INVESTIGATIONS OF PATTERNED GROUND AT SIGNY ISLAND, SOUTH ORKNEY ISLANDS: II. TEMPERATURE REGIMES IN THE ACTIVE LAYER

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ABSTRACT. By means of electric resistance thermometers, soil temperatures were recorded over a period of 2 yr. at two sites on Signy Island. The first site was a large sorted circle and daily readings were taken at depths between 1 and 50 cm. in the central fines and peripheral stones of the circle. At the second site, 3 hr. readings were taken as part of the routine meteorological observations. Depths of the probes were similar to those at the circle site, and additional probes gave a record of the soil temperatures down to permafrost level at 120 cm. Resistance readings were converted to temperatures by means of a computer, which was then programmed to calculate monthly means and standard deviations. Analysis of these records shows rates of freezing and thawing throughout the year, frequency of freeze-thaw cycles at different depths and the difference in regime between the stones and fines of a sorted pattern. Results suggest that in this instance there is no uneven descent of a freezing plane in a manner which would induce cryostatic pressure and the consequent movement of fine material. A comparison is made between freeze-thaw cycles inferred from meteorological data and actual freezing and thawing in the soil. The considerable difference revealed between inferred and actual cycles suggests that air temperatures are an inadequate indicator of soil conditions unless information on snow cover, soil moisture and radiation is available.

WITHIN the framework of a general study of patterned ground at Signy Island, a detailed examination of soil temperatures was undertaken. The aim of the soil study was to provide information concerning the movement of the freezing plane within the active layer. Freeze-thaw activity is generally believed to be one of the most significant factors in the formation of patterned ground and therefore it was pertinent to discover the frequency of such cycles and their relation to the climate of Signy Island. Ice segregation, the motive force of frost-heave, is partly dependent upon the rate of soil freezing (Higashi, 1958) and hence the rate of freezing-plane penetration is also important. Several theories which attempt to account for the formation of patterned ground invoke temperature variations, either as uneven freezing or as contrasting water density, in their explanations. A detailed knowledge of the temperature regime within a large sorted pattern would, therefore, shed light on the validity of such hypotheses. A comprehensive discussion of these theories and a general review of patterned ground has been given by Washburn (1956).

METHODS OF SOIL-TEMPERATURE RECORDING AND ANALYSIS

The most suitable distant-reading method of recording soil temperatures was by means of electric resistance thermometers, and Stantel F22 thermistors were used for this purpose. The cable used was ex-Army field telephone wire, composed of seven strands of steel and one of copper. This was soldered to the thermistor connecting wires and the whole sensor encased in a bonded fibre tube, so that only the sensitive glass tip was exposed, and all the junctions were completely watertight. At the recording end, a Wheatstone bridge circuit with a needle galvonometer as null-detector, powered with a 1·5 V. battery, was used to measure the absolute resistance of the circuit. The thermistors are designed to vary in resistance inversely with temperature, with a range of about 500 Ω for a 40° C variation. A test was conducted which showed that the resistance of the cable did not alter significantly when subjected to a similarly wide temperature variation, so that all changes in resistance could be taken as actual temperature changes at the tip of the thermistor. The only time when the cable showed signs of resistance fluctuation was under strong radiation from either the sun or the radio transmitter aerial. The former was avoided by covering the cables with white-painted boards, but readings could never be made when the radio transmitter was operating on certain wave-lengths.

Before the thermistors were used an initial calibration of the resistance-temperature relationships was carried out on Signy Island, in case any were damaged during their return to England, but fortunately this did not occur. A much more thorough and accurate calibration was undertaken in the Department of Physics, University of Southampton. The thermistors were immersed in a tank of "anti-freeze" under constant agitation and the temperature of the fluid controlled to $\pm 0 \cdot 03^\circ$ C with a refrigerator-heater unit operated by an adjustable contact thermometer. The thermistors were then taken through the range -15° to $+20^\circ$ C with resistance readings made at approximately 3° C intervals. Steep but smooth curves were drawn from these readings for each thermistor, suggesting that the resistance-temperature relationship was almost logarithmic. The problem then arose of determining a formula which described this curve to a sufficient degree of accuracy. This was calculated by means of a "least-squares" curve-fitting programme on the University of Southampton Pegasus Mark II computer. After much trial and error, a formula was devised which defined the curve to an accuracy of $\pm 0 \cdot 03^\circ$ C around freezing point and $\pm 0 \cdot 05^\circ$ C at the extremes. This gave two coordinates for each curve, *a* and *b*, such that

$$T = (a \log_e R + b)^{-1},$$

where T is temperature in degrees Absolute, and R is resistance in ohms.

A conversion programme was then written to incorporate the two coordinates for each thermistor curve. By feeding in the resistance readings for each thermistor in turn, a direct print-out of the corresponding temperatures was obtained in degrees Celsius. At the same time, an additional part of the programme calculated monthly and overall means, variance and standard deviation. An attempt was also made to use a programme of Fourier analysis and auto- and cross-correlation, but this was unsuccessful owing to the presence of unknown variables such as depth of snow cover, intensity of solar radiation and the irregular influence of cyclonic activity. Whilst details of snow cover, radiation, wind and air temperature were kept for the period while soil temperatures were being recorded, no satisfactory classification of these factors has yet been made. It is hoped at a later date to complete this analysis so that the significance of these various parameters in the temperature regime of the active layer can be isolated.

Thermistor Sites

Since there were no suitable patterns close enough to the British Antarctic Survey station to permit the recording apparatus to be kept indoors, a site had to be chosen which would allow daily readings to be taken without interfering with other field work and meteorological duties. Such a site was found approximately 0·8 km. south-west of the station, in a small hollow about 30 m. across and 40 m. a.s.l., where some considerable depth of assorted rock debris had accumulated. Most of this debris was situated on gentle slopes, so that the characteristic patterns were irregular lobes and mounds of fine material separated by depressed zones of coarse rock fragments. Towards the west-facing outlet of this natural basin, however, a rock lip hindered the movement so that an almost horizontal area of more stable material had formed. Only 2 m. to the south a melt stream flowed westward to the bay of Elephant Flats, thus maintaining a high moisture level during the summer months.

Within this small area of level terrain a number of large sorted circles were located and two of these were chosen for the temperature investigation. Thermistors were inserted in the centre of one circle and in the stone border which separated it from the other. Six probes were planted in each place at depths of 1, 2·5, 5, 10, 25 and 50 cm. In order to disturb the surface material as little as possible, a steel rod of the same diameter as the thermistor housing was used to prepare holes for the deeper units. Whilst there is no doubt that this compacted the surrounding soil very slightly, such a method was preferable to excavating the site, which would have completely upset the natural drainage characteristics. Daily readings were commenced on 1 January 1962, although those for the first 4 months have not been used in the main analysis in order to eliminate any irregularity of recording due to resettlement of the soil after its initial disturbance. This 4-month period also allowed the thermistor characteristics to stabilize, since any drift in calibration is believed to occur mainly in the first few months of activity (Mortimer and Moore, 1953).

Although these daily temperature readings taken from a large sorted circle would give an indication of long-term fluctuations, it was clear that a much shorter observation interval would be necessary before diurnal cycles could be identified. Because this was impossible at the same site, a second location was chosen close to the station hut. Here the thermistor cables were carried into the hut and readings taken at 3 hr. intervals as part of the synoptic meteorological observations. At this site the surface slope angle was 10° towards the north-west, and an irregular series of large sorted stripes could be discerned below a 60 per cent cover of thin moss. Eleven thermistors were inserted into the fine section of one of these stripes about 50 m. away from the hut; six were at depths comparable to those in the sorted circle, four others were at 30, 60, 100 and 120 cm., and one was set at a depth of 2·5 cm. in a moss mat. The purpose of this site was two-fold:

i. To provide basic soil-temperature information for the entire active layer.
ii. To provide a short-interval record of diurnal temperature fluctuations as a control, so that similar cycles could be interpolated from daily readings in the sorted circle.

In conjunction with these soil-temperature data, a detailed account of air temperature was maintained throughout the same period. This comprised 3 hr. observations of dry and wet bulb, twice-daily recordings of screen maximum and minimum, and a continuous thermograph chart. Other factors which affect soil temperature, such as precipitation, snow cover and radiation were also noted.

Seasonal Temperature Cycle

Before the geomorphological significance of the soil temperatures recorded during these two years can be determined, it is necessary to examine the normality of the weather conditions during this period. Although there are only records as far back as 1947, this span provides some sort of standard against which the two particular years of observation can be compared. Since these two years (1962 and 1963) were very different, it is important to know which one was the more typical. The mean monthly temperatures for the period 1947–63 are tabulated with the same totals for the two analysis years in Table I. Data for the period 1947–61 were

Table I. Comparison of mean monthly temperatures for Signy Island

Month	*Mean 1947–63*	*1962*	*1963*
January	+0·7	+1·7	+1·8
February	+0·8	+0·9	+1·7
March	+0·1	−0·1	+0·2
April	−2·2	−0·3	−1·8
May	−6·4	−4·5	−3·0
June	−8·2	−3·1	−7·7
July	−10·5	−8·5	−6·3
August	−9·2	−6·1	−9·6
September	−5·2	−1·8	−6·7
October	−2·6	−0·4	−7·1
November	−1·4	−1·1	−1·9
December	−0·2	+0·7	+0·5
Year	−3·8	−1·9	−3·3

obtained from the *Annual meteorological tables* of the Falkland Islands and Dependencies Meteorological Service (known as the British Antarctic Meteorological Service since 1961). From these figures it can be seen that, with the exception of March, every month in 1962 was above average in temperature. The most important of these warm months were June and September, which caused the cold period of winter to begin late and finish early. The following year was far more similar to the long-term mean and, although it was also slightly warmer overall, the most outstanding month was October, the coldest October ever recorded, which had the effect of extending the 1963 winter by an extra month. Although these air-temperature data by no means offer a complete picture of weather conditions, they provide a fairly reliable indication of what to expect in the soil temperatures. They show that the soil regime of 1963 is more normal than 1962, with the possible exception of the late arrival of spring.

For the above reasons, 1963 has been chosen to illustrate the patterns of temperature variations with depth from month to month. To allow for slight variations in the actual temperature when the interstitial soil moisture changed state from water to ice and from ice to water, a transition zone of $\pm 0 \cdot 5^\circ$ C has been adopted as a freezing-boundary indicator. This freezing boundary, described by Muller (1947) as the "zero curtain", has generally been taken as at the 0° C level (Cook, 1955); it is evident from the Signy Island records that for about $0 \cdot 5^\circ$ C on either side of this the temperature fluctuates almost randomly, but once outside this zone changes are more significant. Fig. 1 shows the soil temperatures classified into three

Fig. 1. Temperature zones of the active layer during 1963.

divisions, above $+0 \cdot 5^\circ$ C, below $-0 \cdot 5^\circ$ C and the transitional freezing boundary. Since each symbol represents 6 days, a fourth category had to be incorporated which indicates that the temperature was alternating between at least two of the classes and not merely passing from one class to the next during that 6-day period. It is immediately apparent that, in spite of the narrow definition of the freezing boundary, the deeper section of the active layer was in this zone for a great part of the year. At 120 cm. the temperature never became consistently positive, but for 7 months it remained within this transition zone, apart from one week of fluctuation. Two reasons may be given for such a phenomenon:

i. The production of latent heat as water turns to ice, temporarily compensating for the upward heat loss and thus stabilizing the temperature in autumn; in spring the reverse process absorbs heat during thawing, so that the rise in temperature is similarly delayed.

ii. The continuous trickle of water at 0° C draining along the top of the freezing plane during spring and summer.

At 100 cm., the temperature was above +0·5° C for less than 2 weeks at the end of January and the beginning of February, and so the proportion of the year within the freezing boundary decreases upwards until at 1 cm. only a single week in the year shows a steady temperature in this class. Fluctuations are far more common at the shallower levels, illustrating the greater influence of diurnal and cyclonic temperature cycles. This variation at the shallow depths also causes the maximum period to occur continuously within the positive class not at the surface but at a depth of 25 cm., where the minor cold spells have no great effect.

Fig. 1 also shows the penetration rate of the freezing plane at the beginning of winter and the rate of thaw at the end of winter. During March, the steadily colder air brought about the termination of positive temperatures, so that from 1 to 120 cm. the soil was within the freezing boundary. This situation obtained with a few minor fluctuations until the second week in April, when at 2·5 and 5·0 cm. the temperature dropped below −0·5° C and remained there. It was a further 2 weeks before the soil at 10 cm. depth finally froze, and another month before the freezing plane passed 25 cm. depth. At this stage, the action speeded up and within the following week soil at 50 cm. depth was frozen; 2½ weeks later a depth of 100 cm. was reached and 1 week after that the soil at 120 cm. was frozen. Thus, from the second week in April until the last week in June, the freezing plane passed from the surface to the permafrost level. The speed-up in freezing appears to have been caused by two factors:

i. A decrease in soil moisture.

ii. A period of low air temperatures (about −10° C) at the beginning of June, with little snow cover present to insulate the surface.

During the previous year a similar situation occurred when the surface did not freeze until the end of June, but when the winter cold finally arrived the surface was still snow-free and penetration of the freezing plane was unhindered, so that in less than 2 months the entire active layer was frozen.

At the end of the 1963 winter, temperatures were constantly below the freezing boundary at all depths until 7 November, at which date the 1 cm. level reached ±0·1° C. Only a day later both the 2·5 and 5·0 cm. levels reached −0·3° C, followed by the 10 cm. level 2 days later. By 18 November the 25 cm. level had entered the freezing boundary, and then at regular weekly intervals the 50, 100 and 120 cm. passed above —0·5° C. Between 7 November and 5 December virtually the entire active layer had been warmed to reach the freezing boundary. This speed of heat transfer in the soil is surprising when the mean air temperature for that November was −1·9° C. The strong solar radiation which was affecting the surface by the time the snow melted was partly responsible, as is evidenced by the high daytime temperatures followed by low temperatures at night. Perhaps more important, however, is the percolation of melt water through the soil, transferring heat to the frozen material beneath. This movement of water is not the convection envisaged by some, due to its maximum density at +4·0° C, since thermometer measurements showed that the water temperature was only +0·1° or +0·2° C. It is rather the gravitational drainage of melt water which reaches the impermeable level of the frost-table and then flows along it. When the zone of frozen material below the draining water reaches the melting point, the water ceases to have any warming effect and thereafter plays the opposite role of keeping down temperatures at this level. Where the frost-table is more or less horizontal, flowage of melt water is restricted and thawing is consequently hindered. This was seen in the fines at the sorted-circle thermistor site, where the warming for the upper 25 cm. was exactly similar to the control site, where drainage was efficient; below this depth, where the frost-table was almost level, the penetration of heat was much slower than on the slope behind the British Antarctic Survey hut. A similar effect was found at the site of soil sample series J (Chambers, 1966), where poor drainage caused the surface to be almost permanently waterlogged. This blanket of water, with a very high specific heat relative to the air spaces in the soil, prevented the strong heating of the surface to such an extent that the frost-table was maintained at a depth of about 40 cm. throughout the entire summer. It seems likely that the high water content of the frozen material also hindered its thawing. Contrasting strongly with this site is the well-drained slope on the eastern flank of Moraine Valley. Under the influence of a 9° slope the water drained away rapidly, allowing the maximum influence of strong summer radiation which caused the active layer to warm up at a rate much faster than that at the control thermistor site near the station. These examples show the great variety of situations found on Signy Island at sites where the depth of the permafrost table and the rate of heat transfer within the active layer is regulated by the soil-water conditions. The danger of generalizing from the limited information available is evident where such local contrasts occur, although the active layer at the control site was one of the most typical environments on the island.

The analysis of soil temperatures throughout 1963 reveals a wide range at each depth. This is illustrated in Fig. 2, where the mean monthly temperature at each depth is shown for five

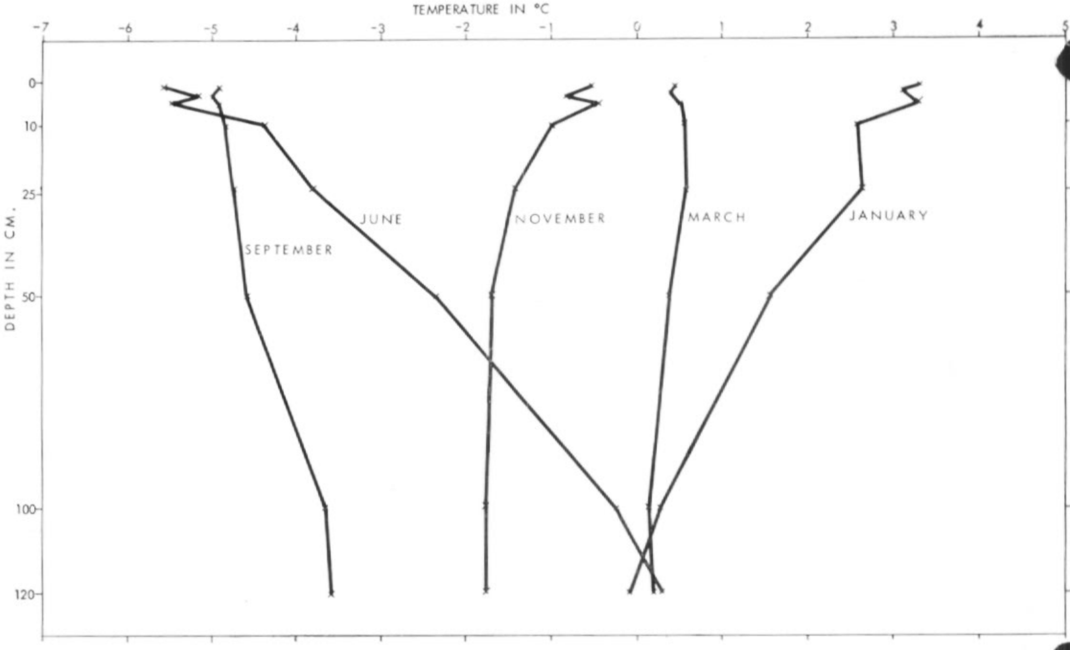

Fig. 2. Temperature profiles at the control thermistor site for five selected months in 1963.

selected months. In January, surface heating was at a maximum with mean temperatures in the upper 5 cm. well above +3·0° C and a more or less gradual decrease with depth until at 120 cm. it was still below 0° C. The partial moss cover of the site, together with its north-westerly aspect, mean that the high figure for the shallow levels is warmer than at most places on the island. This is substantiated by the unusual presence of a few tussocks of grass, which selects only the most favoured sites (Holdgate, Allen and Chambers, 1967). By March the active layer was almost isothermal, with only a gradient from +0·4° C at the surface to +0·2° C at 120 cm. This situation was brought about by a gradual cooling of the upper levels caused by decreasing solar radiation and lowering air temperatures. At the same time the deeper levels warmed slightly as summer radiation penetrated to the base of the active layer. As winter cooling proceeded, the temperature recorded by the shallower thermistors dropped lower and lower until in June the mean in the top few centimetres was about −5·5° C. However, the deeper ones were still warm, so that a steep gradient exactly opposite to that in

January prevailed, with the 120 cm. level still at its March figure of +0·2° C. The severe cooling at this time was accentuated by lack of snow cover, which allowed maximum heat loss by radiation in the long winter nights and maximum influence of cold air masses drawn in by depressions passing to the north. With the complete snow cover which occurred in July, the surface did not reach any lower temperatures, but the heat loss from the active layer caused the deeper layers to cool rapidly, so that by September the steep gradient at depth had once more disappeared leaving a narrow range from −4·9° C at the surface to −3·6° C at 120 cm. Throughout the freezing of the active layer, there was no hint of an upward movement of the permafrost freezing plane. The continued flow of water at permafrost level long into the winter appeared to hinder any such upward advance of the ice at the cessation of summer heating.

The situation in September was maintained throughout October, when a little warming of the soil took place in spite of continuously low air temperatures. The rise in soil temperature was quite uniform, however, raising the level at each depth by about 0·5° C. It has already been pointed out that in 1963 October was abnormally cold, so that in most years at this time a greater degree of surface heating would have taken place. The situation for November, shown in Fig. 2, illustrates the effect of surface heating with the gradual disappearance of the snow cover. At this time the upper few centimetres were characterized by rapid and violent diurnal fluctuations with several freeze-thaw cycles. The deeper thermistors, on the other hand, show little effect of these variations, but the temperatures recorded by them continued to rise steadily. The full influence of surface heating is not apparent, since the ground was snow-covered for the first half of the month. The January means (Fig. 2) show the final summer picture, which starts the cycle over again. The presence of the permafrost table only a few centimetres below the 120 cm. thermistor is noticeable in the low summer means for that depth, where the highest temperature ever recorded was +0·7° C on 17 February 1963 at 03.00 hr. L.M.T. Whilst it is clear that the upper zone of the permafrost had an annual cycle of about 3° C, the incoming summer heat was never sufficient to bring it above melting point. When this thermistor site was excavated in March 1964, ice was found only a few centimetres below the 120 cm. probe, and the coarse gravelly material immediately above that level was saturated with water draining down the slope.

Short-term Temperature Cycles

The influence of the diurnal fluctuations of solar radiation on soil temperature is far more difficult to analyse than the seasonal cycle outlined above. The passing of a cloud across the sun or the falling of a shower of rain affect temperatures when the top few centimetres of the soil are examined on this scale. To assess the relative importance of all such factors is well-nigh impossible, since their effect is never isolated. Thus each 3 hr. observation of the soil temperature at a depth of 5 cm. depends not only upon the season of the year and the time of day but on the weather during the previous half-hour or so. The superimposition of these factors associated in cycles of contrasting amplitude means that any single observation may reflect the dominance of any one cycle. The irregularity of cyclonic activity and cloud cover precluded the use of a simple harmonic analysis on these data, since the prediction of any consistent frequency was impossible. Fig. 3 illustrates the difference in soil temperature between several sunny days followed by several dull days in January 1963. A diurnal variation can be seen in the air temperatures, plotted at the top of the diagram, together with the sunshine which occurred during the period. There was no snow cover at this time and the melt water had drained away, although the surface was still moist. The highest air temperature recorded at a synoptic observation during this time was +4·8° C at 18.00 hr. L.M.T. on 4 January, 3 hr. after the highest 1 cm. soil temperature of +16·3° C was observed. On this day there were 15 hr. of strong sunshine with no wind, so that heating of the air by the warm ground was at a maximum. On the following day, 5 January, when both air and soil temperatures were similarly high (air: +4·6° C; 1 cm. soil: +14·6° C), the weather was completely different, with a fresh breeze veering from south-easterly at 17 kt. (8·8 m./sec.) to north-westerly at 5 kt. (2·6 m./sec.), and occasional sleet and slight rain. The factor which appeared most significant in this heating was the lack of dense cloud, allowing strong incident

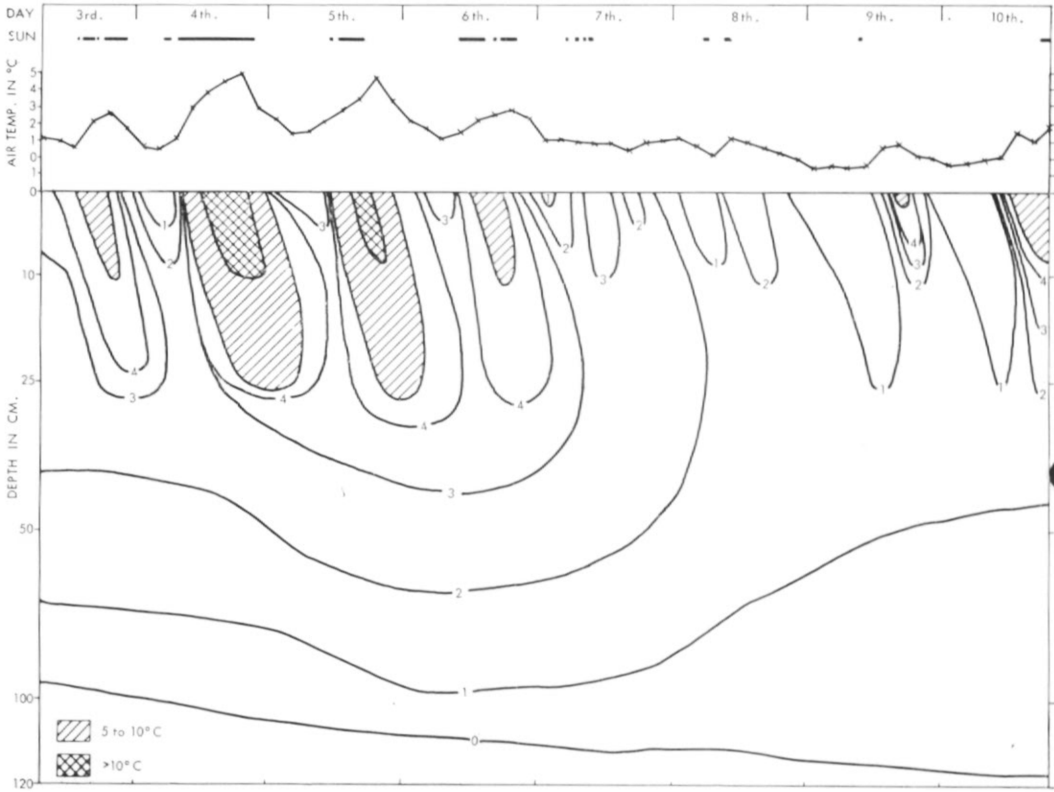

Fig. 3. Soil and air temperatures during 3–10 January 1963.

radiation from the high summer sun. On 7 and 8 January, when there was an almost continuous cover of low and medium cloud, the 1 cm. soil temperature did not rise above +3·4° C. The heating and cooling of the soil brought about by changing air masses was far more gentle and gradual than the intense fluctuations caused by radiation. After the sunshine of 4 January 1963, the 1 cm. soil temperature dropped 10° C in 3 hr. with a corresponding drop of only 2° C in the air temperature. It was not unusual for the situation to be reversed during the passage of a cold front when it has been known for the air temperature to drop 7° C in 3 hr. while the soil temperature rarely fell more than 2° C.

This contrast between the effect of radiation and air temperature on the soil was most significant in spring and autumn, when air temperatures were frequently below freezing point and there was a relatively strong insolation on to a snow-free surface. On 3 October 1962 the air temperature did not rise above −0·6° C all day, but at 1 cm. depth the soil reached +5·6° C as a result of strong sunshine, and even during the following night the soil temperature remained at +0·1° C in spite of the minimum air temperature of −4·7° C. Thus in the daytime no thawing would have been inferred from screen temperatures, and at night freezing would have been assumed, which illustrates the errors inherent in the calculation of freeze-thaw frequencies from mere air-temperature records.

In the absence of more adequate data, several workers have attempted to analyse freeze-thaw activity from nothing but daily maximum and minimum screen temperatures, but in the light of the soil-temperature investigation at Signy Island their results appear highly suspect. Without taking into consideration snow cover, radiation and soil moisture content, it is impossible to calculate with any accuracy the presence or absence of freezing in the soil. Russel (1943) suggested that an air temperature below 28° F (−2·2° C) indicated an effective freeze at ground level, and that a thaw could be inferred from an air temperature above freezing point. Fraser (1959) sought to improve on Russel's definition and proposed a range of 28° to 34° F (—2·2° to +1·1° C), whilst D. W. Boyd (Fraser, 1959, p. 42) used an even wider range of 25° to 35° F (—3·9° to +1·7° C). It is evident, however, that each separate occasion of freezing and thawing requires a different degree of heating or cooling, dependent upon the ambient temperature and water content of the soil, the duration of the fluctuation, the intensity of solar radiation and the character and depth of any snow cover. Beckel (1957) stressed the importance of depth and compaction of snow as a variable factor in the insulation of the soil surface and in damping the cycle of fluctuating air temperature. On Signy Island the situation often arose in spring, when the surface was covered by a layer of compact snow and ice 4 or 5 cm. thick, that solar radiation would penetrate the snow and thaw the soil beneath to a depth of 1 or 2 cm., even when the air temperature was below freezing point. This difference between screen temperatures and actual freeze-thaw cycles was illustrated by Matthews (1962) and Andrews (1963) in their work at the McGill Sub-Arctic Research Laboratory. By measuring vertical movement at the soil surface, they were able to determine exactly when ice segregation took place, and a comparison of screen temperatures over a period of 43 days revealed several anomalies. A similar comparison was made for a 1 month period at Signy Island in October 1962. Eight actual freeze-thaw cycles took place at 1 cm. depth during that month, according to the definition of a freeze-thaw cycle as the fall of soil temperature below —0·5° C and its subsequent rise above +0·5° C. On 11 other days in that month the air temperature dropped below 0° C and the soil temperature remained above freezing point, whilst on 5 days the air temperature went below —2·2° C (28° F) and on 4 days below —3·9° C (25° F) without the freezing of the soil at 1 cm. depth. Snow cover was the major factor in preventing freezing of the soil during this time although the presence of melt water also hindered the cooling.

The occurrences of all freeze-thaw cycles which were recorded during the period January 1962 to December 1963 are tabulated in Fig. 4. The most surprising feature is the rapid decrease of cycles with depth until below 10 cm. only the annual freezing and thawing took place. The reason for this failure of the cold spells to penetrate deeply into the soil appears to be the relatively brief duration of the cooling. It has already been observed in Fig. 1 that even at a depth of 10 cm. the soil remains for several weeks within the freezing boundary before the

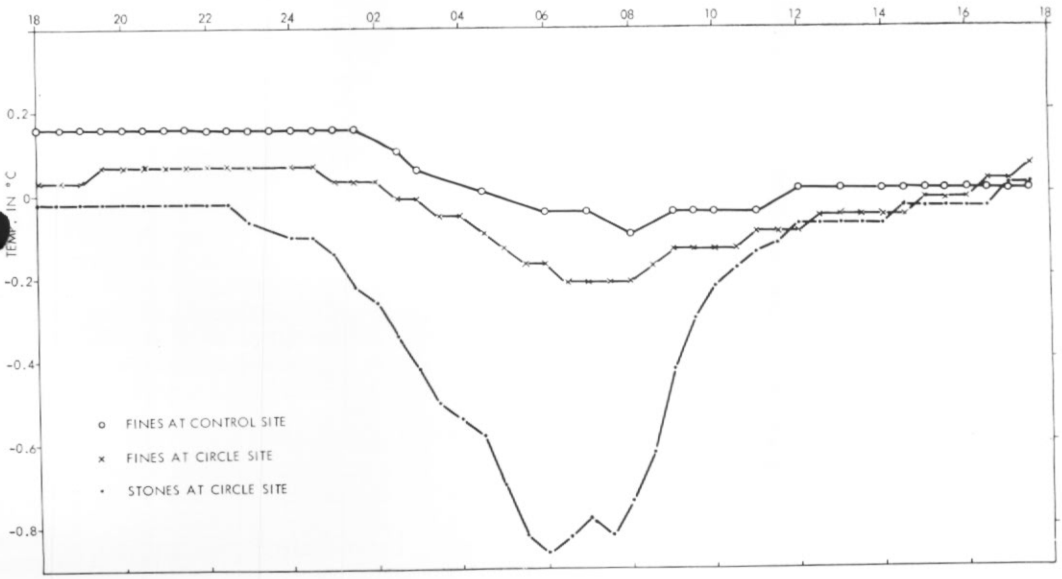

Fig. 4. Half-hourly soil temperatures at 5 cm. for three sites, 20–21 February 1963.

temperature finally drops below −0·5° C. The freeze-thaw cycles, on the other hand, are usually brought about by cyclonic disturbances together with some radiational cooling, and these rarely last more than a few days.

Temperatures within a Sorted Circle

Although this freeze-thaw information was gathered at the control thermistor site, a comparison between this and the fines at the stone circle site shows that the two are quite similar. The main differences between the sites are:

i. The circle site is poorly drained and wetter.
ii. The control site accumulates less snow in winter.

The result is that the high moisture content of the circle site makes it slower to freeze and slower to thaw, and that the control site experiences extremes of temperature from which the circle site is insulated by 30 or 40 cm. of snow. These factors do not influence the frequency of spring and autumn freeze-thaw cycles to any great extent and, although on one or two occasions cycles were recorded at the control site but not at the circle site, the reverse was also true, so the total may be taken as reasonably accurate for both sites. This does not apply to the stones at the circle, however, for these experience a totally different regime. Here heat transfer is far more rapid than in the moist soil, so that extremes are always greater among the stones. This is revealed by the consistently high standard deviation of the monthly temperatures, as in January 1963, when in the stones at 10 cm. depth the mean temperature at 18.00 hr. L.M.T. was +4·5° C, with a standard deviation of 2·6, compared with the same depth in the fines, where the mean was +4·2° C with a standard deviation of 2·0. The only exception to this situation was at the spring thaw, when the trough around the stones was full of water, which kept the temperature very steady whilst the fines were subjected to daily warming from the sun. During the 2 yr. period of observation the stones must have undergone many more freeze-thaw cycles than the adjoining fines but, because the stones were dry for most of that time, the frequent passage of the freezing plane had no significance, since there can have been little ice segregation. Table II illustrates the differences between the control, the stones and the fines as shown by observations at 30 min. intervals for 24 hr. on 20 and 21 February 1963. The depth of 5 cm. was chosen for this comparison, although the 1, 2·5 and 10 cm. depths were found to exhibit the same pattern of change to a greater or lesser extent. Below 10 cm., however, the diurnal fluctuation was lost and all three sites experienced a steady drop of about 0·2° C at 25 and 50 cm. during the 24 hr.

Rapid heat transfer through coarse material has been proposed as the means by which uneven freezing of the active layer takes place. This situation is necessary before there can be any movement of unfrozen fines by cryostatic pressure, according to Washburn (1956). At first sight, the extremes of temperature within the stones of the Signy Island circle appear to substantiate the validity of this process, since it is clear that the coarse material froze 3 weeks before the fines at the same depth. Cook (1955) found a similar effect during his investigation of temperatures within an active layer of only 20 cm., where rock fragments at permafrost level froze 3 weeks before the adjoining lines. At Signy Island, however, the sorting observed at the surface of the circle was only about 20 cm. deep and it did not extend to the permafrost level at all, so that the contrast in date of winter freezing decreased rapidly with depth. At 25 cm. depth there was only a 10-day gap between stones and fines, and at 50 cm. it had narrowed to less than 2 days. By the time the freezing had penetrated a further 20 or 30 cm. to the permafrost level, it seems likely that the fusion of the two frozen layers would have been almost simultaneous on a horizontal plane. The concept of the movement of fines under cryostatic pressure appears unacceptable in this instance.

Another interesting feature of the Signy Island soil-temperature regime is the contrast between soil and moss at comparable depths. Fig. 4 shows that at a depth of 2·5 cm. in soil there were 25 freeze-thaw cycles in 2 yr., but only 13 in the moss. The mean monthly temperatures for 1963 are compared in Table III. Holdgate (1964) has discussed the moss environment of Signy Island from the biological aspects, but it is also significant in a study of patterned ground. The insulation which a moss cover affords to the soil surface accentuates differential freezing and frost-heave in adjoining bare patches. Miniature sorted patterns have

TABLE II. FREEZE-THAW FREQUENCIES (CYCLES PER MONTH) IN THE ACTIVE LAYER FOR 1962 AND 1963

	Depth (cm.)								
	1	2·5	*Moss* 2·5	5	10	25	50	100	120
1962									
January								S	
February	1	1							S
March	5	5	4	2					
April	4W	2W	1W	1W	1				
May					W				
June									
July						W	W		
August								W	W
September									
October	8S	4S	1S	3S	S				
November	2	2	1	1					
December	2	2				S	S		
1963									
January								S	
February	1								S
March	5	4	2	2					
April	3W	1W	1W	1W	W				
May						W			
June							W	W	
July									W
August									
September									
October									
November	4S	S	S	S	S				
December	5	2		1		S	S		
Total	42	25	12	13	3	2	2	2	2

W = Winter freeze. S = Summer thaw. S+W = 1 freeze-thaw cycle.

never been observed to occur below a layer of moss, and in most cases vegetation hinders surface movements, not merely by its binding action but by protecting the soil from rapid thawing and frost-heave cycles which promote creep and solifluction.

TABLE III. COMPARISON OF SOIL AND MOSS TEMPERATURES AT 2·5 cm. FOR 1963

1963	*Soil*	*Moss*	*Air*
January	+3·1	+4·1	+1·8
February	+2·4	+3·0	+1·7
March	+0·4	+0·5	+0·2
April	−0·4	−0·5	−1·8
May	−1·3	−0·8	−3·0
June	−5·2	−2·5	−7·1
July	−5·6	−3·4	−6·3
August	−6·9	−5·8	−9·6
September	−5·0	−5·1	−6·7
October	−4·4	−4·1	−7·1
November	−0·5	−0·1	−1·9
December	+2·4	+3·3	+0·5

CONCLUSION

One of the greatest problems encountered during this soil-temperature study was the determination of the precise point of freezing. It is likely that the definition of a freeze-thaw cycle adopted here is too conservative, and that in fact there were more minor cycles when the soil temperature went below 0° C but not below −0·5° C, although the degree of ice segregation which could take place in such circumstances is small. The high chemical content of the ground water of Signy Island meant ice would not form until the temperature had dropped at least 0·1° C below the freezing point, and even the winter snow was found to have a surprisingly high salt content (Holdgate, Allen and Chambers, 1967). It has also been found that much soil water does not freeze at 0° C (Williams, 1964). There was also a possibility of heat conduction by the thermistor housing, causing the temperature of the tip of the sensor to be slightly more extreme than its surroundings. In order to allow for these minor differences, it was decided to use the ±0·5° C definition of a freezing cycle. There is a need for further accurate measurements in this field, coupled with careful investigation of the conditions under which ice forms in the soil.

The number of factors which determine a freeze-thaw cycle has been illustrated by the frequent anomalies between air and soil temperatures. The value of conclusions reached merely from a study of daily air-temperature extremes appears dubious in the light of these findings. There is no doubt that distant-reading soil thermometers are essential before an accurate picture of periglacial soil conditions can be obtained. The addition of some frost-heaving recording device, such as that described by Matthews (1962), would supply most useful information to accompany the soil-temperature record. As yet no quantitative work has been published on the difference between a freeze-thaw cycle and a frost-heave cycle, a distinction which is most important in the consideration of periglacial geomorphology. The implications of the freeze-thaw data discussed here with respect to the up-freezing of stones and other processes operating in patterned ground at Signy Island are discussed in a later paper.

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