TEMPERATURE STUDIES IN A BORE HOLE AT SOUTHERN ADELAIDE ISLAND

By Rorke Bryan

Abstract. Diurnal temperature observations were recorded in a bore hole in the Fuchs Ice Piedmont, Adelaide Island, for a period of 3 months during the 1963–64 summer. The bore hole in which the temperature observations were made was below the firn line at an altitude of 60·6 m. a.s.l. The observed temperatures indicate the presence of a well-marked cold wave in the ice piedmont which persisted until the disappearance of the firn at the beginning of January 1964. Statistical and graphical analyses show that warming from the surface during the 1963–64 summer did not affect the ice temperature at depths of more than 6 m. below the surface. Below that depth temperatures approaching an equilibrium of −5·4° C were recorded. Tentative figures for the penetration rate of temperature changes into the ice piedmont are suggested. There is evidence that the minimum air temperature during the 24 hr. preceding observation is of most significance in effecting changes of ice temperature.

During the summer of 1963–64 daily temperature observations were taken at various depths in a bore hole in the Fuchs Ice Piedmont near the British Antarctic Survey station (lat. 67°46′S., long. 68°55′W.) on Adelaide Island. The bore hole was sited on the lee slope of the ice piedmont at an altitude of 60·6 m. a.s.l. (Fig. 1). The climate and physiography of Adelaide Island have already been described by Bryan (1965).

Methods

All the ice temperatures discussed in this paper were obtained from thermistors placed in one bore hole, drilled to a depth of 10 m. using a 2·5 cm. diameter manual drill with extension rods. Alternate use of auger and coring bits gave the most rapid and satisfactory results, but the progress rate was only 5–10 cm./hr. 10 m. is the maximum practical depth for manual drilling (without a rig) by one individual.

Temperatures were measured by Stantel F22 thermistors placed at depths of 1, 2, 3, 4, 5, 7 and 10 m. in the bore hole. The thermistors were used in conjunction with a Tinsley Wheatstone bridge and galvanometer placed in a junction box fixed to a post above the bore hole. The post, junction box and all cables above the snow surface were painted white to reduce the effect of radiation.

Before being placed in the bore hole, the thermistors were calibrated against a standard N.P.L.-tested alcohol thermometer. The method of calibration was similar to that used by Thomas (1963), temperatures being observed while the thermistors were cooled in an oil-filled vacuum flask. The flask was first cooled by outdoor exposure and later by immersion in a snow/salt mixture. The calibration range was −12·5° to +5·0° C, and the average accuracy was calculated to be ±0·1° C.

Some difficulty was experienced in obtaining a steady reading on the galvanometer, because of heating of the resistance wire by the current from the 4 V battery of the galvanometer. This was corrected by connecting a 10,000 Ω resistance in series.

The resistance of a fixed length of cable was measured and it was found that the error introduced by the maximum length of cable was within the limit of error of thermistor calibration. The thermistors were attached to appropriate lengths of cable, then bound together and lowered into the bore hole. It was immediately filled with water, and then temperatures were allowed to stabilize for 2 weeks before regular daily observations commenced.

Observations

Regular daily observations began on 8 November 1963 and continued until 6 February 1964, readings being taken at 15.00 hr. G.M.T. Data on air temperature at the time of observation, average air temperature during the 24 hr. preceding observation, and maximum and minimum air temperatures during the 24 hr. preceding observation were obtained from the records of the adjacent meteorological station.

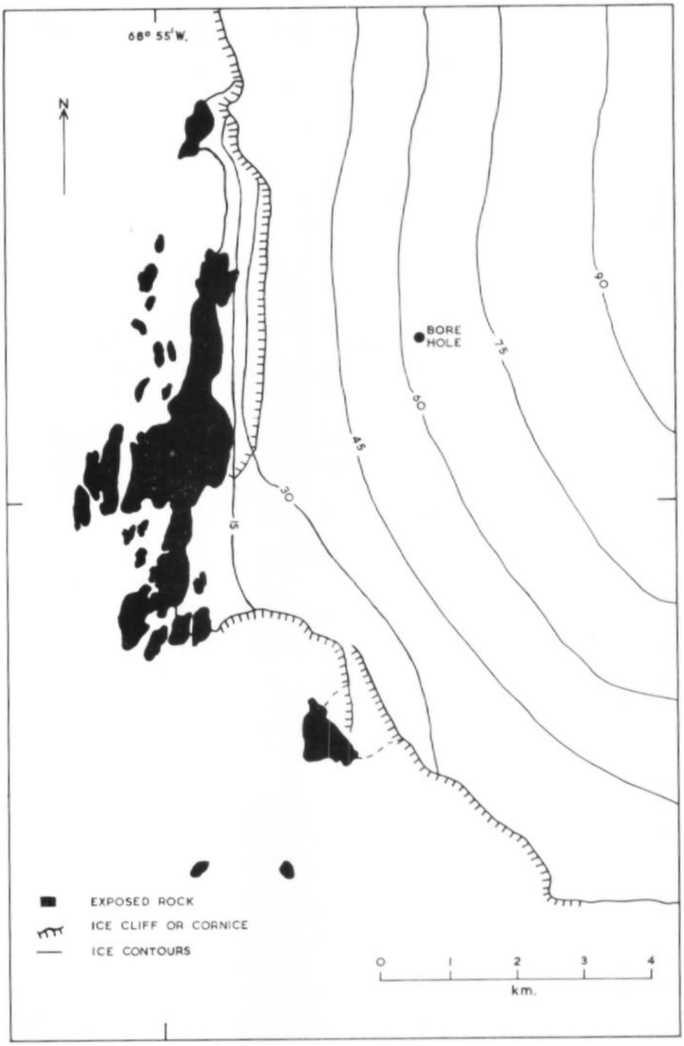

Fig. 1. Map of the environs of the British Antarctic Survey station at Adelaide Island, showing the location of the bore hole used for ice-temperature measurements. The contours are at 15 m. intervals.

The observations are shown graphically in Fig. 2A and B. A break in the electrical circuit prevented any readings being taken from the thermistor at 10 m. Since the thermistors were placed in the bore hole before melting of the winter snow accumulation, the depth of each thermistor below the surface decreased throughout the period of observation. The rate of decrease was not uniform; it followed the pattern of the graphs in Fig. 3 which represent the tracks of thermistors B and C, originally placed at depths of 1 and 2 m., respectively. It has been assumed that thermistors D, E, F and G at original depths of 3, 4, 5 and 7 m., respectively, followed parallel tracks. It seems unlikely that any appreciable differential movement would have occurred between the thermistors during such a short period of observation.

When the thermistors were placed in the bore hole in October 1963, the upper 0·75 m. consisted of hard white crystalline firn. This had melted away completely by 4 January 1964 and melt water was flowing at the surface near the bore hole. At least 3 weeks before that date

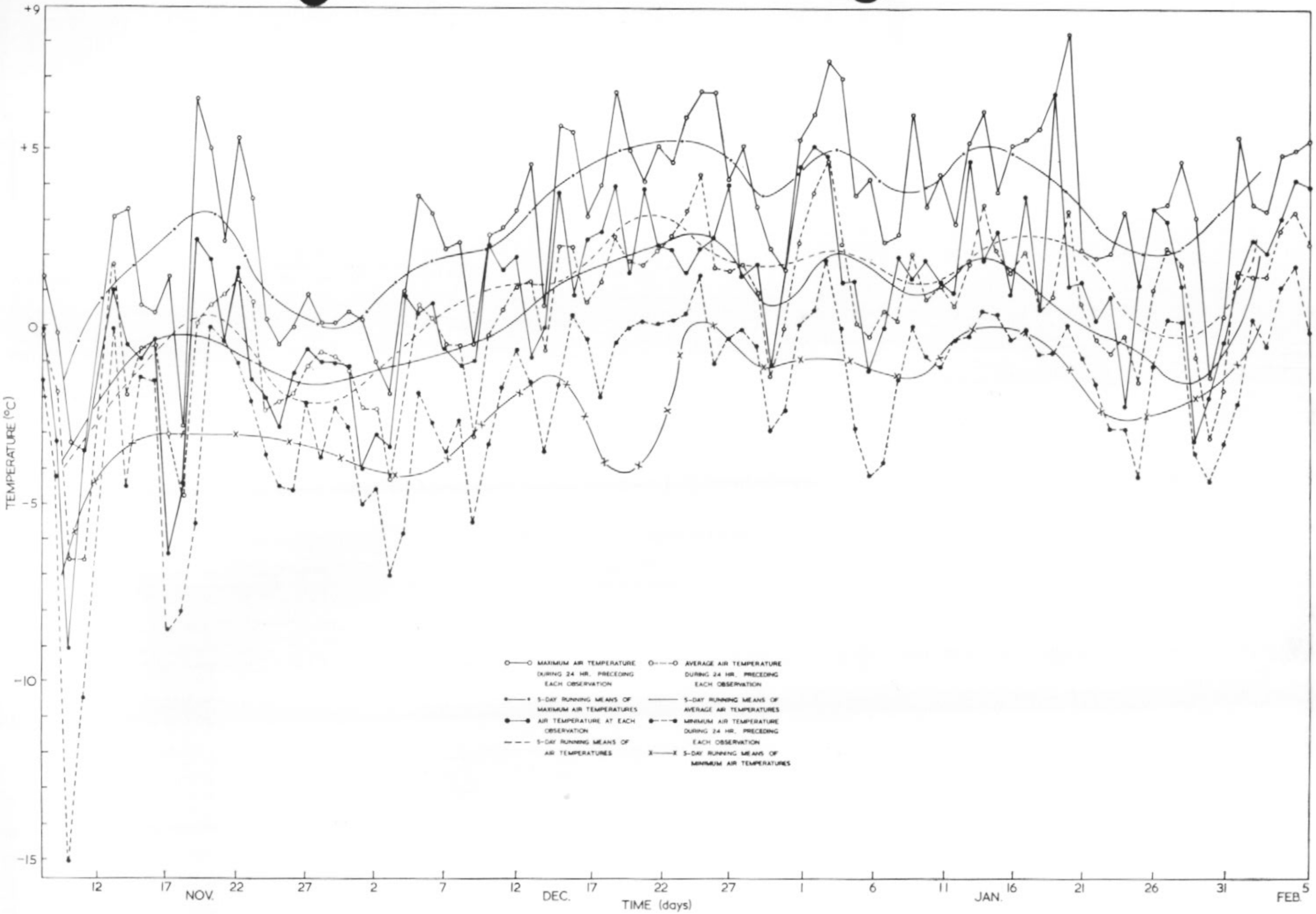

Fig. 2A. Graphs showing air temperatures recorded during the period of observation and 5-day running means of these values.

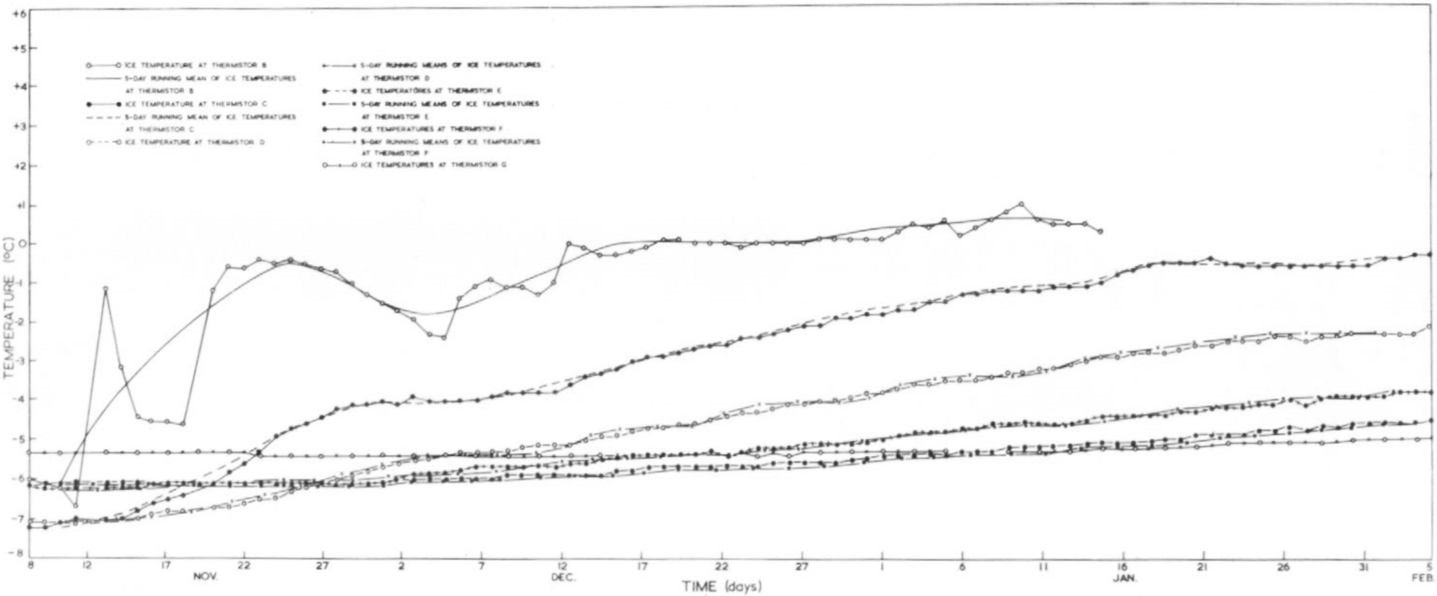

Fig. 2B. Graphs showing ice temperatures recorded in the bore hole and 5-day running means of these values.

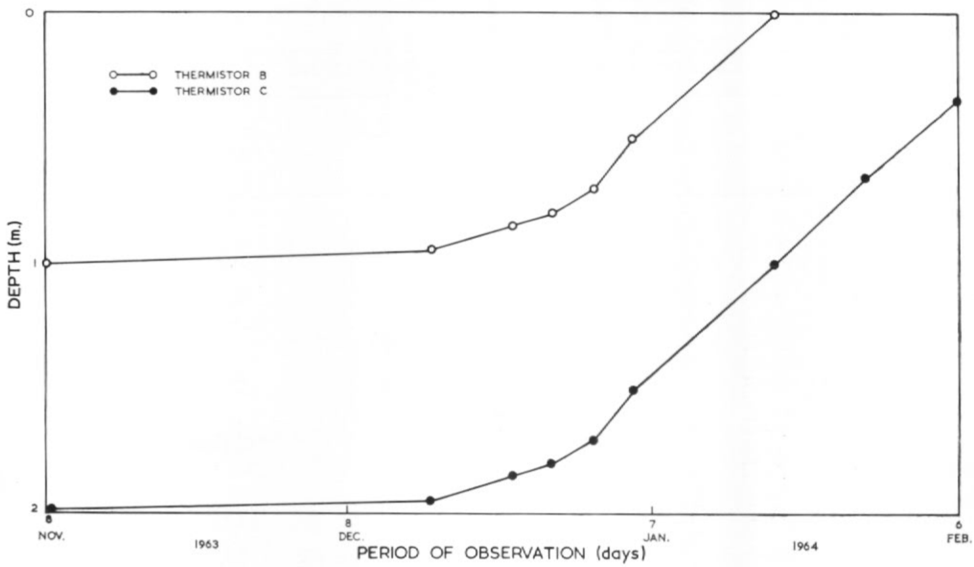

Fig. 3. Diagram showing the decrease in depth below surface of thermistors B and C during the period of observation.

the firn had become oversaturated and melt water had been flowing at the ice surface, causing melting of the superimposed ice and warming of the main ice body, as described by Thomas (1963). After 4 January 1964 the wastage of ice continued until the termination of observations, at which time the surface altitude at the bore hole had decreased by 1·7 m. Thermistor B was exposed at the surface on 17 January, and therefore all subsequent readings from it were discounted.

Air temperatures during the period of observation have been plotted both on a daily basis and as 5-day running means in Fig. 2A. The four sets of temperatures plotted show a strong correlation. Fig. 2B shows the plots of ice temperatures at various depths in the bore hole on the same basis as Fig. 2A. The general pattern of air temperatures during the observation period is reflected in all the thermistors, but the rise in temperature at thermistor G was only 0·4° C during the 3-month period. Because of ablation during this period, thermistor G was elevated from a depth of 7 m. to 5·3 m. The corresponding increase in temperature observed in that thermistor was within the limit of error of calibration until it reached a depth of 6 m.

In an attempt to assess the time lapse involved in the transmission of any given temperature change to depth, a number of correlation coefficients were computed. It was impossible to test all possible patterns of time lapse, but most probable ones were predicted from graphs and these were computed on an I.C.T. Mercury Autocode computer. The results obtained are given in Table I.

In assessing the results obtained, the lower level of significant correlation was set at 750 (a correlation coefficient of 75 per cent). Tests were applied to determine at what level a correlation coefficient can be equated to zero with confidence. Even if two values have no correlation, the coefficient between them is rarely zero. To decide whether or not a coefficient is sufficiently large to indicate statistical relationship a "null hypothesis" is applied (Brooks and Carruthers, 1953).

The magnitude of the required level varies inversely with the number of samples taken. In the present case the number of samples varied from 60 to 90. Calculating to a 5 per cent level, the limits determined were +250 to −250 and +205 to −205 for samples of 60 and 90, respectively (Pearson and Hartley, 1956). This means that all the correlation coefficients lying within these limits can be equated to zero with 95 per cent confidence.

TABLE 1A. CORRELATION COEFFICIENTS BETWEEN AIR TEMPERATURES AND TEMPERATURES AT DEPTH IN THE ICE ON THE SAME DAY

Observation pairs	*Correlation coefficient* ($\times 10^3$)	*Observation pairs*	*Correlation coefficient* ($\times 10^3$)
A–B	564	C–J	483
A–C	543	D–E	977
A–D	521	D–F	949
A–E	464	D–G	159*
A–F	417	D–H	486
A–G	185*	D–I	472
A–H	818	D–J	457
A–I	715	E–F	990
A–J	810	E–G	167*
B–C	795	E–H	433
B–D	726	E–I	419
B–E	638	E–J	417
B–F	586	F–G	165*
B–G	93*	F–H	386
B–H	560	F–I	366
B–I	535	F–J	378
B–J	574	G–H	91*
C–D	984	G–I	110*
C–E	931	G–J	91*
C–F	891	H–I	918
C–G	152*	H–J	992
C–H	510	I–J	796
C–I	492		

Explanation of Tables 1A–E

A. Air temperature at time of observation.
H. Average air temperature during 24 hr. preceding observation.
I. Maximum air temperature during 24 hr. preceding observation.
J. Minimum air temperature during 24 hr. preceding observation.
B–G. Temperatures at thermistors B–G.
* Correlation coefficients which can be assumed to equal zero with 95 per cent confidence.

TABLE IB. CORRELATION COEFFICIENTS BETWEEN AIR TEMPERATURE AT TIME OF OBSERVATION AND TEMPERATURE AT DEPTH AFTER A VARYING TIME LAPSE

Observation pairs	*Time lapse* (days)	*Correlation coefficient* ($\times 10^3$)
A–B	1	613
A–C	4	636
A–D	7	624
A–E	10	601
A–F	14	581
A–G	21	130*
B–C	3	840
B–D	6	783
B–E	9	711
B–F	13	696
B–G	20	116*
C–D	3	989
C–E	6	958
C–F	10	945
C–G	17	155*
D–E	3	987
D–F	7	976
D–G	14	150*
E–F	4	990
E–G	11	135*

The picture emerging from the five patterns of computation is essentially the same in each case. Table IE, showing correlation between minimum air temperatures and ice temperatures, gives the highest coefficients, but the variation between the patterns is not great. There is little correlation between any of the air temperatures and the ice temperatures, but there is a high correlation between all the ice temperatures, except those recorded by thermistor G at 7 m. depth. Applying the levels of significance defined above, the correlation coefficients for thermistor G are the only ones that can be equated to zero with 95 per cent confidence.

Fig. 4 shows 10-day running means of the temperature profiles (plotted in four groups) recorded in the bore hole. The first profile (for 8–18 November) shows the presence of a well-marked cold wave, which has receded slightly in the second profile (for 19–29 November). The second profile shows marked increases in temperature at 1 m. depth, which suggests that melting of the superimposed ice by surface melt water had acutally started before the end of November. The temperature profile for 27 November 1963 was found to coincide almost exactly with the second profile. This makes an interesting comparison with a temperature profile measured 2 years previously on the Galindez Island ice cap (Thomas, 1963). In pattern the two profiles are strikingly similar to one another, although the cold wave at Adelaide Island is more pronounced. In general, the temperatures in the bore hole at Adelaide Island

TABLE IC. CORRELATION COEFFICIENTS BETWEEN AVERAGE AIR TEMPERATURE DURING THE 24 hr. PRECEDING OBSERVATION AND TEMPERATURE AT DEPTH IN THE ICE AFTER A VARYING TIME LAPSE

Observation pairs	*Time lapse* (days)	*Correlation coefficient* ($\times 10^3$)
H–B	2	445
H–C	4	628
H–D	8	614
H–E	10	579
H–F	13	575
H–G	18	127*
B–C	2	839
B–D	6	793
B–E	8	737
B–F	11	721
B–G	16	117*
C–D	4	990
C–E	6	961
C–F	9	943
C–G	14	165*
D–E	2	987
D–F	5	975
D–G	10	162*
E–F	3	991
E–G	8	168*
F–G	5	156*

are about 2° C lower than those at equivalent depths on the Galindez Island ice cap. However, a more detailed comparison cannot be made without further knowledge of the air-temperature conditions at Galindez Island.

A comparison of the remainder of the profiles in Fig. 4 shows the continued presence of the cold wave until the profile for 9–18 January 1964. By the next profile it had disappeared and the profile for 29 January–6 February shows a positive gradient down to the limiting depth of observation.

DISCUSSION

It has been suggested that use of the term "ice piedmont" for the Fuchs Ice Piedmont of Adelaide Island is possibly not strictly correct (Bryan, 1965). This nomenclature was originally introduced by Ahlmann (1933, 1948) to describe a glacier which is not independent but formed by the fusion of the lower parts of two or more independent glaciers. Although the Adelaide Island feature is partially nourished by valley glaciers, it is chiefly supported by the accumulation of snow and rime ice (Bryan, 1965), and it is capable of independent existence.

TABLE ID. CORRELATION COEFFICIENTS BETWEEN MAXIMUM AIR TEMPERATURE DURING THE 24 hr. PRECEDING OBSERVATION AND THE TEMPERATURE AT DEPTH IN THE ICE AFTER A VARYING TIME LAPSE

Observation pairs	*Time lapse* (days)	*Correlation coefficient* ($\times 10^3$)
I–B	3	455
I–C	4	611
I–D	5	584
I–E	9	552
I–F	13	546
B–C	1	797
B–D	2	758
B–E	6	725
B–F	10	713
C–D	1	987
C–E	5	956
C–F	9	941
D–E	4	987
D–F	8	975
E–F	4	992

In this case it was not possible to predict a possible line of correlation with G, so any coefficient would certainly lie within the zone of zero correlation.

In 1948 Ahlmann defined his morphological classification of glaciers in terms of area-distribution curves. In this definition, a "piedmont glacier" has an area-distribution curve in which the highest proportion of the surface is at the lowest altitude. Since the topographical survey of Adelaide Island is not yet available, it was not possible to plot an area-distribution curve for the Fuchs Ice Piedmont, but general field observation of the feature shows that the highest proportion of the surface is near the greatest altitude. The Fuchs Ice Piedmont conforms closely with Ahlmann's class A, or *glacier cap* (Ahlmann, 1948), and the only justification for the use of the term "ice piedmont" for the feature is its position fringing a mountain chain, but this is incorrect usage of the term.

The bore hole was situated below the firn line of the glacier cap, which was at a height of 202 m. a.s.l. during the 1963–64 summer. No regular observations were made in the accumulation area of the glacier cap and hence no overall figure for firn thickness is known. However, pit studies indicate that any formation of melt water in this area during the summer is very localized. The glacier cap therefore corresponds to Ahlmann's geophysical classification of high-polar glaciers (Ahlmann, 1933, 1935, 1948).

The pattern of temperature changes in the ablation area of this glacier cap has been determined by graphical and statistical methods. The former indicate a strong correlation between air and ice temperatures but this is only partially borne out by statistical analysis. It is possible that the patterns chosen for computation were not those with the highest level of correlation but this is unlikely because they were chosen from the graphs. The most probable explanation is that until 4 January 1964, when all the firn near the bore hole disappeared, the relationship between air and ice temperatures was indirect.

TABLE IE. CORRELATION COEFFICIENTS BETWEEN MINIMUM AIR TEMPERATURE DURING THE 24 hr. PRECEDING OBSERVATION AND THE TEMPERATURE AT DEPTH IN THE ICE AFTER A VARYING TIME LAPSE

Observation pairs	*Time lapse* (days)	*Correlation coefficient* ($\times 10^3$)
J–B	2	354
J–C	4	567
J–D	7	542
J–E	12	518
J–F	15	499
J–G	17	120*
B–C	2	843
B–D	5	800
B–E	10	753
B–F	13	739
B–G	15	122*
C–D	3	990
C–E	7	966
C–F	10	948
C–G	12	162*
D–E	4	990
D–F	6	978
D–G	8	164*
E–F	3	992
E–G	5	169*
F–G	2	165*

Oversaturation of the firn appears to have occurred by the last week of November 1963. After that melting of the superimposed ice by melt water and warming of the main ice body took place. Both graphical and statistical methods of analysis support the conclusion that warming from the surface did not affect depths greater than 6 m. below the ice surface during the period of observation. At a depth of 7 m. the temperature was $-5\cdot4°$ C and this appears to be almost constant. This temperature is slightly higher than the mean annual air temperature of $-6\cdot2°$ C, but this value is based on the observations for only 1 year, which was apparently an unusually cold year for the area (Bryan, 1965).

Attempts to determine which air-temperature value was most closely correlated with the ice temperature, and to determine the rate of penetration of temperature changes to depth, were inconclusive. The results obtained indicate that the minimum air temperature during the 24 hr. preceding each observation is the most significant one. The results for the rate of penetration suggest a decreasing rate with depth, penetration to a depth of 1 m. taking 2 days; 2 m., 4 days; 3 m., 7 days; 4 m., 12 days; and 5 m., 15 days.

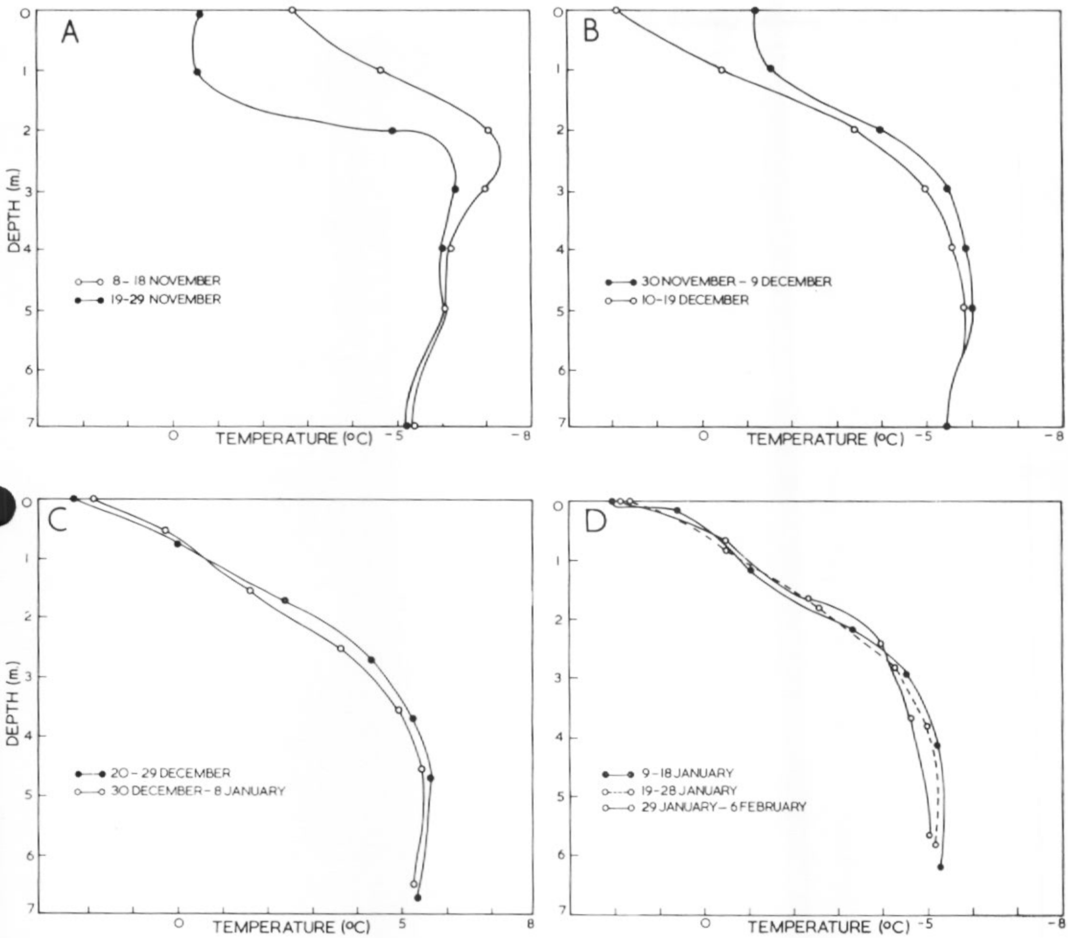

Fig. 4. Diagram showing 10-day running means of temperature profiles in the bore hole during the period of observation.

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