Wisconsin 1993). Thus, no simple method exists for adjusting daily UWAWS temperature data to obtain "proxy" daily values for FB.

Another way to obtain proxy FB data is to average the UWAWS data over a specified interval and adjust it to take into account the derived climatological inversion strength. The 1993 AWS comparison shows that inversion strength is too variable on monthly time scales to apply a general correction but a three month period is suitable. On a month-by-month basis the UWAWS-ECPAWS temperature difference from April–August 1993 varies by about 0.5°C from the overall average difference of 1.1°C for this period (Table I). Thus the accuracy of proxy FB averages calculated over the standard 3 month winter (June–August) season after allowing for the average inversion of 1.03°C between UWAWS and FB (allowing for the height difference between ECPAWS and FB) ought to be to 1°C. These FB proxy winter season averages have been obtained using all available UWAWS data in the period 1986–93 apart from 1988 when the winter UWAWS data have been found to be erroneous (Appendix B). In this way the winter season average temperature record for FB has been extended to 14 years (Appendix A). It is shown later that all but two of the FB proxy winter average temperatures lie within the range of the station-based estimates thus lending confidence in the method. At least one of the two outliers can, as noted below, be accounted for by the extreme conditions present in one year in the WAP. Given the somewhat limited accuracy of the proxy FB winter season averages, however, long-term temperature trends at FB are only worked out for the summer period based entirely on station data.

Data quality-control and handling

Details of data quality-control checks and of the effect of relying on twice-daily observations are given in Appendix B. Given the occasional incompleteness of the FB data as well as UWAWS data collected from the GTS, monthly average temperatures for both locations have only been calculated in those cases with at least 23 days of observations. In the case of seasons a minimum of two months with at least 23 days of observations have been used to compute averages along with data for the third month as long as there at least 15 days with observations. This procedure was chosen to obtain as reliable an estimate of seasonal air temperature as possible and was followed in three individual seasons. Long-term monthly means were substituted in another five months when data were lacking or insufficient. Equivalent seasonal averages have been obtained for FAR and MGB. The absence of data for MGB in 1961 and gaps in the FB winter record mean that overlapping winter average temperature data for FB and other WAP stations are available for just 13 years compared to 17 for summer.

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Mean climatic conditions

Latitudinal temperature gradient

Mean summer (December–February) season temperatures at FAR and MGB are comparable but a latitudinal temperature gradient of 0.6°C (deg. lat.)$^{-1}$ exists between MGB and FB (Tables II & III). By comparison a poleward reduction in temperature appears throughout the WAP in winter; the latitudinal gradient between FAR and MGB is 0.9°C (deg. lat.)$^{-1}$ but rises to 1.9°C (deg. lat)$^{-1}$ between MGB and FB (this value is reduced by only 0.3°C if the above-noted average winter inversion between FB and UWAWS is not taken into account). A plot (Fig. 3) of the annual variation of air temperature for all stations including UWAWS (extracted from all the original data for this station excluding the problematic data of 1988) indicates that MGB temperatures are within 2°C of those at FAR in every month except June. By contrast, temperatures at UWAWS are 6°C lower than MGB in all months of the year except December and January. In addition, the mean monthly temperature at UWAWS is below -10°C between March–October but is only this cold in July and August at MGB and in no period at FAR.

The lack of readily available meteorological data for the region south of MGB to date has made it difficult to assess the homogeneity of the climate of the WAP as a whole. Attempts to do this have rested on limited surface air temperature data, including those from FB for single years (Pearce 1963, Sanderson 1978), and on more widely available proxy annual average temperature information based on extensive 10 m snow temperature measurements (Martin & Peel 1978, Reynolds 1981, Morris & Vaughan 1994). The FAR-MGB winter temperature gradient derived here is directly comparable to the annual average latitudinal gradient found from snow temperature information. It follows, however, that the snow-based measurements hide the negligible summer latitudinal air temperature gradient between these two locations. More significantly, however, the winter gradient between MGB and FB is almost double the annual average snow-based value, a fact that points to a distinct climatic transition south of MGB at this time of year. The distinctiveness of the climate of the George VI Sound at this time is also borne out by the depression of temperatures at UWAWS relative to MGB over an extended period from late autumn to mid-spring (Fig. 3). FB data show the same characteristics. Hence winters in the George VI Sound are longer and colder than could be deduced either simply by extrapolation from FAR and MGB data or from 10 m snow temperature information for the Peninsula as a whole. It is thus deduced that the climate of the WAP as a whole is less homogeneous than considered previously. Other aspects of the mean climate of FB supporting this view are now examined.

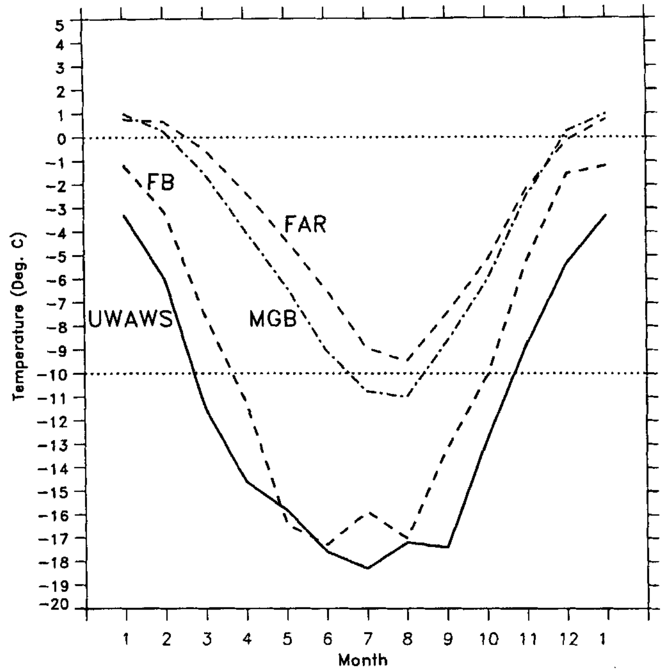

Fig. 3. The annual variation of surface temperature (°C) at UWAWS (solid line), FB (thick dash), MGB (dash-dot) and FAR (dashed). Note that data for FB and UWAWS are for separate periods and that sample sizes for both are limited compared to other stations. FB autumn and spring monthly temperatures are also based on a limited sample.

Table II. Mean, standard deviation (s d) and range of summer (December–February) and winter (June–August) season temperature (°C) at FB, MGB and FAR. FAR statistics are for the period from 1961 onwards to allow direct comparison to Fossil Bluff. Use of the longer period of daily observations available from 1956 onwards for Faraday yields comparable statistics for the summer season but the winter mean temperature (-8.9°C), standard deviation (3.5°C) and range (14.2°C) differ and reflect colder winters in the 1950s. Bracketed winter s d values are for the 13 winters of overlapping data for all stations.

Season/Station	Mean (°C)	s d (°C)	Range (°C)
Summer			
Fossil Bluff	-1.9	0.9	3.0
Marguerite Bay	0.5	0.7	3.0
Faraday	0.4	0.6	2.5
Winter			
Fossil Bluff	-17.5	3.0 (3.1)	10.2
Marguerite Bay	-10.3	3.0 (3.3)	14.0
Faraday	-8.3	2.9 (3.0)	10.9

Table III. Estimated summer (December–February) and winter (June–August) latitudinal temperature changes (°C (deg lat)$^{-1}$) for different transects of the West Antarctic Peninsula.

Transect	Summer temperature change (°C (deg lat)$^{-1}$)	Winter temperature change (°C (deg lat)$^{-1}$)
Faraday–Marguerite Bay	0	0.9
Marguerite Bay–Fossil Bluff	0.6	1.9

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Winter–summer range and absolute monthly temperature

Inspection of Table IV reveals that the mean summer–winter temperature range at FB is 16.1°C with January being the warmest month and June the coldest. The range at MGB is 12°C and 10.3°C at FAR with the reduction mainly due to raised winter temperatures. Pearce (1963) has suggested the incidence of months with average surface air temperatures below -16.7°C (0°F) as a useful measure for depicting climatic conditions in the Antarctic Peninsula; 48% of winter months meet this criteria in the FB station record and 72 % of the UWAWS data. Elsewhere the values are 7% at MGB and 3% at FAR. Differences in wintertime conditions in the FB area also show up in Table V giving the frequency of monthly average temperatures in 5°C intervals; 26% of winter months at FAR and 49% at MGB experience temperatures of -10°C or lower compared to 95% at FB and 100% at UWAWS. In summer monthly average temperatures exceed 0°C in just over two thirds of observations for both coastal stations but only 10% at FB.

Previous comparative analyses (Pearce 1963, Morris & Vaughan 1994) of temperature data for individual years for FB and coastal stations in central and northern parts of the WAP yield conflicting views over the severity of the climate of FB. Morris & Vaughan (1994) highlight a marked increase in the annual temperature range at FB compared to further north based on one year of UWAWS data. In contrast, Pearce (1963) contends that the FB climate is not severe citing a dearth of months with average temperatures of -16.7°C (0°F) using data for 1961. Given that average temperatures in almost half of all winter months at FB and more than this at UWAWS remain below the Pearce (1963) threshold of -16.7°C and that the mean winter season temperature at FB (using station observations and estimated values derived from UWAWS data) is -17.5°C (Table II), it is clear that the FB climate is in fact severe compared to stations further north. Along with the infrequency of summer months with average temperatures above freezing at FB, present results suggest that the coastal climate at MGB is replaced by an essentially continental regime a few hundred kilometres to the south.

Interannual variability

Streten (1967), Limbert (1974) and King (1994) have all shown that the region of the WAP and the nearby South Shetland and South Orkney Islands exhibits high interannual temperature variability, with greater variability during winter than summer. Despite its southerly location and colder climate, temperature variations at FB show many similarities to those observed at its more northerly neighbours.

In summer the interannual standard deviation of summer season temperatures is less than 1°C at all WAP stations, including FB, and the extreme range of summer season temperatures is also comparable, varying between 2.5–3.0°C (Table II). Summer temperatures at FB and MGB (Fig. 4a) appear to be quite well correlated (r=0.6), although extreme summers at one station are not necessarily extreme at the other. For instance, the extreme warmth of the 1989–90 summer at MGB (temperature anomaly of +1.6°C) is reduced at FB (+1.3°C) while below-normal temperatures at FB in 1991/92 (-0.7°C) do not extend to MGB (+0.1°C).

In winter (Fig. 4b) the extreme range of seasonal average temperatures is 14°C at MGB but only 10.2°C at FB and the correlation coefficient between FB and MGB seasonal temperatures rises to 0.7 at this time. From Fig. 4b and Table VI it is clear that the one recorded anomalously warm winter (temperature >mean + 1 s d) at FB in 1971 is attended by similar conditions at MGB. Anomalously warm conditions are also found at MGB in the 1974 winter, the second warmest at FB. By contrast, cold winters (temperature <mean - 1 s d) at FB are not necessarily also cold at MGB. King (1994) derived a correlation coefficient of 0.95 between the FAR and MGB annual average temperatures. It thus appears that, while FB is often influenced by processes that drive temperature variations in more northern parts of the WAP, local meteorological conditions and/or those that obtain in the southern part of WAP in general can sometimes lead to temperature anomalies that are not experienced

Table IV. Mean air temperature in the warmest and coldest months and derived annual temperature range (°C) at FB, UWAWS, FAR and MGB.

Station	temp. in warmest month (°C)	temp. in coldest month (°C)	range (°C)
Fossil Bluff	-1.2	-17.3	16.1
UWAWS	-3.3	-18.3	15.0
Marguerite Bay	1.0	-11.0	12.0
Faraday	0.8	-9.5	10.3

Table V. Frequency (%) of occurrence of monthly average temperatures in 5°C classes for the winter season months June–August at FB, UWAWS and MGB. The number of cases is 21 for FB, 18 for UWAWS, 97 for MGB and 102 for FAR. Mean winter temperatures are -17.5°C at FB (based on observed and proxy data), -10.3°C at MGB and -8.3°C at FAR

Place	Below -25°C	-25/-20°C	-20/-15°C	-15/-10°C	Above -10°C
FB	0	23.8	47.6	23.8	4.8
UWAWS	5.6	16.6	50.0	27.8	0
MGB	0	3.1	10.3	35.1	51.6
FAR	0	0	8.8	17.6	73.5

Table VI. 3-way breakdown of years when winter average temperatures at FB and MGB are average, anomalously warm or cold (see text).

	FB cold	FB average	FB warm
MGB			
cold	87	69	-
norm.	75, 86	68, 70, 72 90, 92, 93	-
warm	-	74, 89	71

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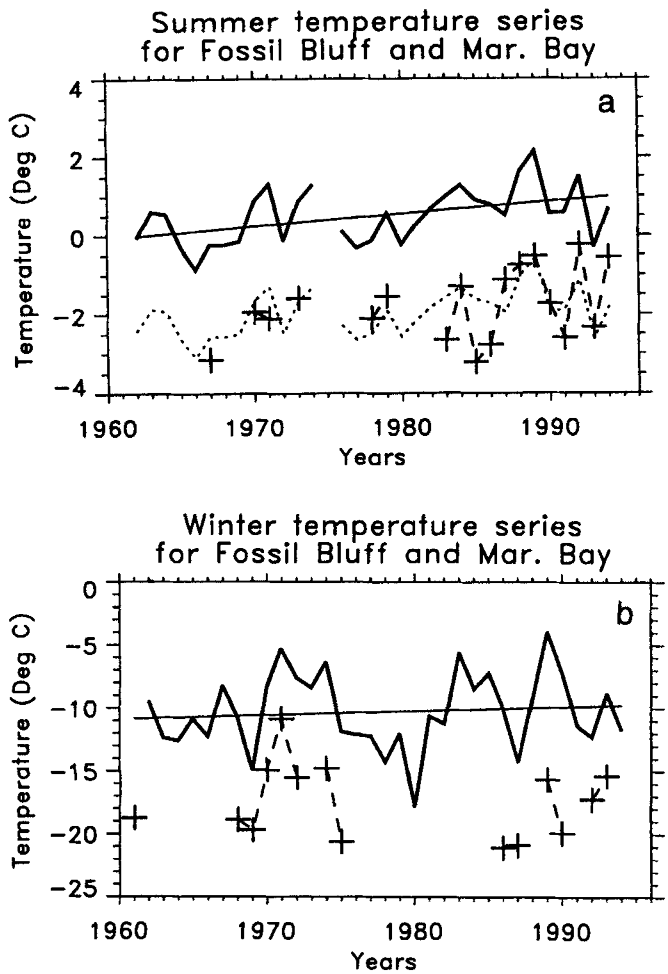

Fig. 4. Time series of **a.** summer and **b.** winter season temperatures for FB (dashed line and crosses) and MGB (solid line) with trend (°C a^{-1}) line superimposed for MGB derived for the period 1961 to 1994 for present purposes. The dotted line in **a.** is the summer temperature for FB as estimated by regression analysis of MGB data on FB data. This shows the imperfectness of the FB temperature estimates against the observed (see text). Note that there is no winter data for MGB in 1961 and that winter data is lacking for FB in many years. Each summer season starts in the year when December falls, e.g. the value for 1967 is for the period December 1967–February 1968. The summer season average for FB for 1989–90 has been estimated using data for the University of Wisconsin AWS that operates at the nearby Uranus Glacier (see text).

further north and, in particular, to depression of temperatures in some winters. This is consistent with the more continental climate regime found at FB.

A key feature of the interannual variability in air temperatures in the WAP and islands further north both on the annual time scale and outside of the summer period is that it systematically amplifies toward higher latitudes (Streten 1967, Limbert 1974, King 1994). To date, however, there has been no indication of whether this poleward increase is maintained south of MGB. Present results indicate that this is not so. Thus the standard deviation of winter temperature decreases from 3.3 to 3.1°C between MGB and FB in the 13 years of overlapping winter record for the two stations (Table II). Given that the second coldest winter at MGB in this 13 year overlap fell in 1987, the extreme proxy-based temperature for FB for this time would seem plausible. The same explanation may not be invoked in the case of 1986, the coldest winter in the FB record but again based solely on UWAWS data. The possibility, however, that local conditions in George VI Sound became dominant in controlling temperatures in the area at this time cannot be ruled out. Further inspection of the MGB and FB winter season temperature records (Fig. 4) and Table VI reveals that the reduced variability at FB again mostly stems from the fact that warm conditions at MGB do not always extend to the more southern station. Recalling that the range of extreme winter season average temperatures at FB also decreases between MGB and FB, these observations reinforce the finding that MGB and FB interannual fluctuations do not always go hand-in-hand and that the meteorological conditions at FB do in fact lead to damped interannual variability compared to stations further north. At the same time, however, the entire WAP is clearly a region of enhanced variability compared to the oceanic islands immediately to its north and, as noted by King (1994), also compared to the rest of the Antarctic continent.

Long-term change

A least squares linear fit to the FB summer season temperature data for the period 1967–94 produces a positive temperature trend of 0.4°C decade^{-1}. This compares with 0.3°C decade^{-1} at MGB and 0.2°C decade^{-1} at FAR for the same era. Autocorrelation is present in the FB summer data as with other air temperature records for the WAP (King 1994) and, owing to the incompleteness of the summer temperature record, it is not possible to determine the statistical significance of the summer trend. Positive temperature trends also appear in individual summer months and are greatest in January reaching 0.6°C decade^{-1}. In January, when average monthly temperatures are available for a total of 19 years (18 directly observed and one (1990) based on adjusted UWAWS data), serial correlation is not evident (the correlation between FB temperatures at 0 and 1 year lag for January is negligible at -0.12) and the temperature change is statistically significant (using Student t-test) at less than the 5% level. Scrutiny of Table VII reveals that the 1992–93 summer is the warmest at FB (-0.23°C) followed by 1989–90 (based on FB data for February 1990 and UWAWS data for December 1989 and January 1990 that have been adjusted using observed summer lapse rates between FB and UWAWS). The sequence differs for MGB where the 1989–90 summer is warmest and 1992–93 only the third warmest. Likewise, the 1989–90 summer is the warmest on record at FAR (not shown). In addition, December

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Table VII. Ranking of the four warmest summers (December–February) at FB and MGB. Note that the FB value for 89/90 is an estimate taking station data for February 1990 and UWAWS data for December 1989 and January 1990 and adjusting the latter using observed summer lapse rates between FB and UWAWS.

	FB		MGB	
Rank	season	temp. (°C)	season	temp. (°C)
1	92/93	-0.23	89/90	+2.14
2	89/90	-0.53	88/89	+1.62
3	94/95	-0.56	92/93	+1.52
4	88/89	-0.75	71/72	+1.30

1992 is the warmest month on record at FB (Table VIII) followed by January 1995. February 1990 is also the warmest February on record at FB. Moreover, all but one summer month with an average temperature above 0°C at FB falls in the period since 1989, a fact that is remarkable given the above-noted climatological rarity of this condition at FB.

Previous studies (Raper *et al.* 1984, Jones *et al.* 1986, Jones 1990, Jacka 1990, Weatherly *et al.* 1991, Chapman & Walsh 1993, King 1994) of WAP station data north of 68°S have detected an all-year-round systematic rise of surface temperature since the mid-twentieth century but give no indication of whether such behaviour is representative further to the south. Present results do point to the existence of a systematic temperature rise in this area at least during the warmest part of the year. This summer warming is highlighted in the period 1987–94 that, apart from a couple of years, is one of prolonged summer warmth at FB not seen prior to this time. The same prolonged period of summer warmth also shows up in MGB. In an analysis of the MGB and FAR air temperature records up to 1990 Morrison (1990) also highlights the unusual warmth at the end of the period and reports that 1989 was the warmest year on record at both MGB and FAR. Present results thus point to the existence of secular climatic change affecting the entire WAP at least during the warmest part of the year.

Despite the general accord in long-term summer air temperature changes at FB with those of stations to the north it is again clear that air temperature behaviour at FB does not entirely mirror that at MGB. The delay of several years in the occurrence of greatest summer warmth at FB and, in particular, the greater rate of warming at the inland site than elsewhere in the WAP were both unexpected. These observations thus provide further evidence of differences in meteorological conditions in the vicinity of FB compared to the rest of the WAP. A contribution to warming at FB in summer – but not in winter at this station or at any time of year at the the more northern stations that are not located on or adjacent to ice shelves – likely comes from modification of the surface albedo by surface melting of the adjacent George VI Sound ice shelf. Meltwater reduces surface albedo that then leads to a positive radiation-air temperature feedback. Such melting has been increasingly observed in summers in the FB area. It thus does seem that local conditions could favour increased

Table VIII. Ranking of the four warmest summer months (December, January and February) at FB and MGB.

	FB		MGB	
Rank	date	temp. (°C)	date	temp. (°C)
1	12-92	+0.86	2-90	+2.67
2	1-95	+0.61	1-90	+2.53
3	1-89	+0.14	1-72	+2.07
4	2-90	+0.13	1-89	+2.04

warming at FB in summer compared to elsewhere in the WAP. Other work (Vaughan & Doake 1996) shows no recent change in the extent of the George VI ice shelf but also the first recorded retreat of the Wilkins ice shelf on the west side of Alexander Island in the late 1980s and early 1990s, i.e. around the time of commencement of unusually warm summers at FB and MGB. Taking the present results as well findings from other studies together, it is thus surmised that there has been a secular change in climate in summer along the entire length of the WAP within the last three decades. Unfortunately, the data are not adequate to determine if this has also been happening at other times of the year.

Conclusions

Construction of a surface air temperature record for FB based on winter and summer observations collected since the early 1960s and supplemented by data from a nearby AWS has made possible a detailed analysis of some of the mean and time-varying characteristics of the climate of the southern part of the WAP for the first time. The analysis reveals a number of important similarities and differences between FB and stations further north, one of the main findings being that its climate can be described as continental rather than maritime as in more northern parts of the WAP. This is evident in a longer and colder winter so that winter season average temperatures seldom approach those frequently encountered further north. As a result, except during the short summer, the WAP as a whole displays a lack of homogeneity in its climate that does not show up in studies based on snow temperature data, that can only provide a proxy estimate of the annual mean temperature.

Despite evident differences in long-term climatic conditions between FB and other parts of the WAP, the region as a whole is one of enhanced interannual variability. The analysis shows for the first time that winter temperature variability appears to peak to the north of FB in the Marguerite Bay area but winter and summer temperature variations at FB do often follow those that appear elsewhere such that warm conditions at FB also appear at MGB. By contrast, the reverse does not apply so that warm conditions can develop at MGB but not at FB pointing to important differences in the controls on air temperature at the southern station. On multi-decadal time scales, the FB station data have also revealed that the previously reported warming in central and northern parts of the WAP extends at least as far south as 71°S in the warmest part of the year. The most pronounced warming at FB in summer appears to have been delayed compared to central and northern parts of WAP so that the warmest summers on record have all occurred in the last few years. As a result, the notion of a secular climatic change having affected the entire WAP since at least the 1960s does in fact appear to be borne out.

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Appendix A

Tabulation of summer and winter season average temperatures

The following tables give winter (June–August) and summer (December–February) season average temperatures for FB and other stations used in this study. FB winter season values from 1986 onward (italicized) are based on UWAWS data and these have been adjusted (see main text) to allow for a climatological inversion in the George VI Sound at this time of year. 1°C should be added back to these values to obtain the temperatures for UWAWS. The bracketed summer season value for FB for 1989/90 (not used to derive summer season statistics) has been estimated using data from the University of Wisconsin AWS that operates at the nearby Uranus Glacier.

Appendix Table I. Average winter (June–August) and summer (December–February) temperatures (°C) for Fossil Bluff. Proxy winter values are shown italicized. The bracketed value shown for the summer of 1989–90 is also a proxy (see text). This was not included in the analysis but is shown for information.

Year	JJA	DJF	Year	JJA	DJF
1961	-18.8	.	1983	.	-2.7
1967	.	-3.2	1984	.	-1.3
1968	-18.9	.	1985	.	-3.2
1969	-19.7	.	1986	*-21.1*	-2.8
1970	-14.9	-1.9	1987	*-20.9*	-1.1
1971	-10.9	-2.1	1988	.	-0.8
1972	-15.5	.	1989	*-15.7*	[-0.5]
1973	.	-1.6	1990	*-19.9*	-1.7
1974	-14.8	.	1991	.	-2.6
1975	-20.6	.	1992	*-17.2*	-0.2
1978	.	-2.1	1993	*-15.4*	-2.3
1979	.	-1.6	1994	.	-0.6
Mean				-17.5	-1.9

Appendix Table II. Listing of winter (June–August) and summer (December–February) temperatures (°C) for Faraday and Marguerite Bay used in the analysis.

	Faraday		Marguerite Bay	
Year	JJA	DJF	JJA	DJF
1960	.	1.03	.	.
1961	-10.70	-0.24	.	.
1962	-7.71	-0.01	-9.46	-0.06
1963	-10.35	0.38	-12.38	0.61
1964	-10.31	0.39	-12.59	0.54
1965	-10.25	-0.26	-10.88	-0.31
1966	-11.56	-0.79	-12.24	-0.87
1967	-7.70	-0.17	-8.26	-0.23
1968	-6.71	-0.18	-10.69	-0.23
1969	-10.76	-0.13	-14.97	-0.15
1970	-7.01	0.81	-8.40	0.88
1971	-3.96	1.09	-5.28	1.30
1972	-5.87	0.59	-7.58	-0.14
1973	-7.43	1.38	-8.41	0.87
1974	-4.76	1.03	-6.37	1.29
1975	-8.18	0.18	-11.87	.
1976	-12.66	0.70	-12.11	0.12
1977	-11.27	-0.32	-12.21	-0.32
1978	-11.85	-0.13	-14.26	-0.13
1979	-9.25	0.27	-12.02	0.55
1980	-14.04	-0.07	-17.88	-0.23
1981	-9.43	0.04	-10.63	0.29
1982	-8.09	0.81	-11.24	0.69
1983	-3.76	0.58	-5.60	0.99
1984	-5.97	1.50	-8.50	1.27
1985	-5.27	1.24	-7.24	0.90
1986	-7.50	-0.12	-10.17	0.79
1987	-13.76	0.41	-14.27	0.51
1988	-6.46	1.27	-9.10	1.62
1989	-3.14	1.65	-3.94	2.14
1990	-5.05	0.41	-7.23	0.56
1991	-6.89	-0.06	-11.39	0.58
1992	-9.95	1.25	-12.28	1.52
1993	-5.97	0.23	-8.83	-0.30
1994	-7.98	0.72	-11.74	0.69

Appendix B

Data quality-control

Both the FB station and UWAWS data have been quality-controlled. No problems were found in the station data for FB from scrutiny of the daily data, e.g. range checks, or by comparison of derived monthly temperature anomalies with those from MGB. On the other hand, the UWAWS temperature signal is damped during much of 1988 including most of the winter period. This problem shows up in a lowering of the standard deviation of daily temperature worked out for every month. The magnitude of the standard deviation exhibits a well-defined annual cycle in all years at FB, FAR and MGB and all but one at UWAWS with highest values in winter. In 1988 this behaviour is lacking in UWAWS data which has thus been excluded from the analysis.

The impact of reliance on twice-daily observations for obtaining monthly and seasonal averages for FB has also been determined. Monthly averages derived using two (every 12 hours), four (every 6 hours) and eight (every 3) observations for FAR and MGB agree to within 0.5°C in all cases but it should be noted that averages based on two values are lower than those worked from four or more values. A similar exercise using available daily data both for UWAWS for three Julys and for FB for 14 winter months with contrasting warm and cold conditions also yielded no significant differences. At FB averages based on varying observation frequency differed by not more than 0.7°C in all but one of the 14 cases. Similarly, agreement to within 0.5°C has been found in averages derived for FB for eight out of nine summer months.