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THE SPATIAL DISTRIBUTION OF 10 m TEMPERATURES IN THE ANTARCTIC PENINSULA

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Abstract. Temperatures from 10 m bore holes have been analysed to determine the spatial variation of mean annual surface temperature over the Antarctic Peninsula. In general there is a decrease in temperature of 0.84 deg per degree latitude southwards combined with an altitude lapse rate of 0.68 deg per 100 m. There is a sharp divide between the continental type climate of the east coast and a maritime climate of the central and western regions. Temperatures are approximately 7 deg lower along the east coast compared with those at sites of a similar altitude and latitude on the west.

Résumé. *La distribution spatiale des températures à 10 mètres de profondeur dans la Péninsula Antarctique.* Les températures prises dans des forages de 10 mètres de profondeur ont été analysées pour déterminer la variation dans l'espace des températures moyennes de surface dans la péninsule antarctique. En règle générale, il y a une diminution de température de 0,84 deg par degré de latitude en allant vers le Sud, combinée avec un gradient thermique de 0,69 deg par 100 m d'altitude. Il y a une nette séparation entre le climat de type continental de la côte Est et le climat maritime des régions centrales et occidentales. Les températures sont approximativement de 7 deg inférieures le long de la côte Est à celles de sites de même latitude et même altitude à l'Ouest.

Zusammenfassung. *Die räumliche Verteilung der 10 m-Temperaturen auf der antarktischen Halbinsel.* Zur Bestimmung der räumlichen Änderung der mittleren Jahrestemperatur an der Oberfläche der antarktischen Halbinsel wurden die Temperaturen in 10 m tiefen Bohrlöchern analysiert. Im allgemeinen lässt sich eine Abnahme der Temperatur von 0,84 deg pro Breitengrad nach Süden, überlagert von einer Abnahme von 0,68 deg pro 100 Höhenzunahme festellen. Es besteht ein scharfer Unterschied zwischen dem kontinentalen Klima der Ostküste und dem maritimen Klima der mittleren und westlichen Regionen. Die Temperaturen längs der Ostküste sind im Vergleich zu denen im Westen an Stellen ähnlicher Höhe und Breite etwa 7 deg niedriger.

1. Introduction

Temperature distribution within the upper layers of a glacier is largely governed by variations in the air temperature near the surface. Temperature changes throughout the year are propagated into the ice by heat conduction and the amplitude of these fluctuations decreases with depth. At 10 m depth the annual temperature variation is reduced to about 1% of that at the surface and it is generally accepted (Loewe, 1956) that temperature measurements made at this depth agree closely with the mean annual air temperature at the surface. Studies by the Norwegian–British–Swedish Antarctic Expedition at Maudheim (Schytt, 1960) demonstrated this agreement in the upper few metres; the amplitude of the whole-year wave at 10 m was 0.42 deg. Although satisfactory agreements exist between heat-conduction theory and bore-hole measurements, Loewe (1970) showed that such correlations can only be applied to regions where summer temperatures are not sufficient to produce substantial surface melting. In areas with maxima in excess of 0°C, non-conductive heat transport occurs by infiltration and refreezing of melt water.

A major objective of the Glaciology of the Antarctic Peninsula programme (Swithinbank, 1974) is to establish a climatic record for the region during the last 1 000 years from ice-core studies. It is therefore of paramount importance to establish initially the contemporary spatial trends of climate in the region, to assess the regularity of any climatic patterns, and to identify any areas showing anomalous behaviour. Meteorological stations in the Antarctic Peninsula are sparse and predominantly in the north of the region, thus widespread measurement of 10 m temperatures can relatively quickly extend our knowledge of the climate of the whole region. Our analysis draws together measurements of 10 m temperatures that have been made over several years (Table I). The location of the bore holes and corresponding

TABLE I. 10 METRE TEMPERATURES AS A FUNCTION OF ALTITUDE AND LOCATION

i. Western and central region

Latitude °S.	*Longitude* °W.	*Altitude* m	*Temperature* °C	*Source*
64° 05′	59° 35′	1 806	−14.80	Peel (1976)
64° 13′	57° 38′	1 628	−12.9	Dalinger (unpublished)
64° 42′	63° 52′	590	−1.6	Rundle (1973 p. 347)
66° 25′	64° 57′	1 937	−15.8	J. F. Bishop, pc in 1976
67° 32′	66° 00′	1 750	−16.5	Doake (unpublished)
67° 46′	68° 55′	377	−0.1	C. S. M. Doake, pc in 1976
68° 07′	66° 18′	1 315*	−15.0	Robin (1967, p. 58)
68° 08′	65° 54′	1 125*	−15.0	Robin (1967, p. 58)
68° 10′	66° 49′	380	−1.6	Doake (unpublished)
69° 30′	66° 16′	860	−12.2	C. W. M. Swithinbank, pc in 1972
69° 30′	66° 16′	870	−12.9	Doake (unpublished)
69° 40′	65° 30′	1 994	−19.1	C. S. M. Swithinbank, pc in 1972
69° 47′	75° 13′	565	−12.2	Doake (unpublished)
70° 01′	64° 29′	2 131	−21.0	J. F. Bishop, pc in 1976
70° 25′	64° 32′	1 861	−20.7	J. F. Bishop, pc in 1976
70° 43′	63° 09′	1 860	−18.2	I. Rose, pc in 1972
70° 50′	64° 27′	1 987	−21.4	J. F. Bishop, pc in 1976
70° 53′	64° 57′	1 860	−20.2	J. G. Paren, pc in 1977
70° 55′	68° 04′	18	−10.0	J. F. Bishop, pc in 1976
70° 59′	66° 15′	1 101	−14.8	C. W. M. Swithinbank, pc in 1972
71° 03′	68° 22′	42	−8.0	Pearson and Rose (unpublished)
71° 03′	68° 23′	175	−7.0	Pearson and Rose (unpublished)
71° 06′	68° 06′	21	−8.9	Pearson and Rose (unpublished)
71° 07′	62° 20′	1 050	−16.59	Peel (1976)
71° 14′	63° 22′	1 752	−22.10	Peel (1976)
71° 15′	64° 30′	2 010	−23.67	Peel (1976)
71° 18′	67° 29′	258	−7.8	J. F. Bishop, pc in 1976
71° 18′	67° 37′	20	−9.12	J. Walton, pc in 1975
71° 18′	67° 29′	290	−8.36	Peel (1976)
71° 19′	68° 00′	22	−9.3	J. F. Bishop, pc in 1976
71° 23′	65° 30′	1 547	−20.00	Peel (1976)
71° 29′	66° 58′	946	−13.10	Peel (1976)
71° 42′	64° 05′	1 886	−20.4	J. F. Bishop, pc in 1976
71° 52′	68° 00′	30	−10.2	J. Walton, pc in 1975
71° 58′	67° 33′	35	−9.0	J. F. Bishop, pc in 1976
72° 00′	67° 09′	40	−8.45	J. Walton, pc in 1975
72° 07′	68° 48′	228	−10.9	J. F. Bishop, pc in 1976
72° 12′	72° 38′	43	−8.7	Pearson and Rose (unpublished)
72° 12′	72° 47′	25	−9.47	J. F. Bishop, pc in 1974
72° 13′	71° 50′	30	−9.72	Peel (1976)
72° 14′	67° 39′	35	−8.7	Pearson and Rose (unpublished)
72° 18′	72° 02′	42	−7.4	Pearson and Rose (unpublished)
72° 19′	67° 05′	35	−7.4	Pearson and Rose (unpublished)
72° 30′	72° 50′	488	−13.30	Peel (1976)
72° 47′	64° 30′	1 797	−21.8	J. F. Bishop, pc in 1976
72° 50′	75° 00′	539	−13.32	Peel (1976)
73° 42′	64° 47′	2 007	−23.8	J. F. Bishop, pc in 1976

ii. East coast

Latitude °S.	*Longitude* °W.	*Altitude* m	*Temperature* °C	*Source*
65° 32′	59° 52′	30	−8.4	G. W. B. Mackinlay, pc in 1972
66° 52′	63° 08′	18	−11.2	G. W. B. Mackinlay, pc in 1972
68° 07′	66° 06′	940*	−17.0	Robin (1967, p. 58)
68° 32′	61° 06′	290	−14.9	Doake (unpublished)
70° 35′	60° 50′	396	−17.51	Peel (1976)
71° 03′	10° 56′	37	−17.61	Schytt (1960)
72° 13′	60° 16′	130	−17.6	P. J. Martin, *in* Paren (unpublished)
75° 31′	26° 37′	29	−18.4	MacDowall (1964)

* Estimated.

pc Personal communication of data collected whilst serving with the British Antarctic Survey.

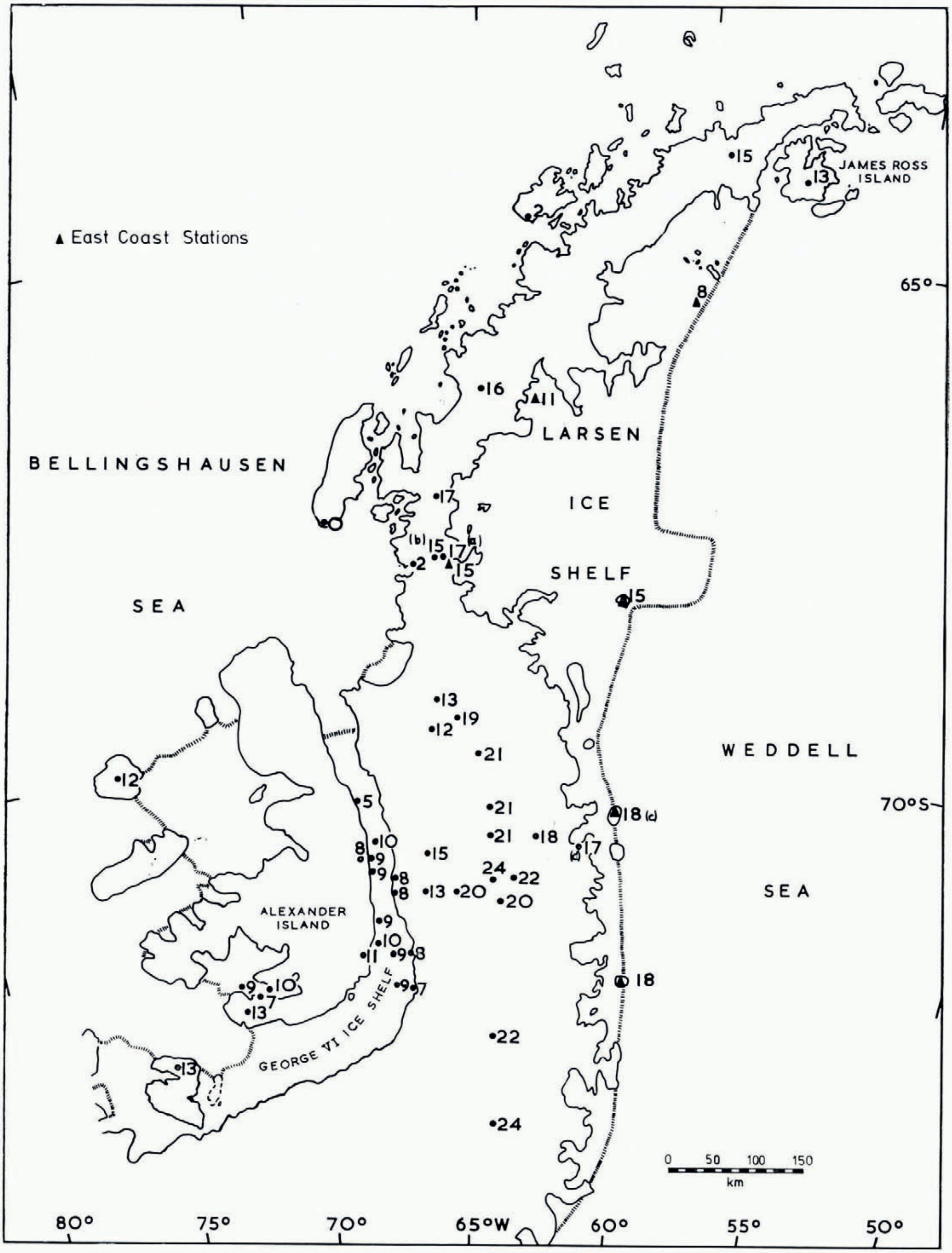

Fig. 1. Distribution of 10 m temperatures in the Antarctic Peninsula (expressed as degrees below 0°C).

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temperatures are shown in Figure 1. Experience shows that there is extensive summer melt where the mean annual temperature is greater than -5°C. This is likely to raise the 10 m temperature significantly above the mean annual air temperature, and therefore these data have been excluded from our analysis.

2. Multiple regression of temperature against altitude and latitude

Over much of the Antarctic Peninsula the weather pattern is dominated by a series of eastward-moving depressions which penetrate the region from the Bellingshausen Sea. On reaching the mountain barrier the air is uplifted and will cool adiabatically. It may therefore be expected that on average, altitude will have a first-order influence on temperature. Latitude influences temperature by controlling the input of solar radiation and by broadly defining the distance from the pole-centred ice sheet. The oceanic moderating influence on the climate, which may be roughly related to the distance from open water, is seasonally dependent on the extent of sea-ice coverage. In broad terms this should also be latitudinally dependent. In attempting to define a relationship between temperature and geographical position in the region we have therefore assumed that altitude and latitude are the dominating factors. Short-term meteorological effects such as föhn wind activity and katabatic winds may be significant in localized areas, but we assume that in general they have a negligible influence on mean annual temperature. To a first approximation we have assumed that the 10 m temperature may be expressed as a linear function of both latitude L and altitude A:

$$T = a(L-70^\circ)+b(A)+c, \tag{1}$$

where a, b, and c are multiple regression coefficients.

When this relationship was applied to all the available data it was found that points measured on the seaward side of the escarpment along the eastern edge of the peninsula (marked as triangles in Figure 1 and hereafter referred to as east-coast stations) deviated systematically from the trend observed at all other stations. These points have therefore been treated separately and the regression was applied to the remaining stations. The regression coefficients with their standard errors were evaluated as follows:

$$\begin{aligned} a &= (-0.84\pm0.09) \text{ deg/}^\circ\text{lat.}, \\ b &= (-6.82\times10^{-3}\pm0.23\times10^{-3}) \text{ deg/m}, \\ c &= -7.07 \text{ deg.} \end{aligned}$$

The coefficient of correlation for temperature versus altitude was 0.98 and for temperature versus latitude it was 0.82. A t-test shows that these coefficients are very highly significant. The standard error of the estimate of temperature on altitude and latitude was 1.2 deg. Part of the scatter is due to real variations in mean annual temperature during the period throughout which the 10 m temperatures have been measured. D. W. Limbert (personal communication) has estimated the standard deviation of mean annual temperature for the period 1948 to 1972 as 1.6 deg for Argentine Islands. The corresponding average year-to-year variation was 1.2 deg. This behaviour is typical of the whole region (Limbert, 1974). In consideration of the complex topography of the Antarctic Peninsula combined with the large swing in mean annual temperature the linear fit is believed to describe the data fully.

3. Variation of temperature with altitude

All the data have been normalized to lat. 70° S. using the calculated regression coefficients. The relationship between temperature and altitude is given in Figure 2, which also includes the east-coast data normalized using the same coefficients. The east-coast data are evidently displaced by approximately 7 deg to lower temperatures compared with the rest of the region. The boundary between the two climatic regimes is sharp (compare for example data for

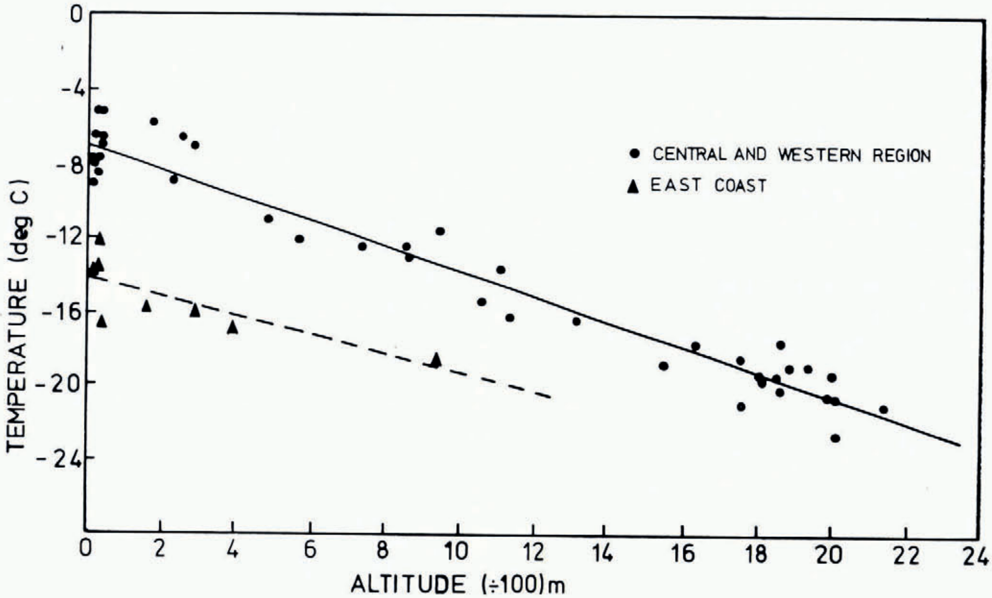

Fig. 2. Regression of 10 m temperature versus altitude, normalized to lat. 70° S.

points (a) lat. 68° 07′ S., long. 66° 06′ W. and (b) lat. 68° 07′ S., long. 66° 18′ W. also points (c) lat. 70° 35′ S., long. 60° 50′ W. and (d) lat. 71° 07′ S., long. 62° 20′ W.) and appears to lie within a few kilometres of the eastern escarpment. It is noteworthy that data obtained at Maudheim (lat. 71° S., long. 11° W.) and at Halley Bay (lat. 75.5° S., long. 26.5° W.) on the edge of the ice sheet, fit the trend of east-coast stations.

The altitude lapse rate for west and central peninsula areas is 0.68 deg/100 m. There are insufficient points over a wide altitude range for east-coast stations to provide a good estimate of the average lapse rate in this area. It does however appear to be smaller than that of the west coast. The decrease in temperature with increasing altitude is a direct result of the adiabatic rate of temperature change for vertically moving air. This lapse rate varies with both temperature and mixing ratio from a dry rate of 0.98 deg/100 m to a saturated rate of 0.44 deg/100 m at 20°C which increases with decreasing temperature to 0.87 deg/100 m at −20°C. The observed altitude lapse rate is comparable with the saturated adiabatic lapse rate that may be expected for the mean conditions of the peninsula.

The results are compatible with studies made by Shimizu (1964) of 10 m temperature variations in the continental and Ross Ice Shelf areas of West Antarctica. He obtained an altitude lapse rate (uncorrected for the effects of latitude or continentality) of 0.82 deg/100 m. A good data fit was obtained when he split this into a simple altitude lapse rate of 0.65 deg/100 m combined with a non-linear latitudinal lapse rate.

Inland from Halley Bay, Peel (1976) reported a lapse rate of 0.90 deg/100 m, close to the saturated adiabatic lapse rate at the lower temperatures of this region. Schytt (1960) related mean temperatures with altitude using data collected during field journeys from Maudheim (lat. 71° S., long. 11° W.). Because the effect of latitude was combined with changes in local conditions, he was unable to obtain a good linear relationship, but indicates a lapse rate of 0.55 deg/100 m for elevations between 500 m and 2 000 m. Above 2 000 m all the observed temperatures were lower than those expected from the linear trend which he suggests is due to the effect of increasing continentality.

4. Variation of temperature with latitude

In Figure 3 the data have been normalized to sea-level and temperature has been plotted against latitude. For central and western areas of the peninsula, the gradient is −0.84 deg per degree increase in latitude, constant between lat. 64° S. and 74° S. The east-coast data are sparse but tentatively suggest a slightly enhanced gradient. This value compares with an average change of −1.1 deg/degree of latitude reported (Shimizu, 1964) for the continental region of West Antarctica. A value of approximately −2 deg/degree of latitude was recorded (Peel, 1976) for a line of stations stretching 450 km inland from Halley Bay. The latitudinal temperature gradient for central and western parts of the peninsula is similar to the mean sea-level latitudinal temperature gradient in oceanic areas in the same latitude range (Schwerdtfeger, 1970, p. 262). The slightly larger gradient on the east coast may reflect a more continental regime in this area.

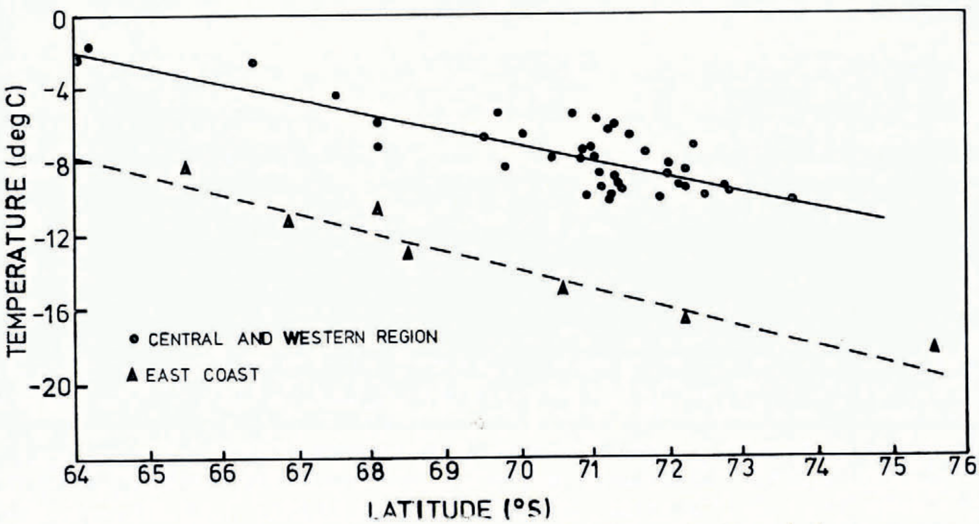

Fig. 3. Regression of 10 m temperature versus latitude, normalized to sea-level.

5. Regional climatic differences

Figures 2 and 3 show clearly that there are two distinct climatic regimes in the Antarctic Peninsula, with a divide close to the eastern escarpment. There is a marked difference in the temperature of approximately 7 deg between stations similarly placed on the two sides of the peninsula. This is in accord with meteorological observations in the north of the peninsula at Snow Hill Island, Hope Bay, and Matienzo (Schwerdtfeger, 1970, p. 253–355, 1974) on the eastern side, in comparison with data from the more numerous stations on the west coast. Schwerdtfeger (1975) has shown that the surface climatic regime of the east coast may be dominated by the westward advection of cold air from the Weddell Sea with a marked temperature inversion. Our data suggest that this may be a general feature of the region at least as far south as lat. 72°. Additional support for Schwerdtfeger's hypothesis is indicated by the fit of data for Halley Bay, on the eastern side of the Weddell Sea, to the trend for east-coast stations on the peninsula. The temperature regime in both areas is dominated by the extensive belt of sea ice in the Weddell Sea. Ecological studies (Holdgate, [1964]) have also shown that the peninsula should be regarded as having a maritime zone on the west coast with a continental environment east of the peninsula plateau.

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