Antarctic Science 6 (4): 529–535 (1994)

Snow surface temperatures in West Antarctica

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Abstract: Snow temperatures measured at around 10 m depth over the period 1957–1992 have been used to derive a map of mean annual snow surface temperature corrected to sea level over the Antarctic Peninsula and Filchner-Ronne Ice Shelf. Multiple linear regression analysis has been used to calculate rates of change with latitude, longitude, altitude and time, for data to the west and east of the topographic divide running along the spine of the Antarctic Peninsula. Climate warming on the Filchner-Ronne Ice Shelf follows the trend observed at Halley Bay, a coastal station nearby. High spatial variability leads to uncertainty in the temporal trend for mean annual snow surface temperature in the Antarctic Peninsula but there is some indication that the large trends observed at Faraday and Marguerite Bay, two stations on the west coast of the peninsula, are attenuated inland.

Received 16 September 1993, accepted 14 July 1994

Key words: ice sheets, temperatures, climate

Introduction

In areas where there are no meteorological records the mean annual air temperature at the snow surface is commonly estimated by assuming that it is the same as the snow temperature measured at a depth of 10 m. The accuracy of this estimate depends on: 1) the structure of the snow; 2) the pattern of air temperature variation within the year and; 3) whether there is any long term temperature change. Maps of snow surface temperature in West Antarctica have been published by Shimizu (1964), Thomas (1976), Martin & Peel (1978) and Reynolds (1981). They are based on borehole measurements, not all taken at 10 m depth, and made at different times of the year, over a period of some thirty years. Although the spatial temperature distribution over the continent has been reasonably well established by these authors, the accuracy of the surface temperature estimates has not been sufficient to allow detection of temporal change. Raper *et al.* (1984) have produced an areally weighted time series of Antarctic surface temperature for the period 1957–82 using air temperature measurements. The annual average time series shows a warming of 0.029°C a^{-1} i.e. an increase of 0.9°C over 30 years. This is comparable to the uncertainty in the estimates of surface temperature derived by previous authors from borehole data. It is the purpose of this paper to present an updated map for the Antarctic Peninsula and the Filchner-Ronne Ice Shelf using a more precise method for determining mean annual surface temperature from borehole data (Morris 1991) and to examine whether there is any evidence of long-term change over the region. Fig. 1 shows the location of places and features mentioned in the text.

Derivation of surface temperatures

It is assumed that the accumulation, densification and metamorphosis of polar snow is controlled by the local climate in such a way, that the snow cover at sites with the same surface temperature history will develop broadly the same physical properties. In particular, it is supposed that the variation of thermal diffusivity in the upper 10 m of snow will be similar for sites of similar history. In this case the variation of snow temperature, T, with depth, d, and time, t, will be similar for all sites with the same surface temperature history. Given that lateral temperature gradients are extremely small compared to vertical temperature gradients, the temperature in a particular borehole may be expressed in terms of the mean annual surface temperature at that site, T_m, the amplitude of the first harmonic of the annual temperature wave at the surface at that site, a, and a function F which is defined by the equation

$$T(d,t) = T_m + a\,F(d,t) \qquad (1)$$

T_m and a are constants, (cf. Sanderson 1978), characterizing the variation of surface temperature over a particular period of time. The well established method of using borehole measurements at 10 m to estimate T_m is based on the assumption that $F \rightarrow 0$ as $d \rightarrow 10$ m and requires that advection by meltwater or heavy snowfall is not significant (see for example Paterson (1981) p.186). In this paper, a further empirical step is taken: field measurements of $T(d,t)$, T_m and a at four sites in the Antarctic are used to deduce typical examples of $F(d,t)$. It is then assumed that these examples can be used to estimate F for borehole sites elsewhere in the Antarctic. If F can be estimated for a given site a borehole temperature profile measured on a given day of the year can be used to determine both T_m and a. If the snow temperature has only been measured at one depth, both F and a must be estimated to determine T_m.

Measuring 10 m temperature provides a value of T_m associated with a period of a few years up to the date of the measurement. (The lag time for a sinusoidal variation in surface temperature of period 30 yr is *c.* 2.5 yr at 10 m,

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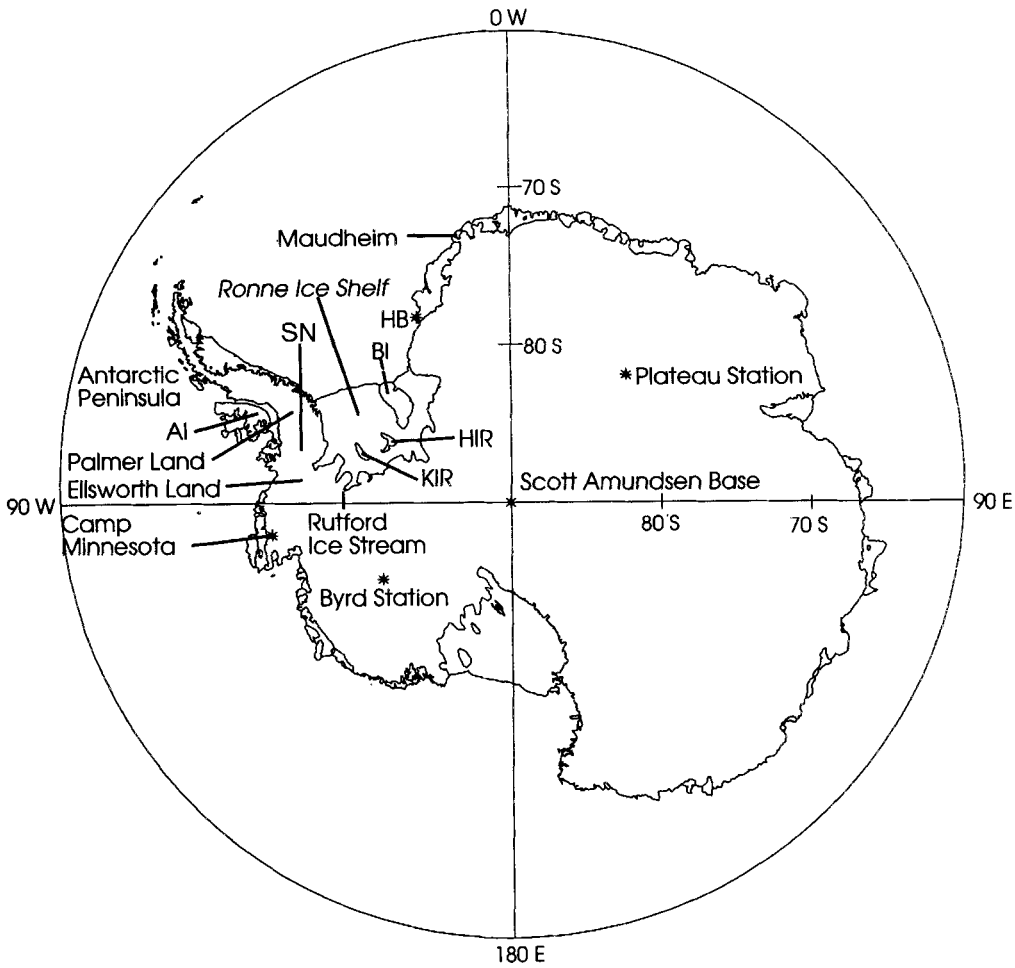


Fig. 1. Map of Antarctica to show the locations of Alexander Island (AI), Berkner Island (BI), Halley Bay (HB), Henry Ice Rise (HIR), Korff Ice Rise (KIR), Ski Hi Nunataks (SN) and other places mentioned in the text.

Table I. Meteorological observing stations.

Station	Lat/°S	Long/°W	Alt/m	T_a/°C	a/°C	Date
Eduardo Frei	62.25	58.93	10	-2.4	4	1970–84
Bellingshausen	62.20	58.93	16	-2.9	4	1947–84
Arturo Prat	62.50	59.68	5	-2.7	4	1966–84
Esperanza	63.40	56.98	8	-5.8	6	1953–77
Bernardo O'Higgins	63.32	57.90	10	-4.2	4	1963–76
Marambio	64.23	56.72	198	-9.1	7	1971–83
Admiralty Bay	62.05	58.40	19	-2.4		1970–78
Deception	62.98	60.57	8	-2.6		1970–78
Hope Bay	62.40	56.98	11	-5.59		1970–78
Palmer Station	64.77	64.08	20	-3.2		1974–80
Faraday	65.25	64.27	10	-3.54	5	1970–78
Rothera	67.57	68.13	20	-6.36	7	1977–86
Adelaide	67.77	68.92	14	-4.7		1970–80
Fossil Bluff	71.33	68.28	55	-11.1	11	1968
Halley	75.52	26.62	29	-18.19	10	1970–80
Eights	75.30	77.12	450	-25.9		1964–65
Ellsworth	77.72	41.12	43	-23.4		1957–58
Siple Station	75.93	84.25	1054	-25.5	12	1982–83
Plateau	79.30	-40.50	3624	-59.8	18	1967–68
Amundsen-Scott	90.00	0.00	2835	-49.3	18	1957–85
Byrd	80.02	119.53	1530	-28.1	10	1957–69
Maudheim	71.05	10.93	37	-17.61	11	1950–51

Paterson (1981)). However, successive borehole measurements at the same site can of course reveal long term changes in mean annual temperature.

Meteorological data from Antarctica

T_m is known and an estimate of amplitude a can be made at sites where air temperature is recorded throughout the year. Table I lists the meteorological observing stations in West Antarctica south of 62°S and between 10°W and 110°W. (Plateau Station has also been included in Table I for convenience).

These stations record or have recorded screen temperature at a fixed height, nominally 1.5 m, above the snow surface. For temperatures warmer than -40 °C the mean annual screen temperature should be within 0.5 °C of the mean annual surface air temperature (Loewe 1970). The average mean annual temperature and the estimate of amplitude a have been determined from the tables of monthly mean temperatures given by Jones & Limbert (1989) or are given in Macdowall (1964), Dalrymple *et al.* (1966), Loewe (1970), Sanderson (1978) and Reynolds (1981). Table II shows Automatic Weather Stations (Stearns & Weidner 1990) in the same area which record air temperature at a nominal height of 3 m which decreases as the station is buried by snow. The mean

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annual temperature and amplitude a for an example year (1989) have been estimated from tables of monthly mean temperatures given by Keller *et al.* (1990).

Fig. 2 shows the departures of monthly mean screen temperature from the annual mean (T_a) for some example stations. The more southerly stations show an asymmetric variation, the so-called "coreless" winter. A key to this behaviour is given by an examination of solar radiation, which has a major influence on air temperature. Between the South Pole and the Antarctic Circle the annual variation of insolation is a truncated sinusoidal curve with a flat section of zero insolation during the winter. The insolation curve can be described by the the sum of two Fourier components with amplitudes A_1 and A_2. The ratio A_2/A_1 varies from 0 at the Antarctic Circle to 0.42 at the Pole. As it increases, so the typical polar annual variation curve develops with a flattened broad region in the winter and a strong narrow peak in the summer.

The amplitude of the first harmonic of the annual temperature wave varies from about 4°C at the northern end of the Antarctic Peninsula to 18°C at the pole. In the south part of the Antarctic Peninsula and on the Filchner-Ronne Ice Shelf a is around 11°C. The uncertainty in estimation of a for a site where no air temperature measurements have been taken is around 2°C. The difference between the values of a for screen and surface temperature at a given site (which arises because the temperature gradient between surface and screen is stronger in winter) is less than 0.5°C and therefore does not add significantly to the uncertainty.

Measured snow temperature variations

The function F is known at sites where snow temperatures have been measured at different depths throughout the year. Data from Halley Bay (Macdowall 1964), Amundsen-Scott Station (previously South Pole Station, Dalrymple *et al.* 1966), Plateau Station (Weller & Schwerdtfeger 1977) and Maudheim (Dalrymple *et al.* 1966) are shown in Fig. 3. The temperatures are shown as deviations from the mean annual surface temperature normalized by the amplitude of the first harmonic of the annual temperature wave at the surface, i.e. the function plotted is F as defined in equation (1). The shape of the curve varies with latitude. The Maudheim and Halley curves are similar (Fig. 3a) whereas a considerable difference is apparent between the Maudheim and Amundsen-Scott curves (Fig. 3b).

The nomogram

For sites in the Antarctic Peninsula and on the Filchner-Ronne Ice Shelf, where snow temperatures have not been measured, it is suggested that F can be estimated by using Fig. 3c as a nomogram (Morris & Vaughan 1991). For a given day the value of F at a given depth can be determined by interpolation between the Plateau Station or the Maudheim curves.

Table II. Automatic weather stations

Site	Lat/°S	Long/°W	Alt/m	T_a / °C	a / °C	Date
Uranus Glacier	71.43	68.93	780	-10.9	7	1989
Cape Adams	75.00	62.50	25	-21	8	1989
Larsen Ice Shelf	66.97	60.55	17	-12	5	1989
Siple Station	75.90	83.92	1054	-24.3	10	1989

For sites on the Filchner-Ronne Ice Shelf and in Ellsworth Land the best estimate of F at the moment is given by the Plateau Station data although snow temperature variations are being recorded at a site on the ice shelf and may be available in 1994 (K.W. Nicholls, personal communication 1991). In Palmer Land the Maudheim curves give a better estimate of F. Note that, as soon as the summer air temperatures rise above the melting point, the shape of the snow temperature curves will change substantially, so the Maudheim curves cannot be applied when the mean annual temperature is warmer than around -11°C.

Data from boreholes

A database of borehole temperature data for the Antarctic Peninsula and Filchner-Ronne Ice Shelf is being compiled at BAS under the auspices of the international Filchner-Ronne Ice Shelf Programme (FRISP). Fig. 4 shows the sites for

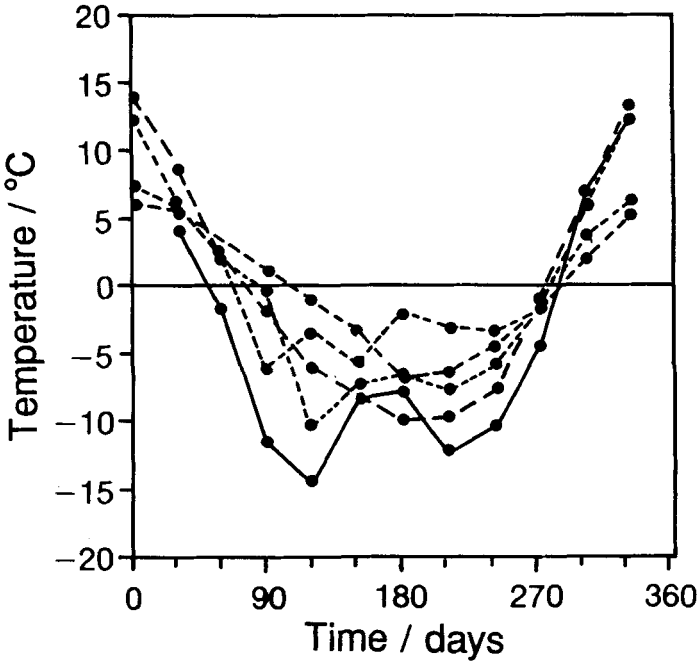


Fig. 2. Deviation of the monthly mean air temperature from the annual mean for Cape Adams Automatic Weather Station (solid line), and Halley, Rothera, the Uranus Glacier AWS and Siple Station (decreasing length of dash).

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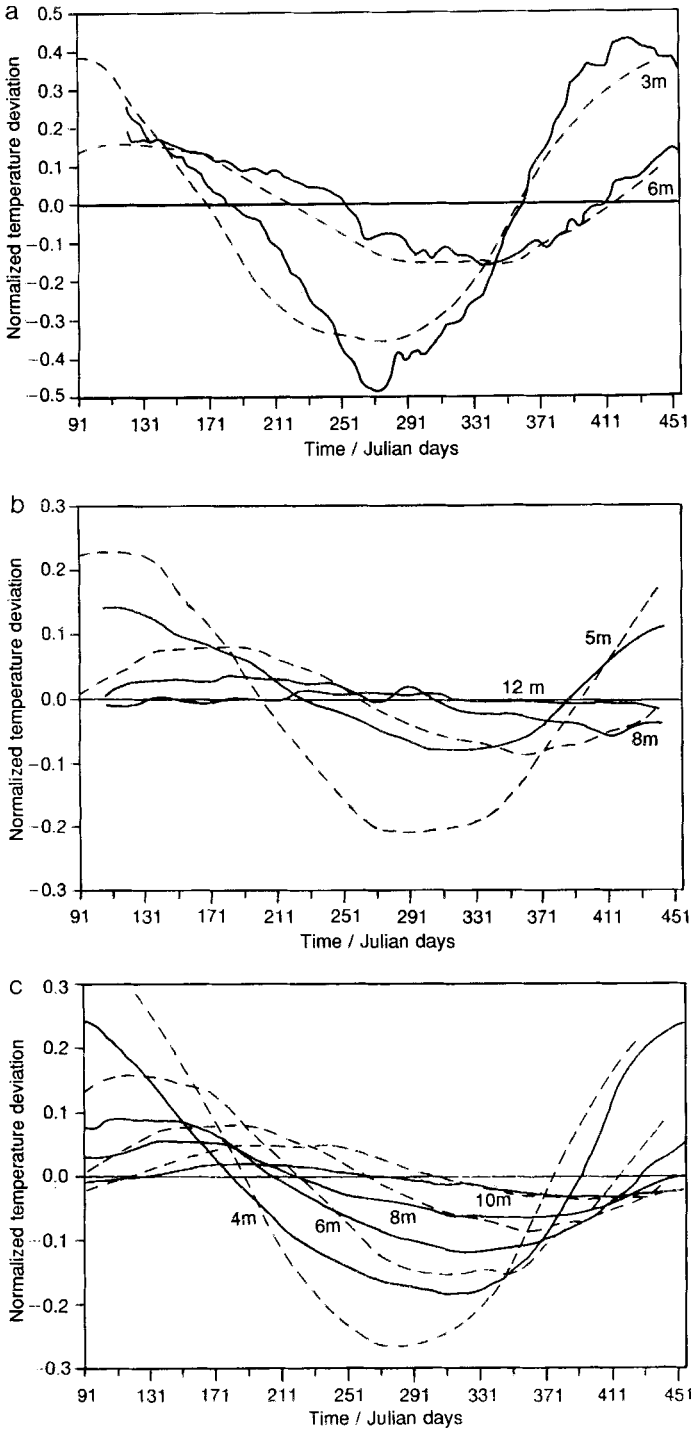


Fig. 3. Normalized deviation of snow temperature from the mean annual snow surface temperature. **a.** Data from Maudheim (dashed line) and Halley Bay (solid line). **b.** Data from Maudheim (dashed line) and South Pole Station (later Amundsen-Scott Station, solid line). **c.** Data from Maudheim (dashed line) and Plateau Station (solid line).

which data have been obtained. So far 238 measurements covering the period 1957–92 have been extracted from published and unpublished sources but there are probably further data to be found, especially from Argentinian and Chilean sources.

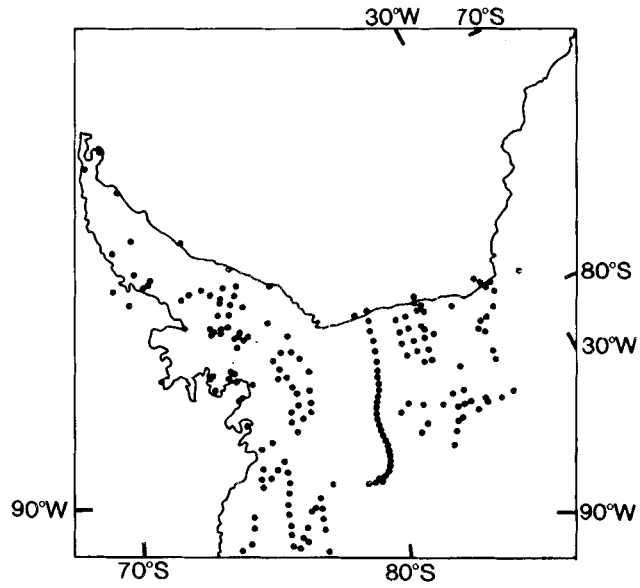


Fig. 4. Sites at which borehole temperatures have been measured. The generalized coast line is schematic only and does not show Adelaide Island which is disconnected from the continental ice sheet.

Ellsworth traverses 1957–58, 1958–59

Early snow temperature measurements on the Filchner-Ronne Ice Shelf were made by US parties (Aughenbaugh *et al.* 1958, Godwin 1959) using a Leeds and Northrup thermohm left in the borehole for at least 2 hours. The depth of the borehole (usually not 10 m) is given explicitly in the record of the US data, as is the date of the measurement, so it is possible to calculate T_m from the measured $T(d,t)$ using the appropriate value of F from the nomogram and an estimated value for a of 11°C. Corrections of up to 0.5°C are required for some of the data from shallow boreholes.

Ellsworth Highland Traverse 1960–61

This traverse covered 2270 km from Byrd Station to Camp Minnesota. Every 45 km a 2 m or 3 m pit was dug and a core taken from the bottom of the pit to 10 m below the surface. The 10 m temperature was again measured by a Leeds and Northrup thermohm set in the drill hole for at least 2 hours. The exact depth of the borehole is not recorded in the published paper (Shimizu 1964) so for the moment it has been taken to be the nominal value of 10 m. Our assumption is that the depth would have been recorded if the drillers had failed to reach at least 9 m and that drilling would not continue past 10.5 m. T_m has been calculated using $a = 13$ °C and is usually about 0.3°C warmer than the borehole temperature using the nominal depth of 10 m. Variation in depth from 9 m to 10.5 m produces a change in the correction of less than 0.1°C.

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Table III. Rates of change of mean annual temperature

Data set	Rate of change latitude/ °C deg^{-1}	Rate of change with longitude/ °C m^{-1}	Rate of change altitude/ °C a^{-1}	Rate of change with time	r^2	n
All sites	1.99 ± 0.08	0.002 ± 0.018	-0.0057 ± 0.0005	-0.045 ± 0.021	0.76	205
Western sites	1.12 ± 0.30	0.148 ± 0.074	-0.0082 ± 0.0006	0.040 ± 0.076	0.77	70
Eastern sites	1.05 ± 0.05	0.066 ± 0.008	0.00008 ± 0.00036	0.014 ± 0.009	0.81	135
Western sites north of 74°S	1.11 ± 0.33	0.098 ± 0.081	-0.0082 ± 0.0007	0.006 ± 0.088	0.75	59
Eastern sites above 700 m a.s.l.	1.23 ± 0.16	0.115 ± 0.034	-0.0040 ± 0.0009	-0.015 ± 0.056	0.78	33
Eastern sites below 700 m a.s.l.	0.99 ± 0.04	0.073 ± 0.008	0.0039 ± 0.0008	0.027 ± 0.008	0.89	102

Antarctic Peninsula Traverse 1961–62

The same methods were used the following year (Shimizu 1964) on a traverse of 1709 km from Camp Minnesota to Ski Hi Nunataks. Again the exact depth of the borehole is not available so it has been taken to be 10 m exactly except at Ski Hi Nunataks and mile 796 station where the depths are taken as 21 m and 25 m respectively. Except for those deeper boreholes T_m calculated using a = 13 °C is about 0.3 °C warmer than the borehole temperature.

GAP network 1971–1992

As part of the Glaciology of the Antarctic Peninsula programme (GAP) a series of borehole temperature measurements were made by British Antarctic Survey scientists. Most of the boreholes were drilled to a nominal 10 m and the temperature measured at the bottom of the borehole after a thermocouple and/or a lagged thermometer had been left there overnight. Most of these temperatures were published by Martin & Peel (1978) and Reynolds (1981). It has been possible to go back to field note books held in the archives of BAS to determine the exact depth and date of each temperature measurement. As a bonus, some glaciologists (notably J. F. Bishop and J. G. Paren) made careful measurements of temperature profiles after the sensor had been left for 12-24 hours in the borehole and using these data it is possible to check the validity of the nomogram for F.

Filchner network 1984–1992

A network of measurements was made on the Filchner-Ronne Ice Shelf south of Filchner Station by a series of German parties (not neccessarily using the same instruments or measurement techniques) and a British group (Reinwarth *et al.* 1985, J.J. Bamber, personal communication 1992). We have assumed, pending further information, that the German temperatures were all measured at 10 m and have estimated mean annual temperature accordingly. The most recent British measurements are fully documented, and were made using a thermistor.

Rutford flowline 1986–87

Temperatures along a flow line running from the Rutford Ice Stream to the Ronne Ice Shelf Front were reported by Jenkins & Doake (1991). These were all measured exactly at 10 m using a lagged thermometer and have been corrected by us using a = 13°C.

South Ronne traverse 1990–91

Borehole temperature measurements on the southern Ronne Ice Shelf were made by Morris (1991) using a thermistor at depths between 7.4 m and 8.9 m. At two sites a German party repeated the measurement a year later (Oerter *et al.* 1990).

Analysis

Regression analysis using all data for which the time of observation is known (205 observations) produces coeffients as shown in the first line of Table III. The rate of change of temperature with altitude is -(0.0057 ± 0.0005) °C m^{-1}. Mean annual surface temperatures corrected to sea level using this value (i.e. a lapse rate of 0.0057°C m^{-1}) are plotted in Fig. 5. The contours are at 2.5°C intervals from -25°C to -7.5°C. Mean annual temperature decreases with increasing latitude, as expected, and the east side of the Antarctic Peninsula is clearly colder than the west side, as established by Martin & Peel (1978). Morris & Vaughan (1991) have established that, because of the strong winter inversion in the Filchner-Ronne Ice Shelf region, mean annual temperature increases with altitude by 0.005°C m^{-1} up to about 700 m a.s.l. so there are warm spots over Berkner Island, Henry and Korff ice rises and the edge of the Plateau south of Berkner Island. Not all of these are resolved in Fig. 5 but they may be seen in a more detailed map of temperatures over the Ronne-Filchner Ice Shelf in Morris (1991).

Fig. 6 shows the variation of mean annual surface temperature (corrected to sea level as above) with latitude. The data collected east and west of the topographic divide running along the spine of the Antarctic Peninsula and into Ellsworth Land form two groups with rates of change with latitude as shown in Table III.

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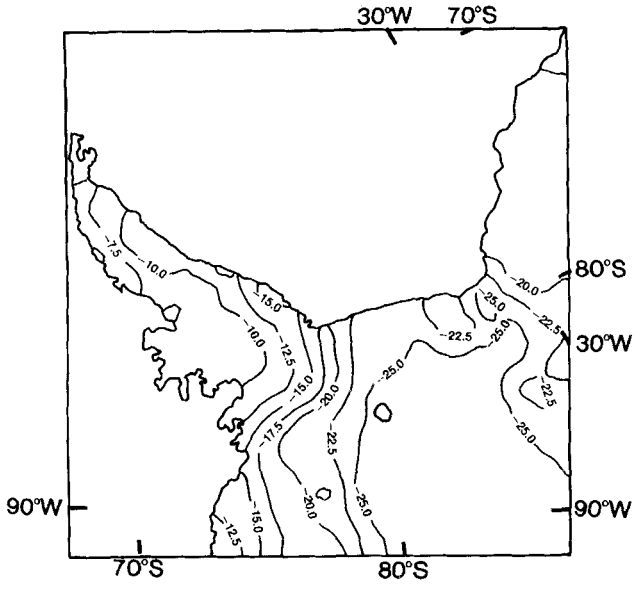


Fig. 5. Mean annual surface temperature (°C) corrected to sea level using a lapse rate of 0.006 °C m^{-1}.

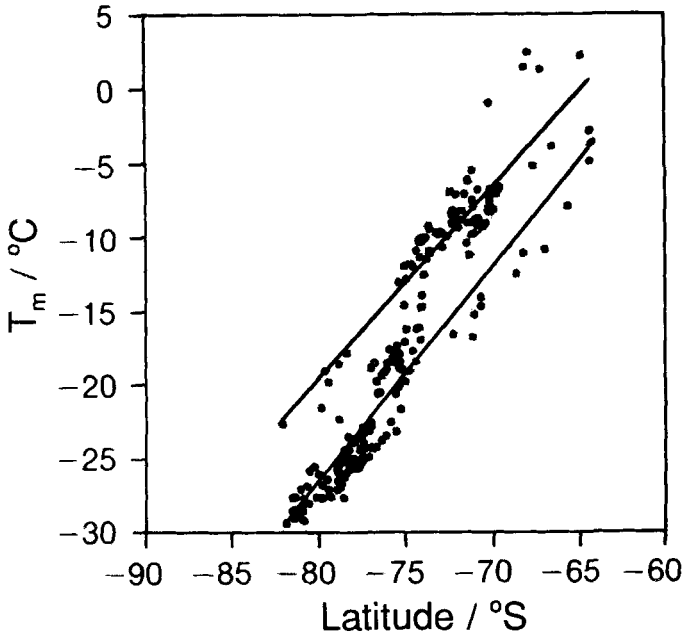


Fig. 6. Variation of mean annual surface temperature corrected to sea level with latitude. Separate regression lines for east and west coast data are shown. West coast temperatures are higher than east coast temperatures.

Separation of the data into western and eastern groups improves the fit but increases the uncertainty in the rate of change with time for the western sites. A further separation into data taken north of 74°S on the west side of the Antarctic Peninsula itself, data east of the divide but above the inversion layer, and data collected on the Ronne-Filchner Ice Shelf

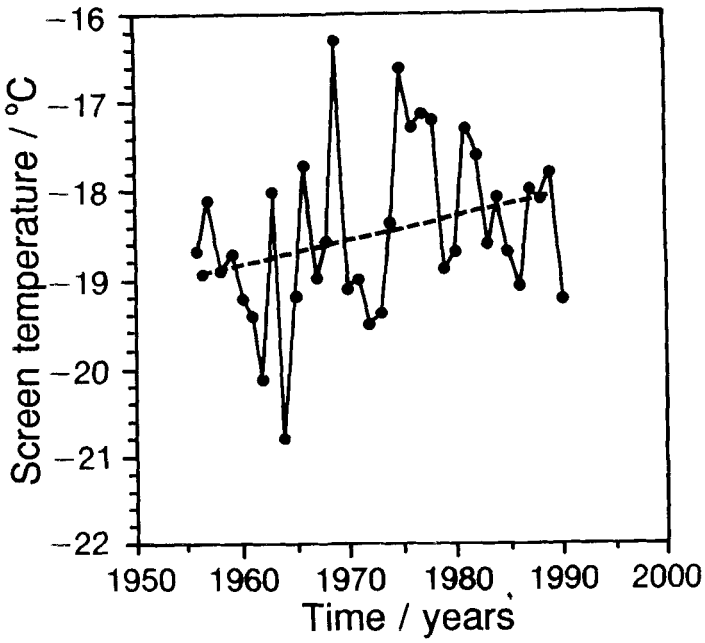


Fig. 7. Mean annual screen temperature at Halley Station.

produces improved fits and more believeable lapse rates. Fig. 7 shows mean annual screen temperature at Halley for 1956–1990. Over this period the warming rate is (0.032 ± 0.015)°C a^{-1} with $r^2 = 0.12$, as reported by King (1994). This is comparable to and compatible with the warming rate of (0.027 ± 0.008)°C a^{-1} obtained for the eastern sites below 700 m asl using borehole data whichwere mostly taken on the Ellsworth Traverses in 1957–59 (26 sites) or between 1984 and 1991 (59 points). It is clear from Fig.7 that if the mean annual temperature over the whole eastern area followed the pattern of variation observed at Halley we should expect a borehole data set weighted in this way to show a warming trend close to that deduced from the observed mean annual temperature series.

Of the 59 western sites north of 74°S only four form part of the 1960–61 Ellsworth Highland Traverse and eight of the 1961–62 Antarctic Peninsula Traverse. The rest are part of the GAP network and most of the measurements (42) were taken in the decade 1971–80. Given this temporal bias it is better to assume that spatial and temporal variability of T_m are independent in the statistical analysis. The spatial rates of change 0.967°C (deg. lat.)$^{-1}$, 0.109°C (deg. long.)$^{-1}$, -0.0079°C m^{-1} have been used to adjust all mean annual temperatures from western sites north of 74°S to an index site. The temporal rate of change of the adjusted temperatures is 0.016°C a^{-1}. This is rather less than the long-term trends in mean annual temperature observed over the last 50 years at two stations in the region, 0.067°C a^{-1}, at Marguerite Bay, and 0.056°C a^{-1}, at Faraday, reported by King (1994). It might be supposed that the warming rate deduced from the borehole data is less than the rate observed at the coastal stations because the borehole data are biased towards a decade when

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there was a cooling of -0.45°C a^{-1} at Faraday and -0.56°C at Marguerite Bay (J.C. King personal communication 1994). However this is not so; removal of the 1971–80 data reduces the warming rate still further to 0.008°C a^{-1}. King (1994) has suggested that the climate at the coastal stations, which are near to the sea ice edge, may be sensitive to small changes in its position. The climate at the inland borehole sites may be less sensitive so the warming trend is reduced. However, before this hypothesis can be pursued a more detailed mathematical analysis and more data are required. Further work will be focused on deriving more sophisticated models for the spatial and temporal dependence of T_m to make better use of the current data set, and on the aquisition of new data in Alexander Island and the southern part of the Antarctic Peninsula. In particular, it will be important to take into account the lag time between borehole temperatures and air temperatures when investigating the temporal variability.

The regression analysis of 10 m temperature data presented in this paper suggests that the temporal variations in mean annual temperature observed at Halley Bay can be applied to a broad area of the Filchner-Ronne Ice Shelf. This is a useful step forward in the study of climatic change in this region. There is some indication that mean annual temperatures over the Antarctic Peninsula north of 74°S do not show such large warming trends as the Antarctic Peninsula coastal stations. If this is true current estimates of the effect of global warming on sea level rise (e.g. Drewry & Morris 1992) which apply the station data to the whole region will have to be adjusted.

Acknowledgements

We should like to thank D. Mantripp, J. Bamber, K. W. Nicholls, R. Mulvaney and H. Oerter for providing unpublished borehole temperature measurements. A. Jenkins provided valuable background information on the Rutford flowline measurements. We are also grateful to C. Stearns, L.W. Morland and J.M.N.T. Gray whose careful reviews helped us to improve this paper.

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https://doi.org/10.1017/S0954102094000787 Published online by Cambridge University Press