THE SIGNY ISLAND TERRESTRIAL REFERENCE SITES: XV. MICRO-CLIMATE MONITORING, 1972–74

By D. W. H. Walton

Abstract. The equipment used at the Signy Island terrestrial reference sites (SIRS) to collect hourly soil temperature and radiation data is described, together with details of reliability and accuracy of data. Analyses of temperature data showed that, although the annual range could be in excess of 60 deg, the maximum diurnal range was only 36 deg. The maximum cooling rate measured at the surface of the *Polytrichum* moss turf was 16.5 deg h^{-1}. Temperatures above +5°C and below −15°C were uncommon at both sites, accounting for less than 15% of all hourly measurements. Absolute maximum and minimum temperatures at the surface of the *Polytrichum* turf were +35.8° and −26.5°C. The frequency of freeze-thaw cycles varied from year to year with a maximum of 64 being recorded in 1972. Radiation as a percentage of the maximum possible for lat. 60°S was less than 50% for 8 months of the year due to cloud cover. Up to 20% of the photosynthetically active radiation penetrated 20 cm of winter snow.

In Tilbrook (1973) an outline was given of the environmental monitoring programme for the SIRS. Recording of soil-temperature profiles and incoming radiation on a regular hourly basis began at the SIRS on 1 January 1972 and is still in progress to provide the necessary physical background data for interpretation of the biological data. This paper describes in detail the equipment used, assesses its limitations and examines the value in biological terms of the information collected during the first 3 years.

Equipment

Grant type D micro-climate recorder

This instrument is built around a Rustrak chart recorder utilizing pressure-sensitive paper. It is a 20-channel instrument, channels 1–19 being allocated to temperature measurement by thermistors and channel 20 to radiation recording. Frequency of recording is controlled by a clock-and-cam system, enabling scan intervals of 15, 30 and 60 min to be selected. At the chosen time, a micro-switch on the cam passes a small current which, by discharging a capacitor, activates a motor. This motor drives a two-stage switching system controlling sensor-channel selection and power for the chart drive motors.

The recorder circuitry is simple. The thermistors are switched in succession into a Wheatstone bridge and the circuit balance recorded by the galvanometer. Two temperature ranges are available: −10° to +40°C and −30° to +20°C. These are selected manually by altering fixed resistors in the bridge circuit. The circuit output to the galvanometer is trimmed to linearize the thermistor-response curve. Adjustment may be made to the output to allow for changes in battery voltage using two potentiometers in the thermistor circuits, whilst a galvanometer adjustment screw permits an accurate zero base line to be maintained. Fixed calibration positions allow circuit errors to be corrected later.

The recorder in use was kept in a field hut between the two SIRS sites. The lower temperature scale was used during the winter and the upper scale during most of the summer. Calibration checks were made on the recorder each time the sites were visited. Time marks were put on the chart and any changes in recorder behaviour or probe disposition were entered in a log. Charts and batteries were changed every 3–4 weeks in the summer but, in winter, batteries were changed more frequently. Completed charts were annotated with regular time marks and checked for completeness of records. They were then returned to the United Kingdom for further processing. The subsequent data handling has been described in Walton (1977).

Sensors

The temperature sensors were Gulton 32TD25 thermistor beads (2 000 Ω at 25°C) encased in stainless steel tubes 50 mm by 3.5 mm. Their time constant was *c.* 20 s with tolerance limits between sensors of ±0.2°C over most of the range. Cable runs from the recorder to each thermistor were 200 m long but, since cable resistance as a percentage of total resistance was very small, its effect was ignored. Five sensors were used at each site to monitor moss and soil temperatures at the following depths: surface, 1.5, 4.5, 7.5 and 10.5 cm.

Incoming solar radiation was monitored by a Kipp and Zonen type CM5 solarimeter mounted horizontally on top of the field hut. No power was available for de-icing so that winter records were unreliable at times due to snow or ice on the dome.

Equipment and data limitations

The Grant recorders were generally very reliable and data capture in the first 3 years of the programme was 97%. Losses were attributable to several causes, although the principal one was undoubtedly mechanical problems with the chart-winding mechanism. Incorrect alignment of charts on the take-up spool often caused buckling of the paper which in turn inhibited free movement of the galvanometer needle. Poor adjustment of the slipping-clutch mechanism resulted in failure of the chart to wind on after each recording cycle. The use of a heater in the field hut during the winter produced high humidity levels. Water absorption by the chart paper caused changes in paper tension on the drive rollers and subsequent buckling of the chart. A problem especially associated with low temperatures was the difficulty experienced by the mechanical clock in initiating recording cycles. This was due to a decline in battery capacity, increased stiction on motors and increased leakage from dielectric capacitors.

Since transcribing errors can be frequent if chart reading is done manually, especially if the data are badly recorded, all data were digitized. Fig. 1 shows examples of both good and poor traces. The elongated shape of some traces is common in older recorders and is due to poor channel switching, excessive damping on the galvanometer, or a combination of both. Where "tails" occurred (arrowed in Fig. 1), traces were read from the end point.

Charts were annotated before being digitized on a Ferranti Freescan digitizing table. After processing to provide a tape file, corrections were made for galvanometer response, changes in battery voltage and recorder electronic characteristics, and the data were edited for obvious errors by a trapping programme; further errors were corrected by visual examination of the file.

The micro-meteorological data collected at the two reference sites were primarily for biological applications. Although limitations in equipment accuracy, the rate of data sampling and the corrections applied to produce the final computer listing, probably make the data set unsuitable for any detailed energy-balance studies, the limits of accuracy are within those commonly used for field measurements of biological activity. Walton (1977) contained a summary of the first 3 years' data from the sites on a 10-day block basis, together with a detailed

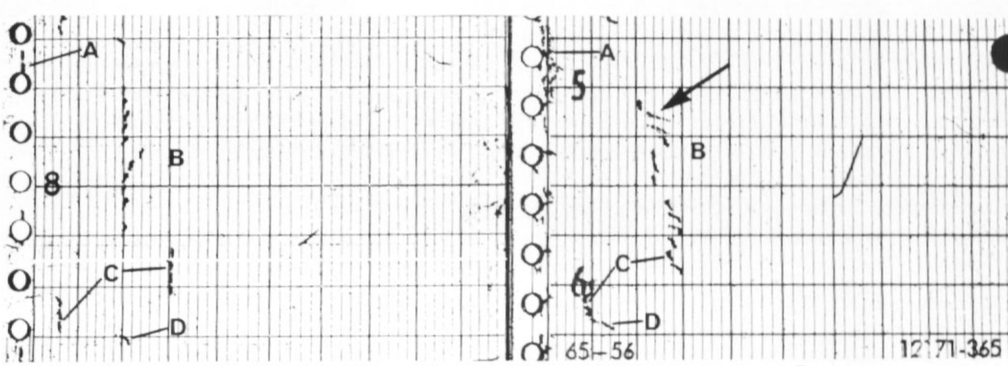

Fig. 1. Example of recording chart from SIRS micro-climate recorder. A, start of recording cycle; B, SIRS soil temperatures; C, calibration resistors; D, radiation. Arrow marks record referred to in text.

assessment of the errors within the system. After all corrections had been made, the absolute accuracy was ±2.3°C for the worst case but normally ±1.2°C or better for most of the data. Accuracy between points on a profile was ±0.5°C. Accuracy of this order is within acceptable limits for most biological purposes with one exception: greater accuracy would be especially useful in the temperature band −2° to +1°C. Energy movements in this region due to changes in the state of water are significant and may be crucial for the activity and survival of many organisms. It is interesting that of many other workers who have published data collected on Grant recorders only a few (e.g. Longton, 1979) have attempted to estimate the errors associated with the system or to set the accuracy of the data in the context of its specific application.

SIRS Micro-climate

Radiation

Meteorological records show Signy Island to be very cloudy throughout the whole year (e.g. Limbert, 1977*a, b*). Clear days are rare. Only once in 3 years did the mean monthly cloud cover fall below 6–8 oktas (Fig. 2a). Cloud amounts were generally least in the winter months (July–September). Direct sunshine, as measured by a Campbell-Stokes recorder at the scientific station, showed strong seasonal differences with a clear monthly maximum in December (Fig. 2b). The high values for August were associated with relatively small changes in mean cloud cover.

The total radiation received throughout each of the 3 years was calculated as a percentage of the maximum possible for lat. 60°S. Although there is a clear annual pattern (Fig. 3), 1973 appears to have been considerably different from the other 2 years. When plotted directly as mean monthly integrated radiation, annual differences appear much smaller (Fig. 4). There were certainly smaller differences in total radiation received than in sunshine received. This is not unexpected since, with high cloud cover, diffuse radiation is a significant proportion of the total received and this was not recorded by the Campbell-Stokes equipment.

Snow-cover is general and persistent over most of Signy Island from early April until October or November, although snow depth on the SIRS is rarely more than 60 cm (Block, 1980). For much of this period the radiation received is not of great biological importance. Where snow-cover is shallow, and more especially as snow depth decreases during melt, radiation penetration to plants may be sufficient to allow photosynthesis (Ahmadjian, 1970). The extent of radiation attenuation in snow varies with the density and structure of the snow-pack (O'Neill and Gray, 1973). Limited measurements by S. P. Kightley (personal communication) of the penetration of photosynthetically active radiation (PAR) through Signy Island snow show that up to 20% of total incident PAR can penetrate up to 20 cm of late winter snow. This would suggest that cryptogamic species with photosynthetic systems adapted to low temperature and light levels would begin net dry-matter production in advance of complete snow melt.

Length of growing season

It is often difficult in cold regions to set useful general limits on the summer period or growing season as is frequently done in temperate regions. Some plants can grow beneath the snow (Ahmadjian, 1970), whilst many invertebrates show considerable activity at sub-zero temperatures. An arbitrary temperature limit is not satisfactory nor, in some instances, is the presence or absence of snow-cover. On Signy Island, snow may fall on any day of the year and ground temperatures may fall below zero even in the summer. Nevertheless, it might be useful to define the Signy Island summer as the period between the onset of general ground thaw and the onset of general freezing of the whole soil profile for two reasons:

i. This period corresponds with the general availability of liquid water to organisms.
ii. The optimal growth temperatures for all organisms so far investigated are above 0°C.

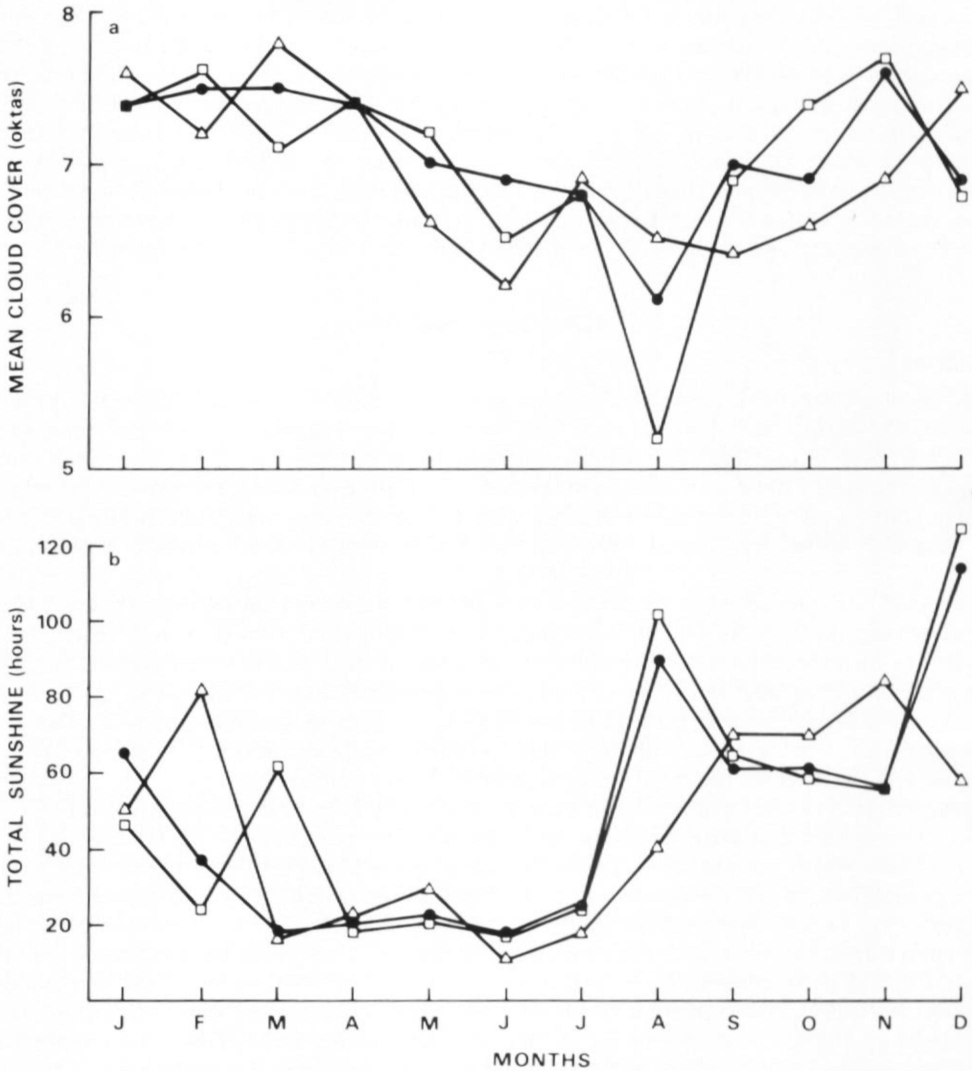

Fig. 2. a. Mean monthly cloud cover (based on daily noon assessments) over the year.
b. Total monthly sunshine received by a Campbell-Stokes recorder.
● 1972; △ 1973; □ 1974.

During the thaw, release of latent heat by melting of ice typically produces an isothermal temperature profile which can persist for many days. This "zero curtain" effect may be of particular biological importance, since at this time free water is available throughout the soil profile together with nutrients released by earlier freeze-thaw cycles.

SIRS 1 began to freeze and to thaw before SIRS 2 in each of the 3 years studied (Table I). The freezing of the soil profiles was more variable than the thaw, although it always began before mid-April at both sites. Re-melting occurred frequently on days with high radiation levels and no clear zero-curtain effect was discernible. Depending on the criteria used to define winter, this season varied from 189 to 253 days. For non-motile surface organisms, such as mosses and

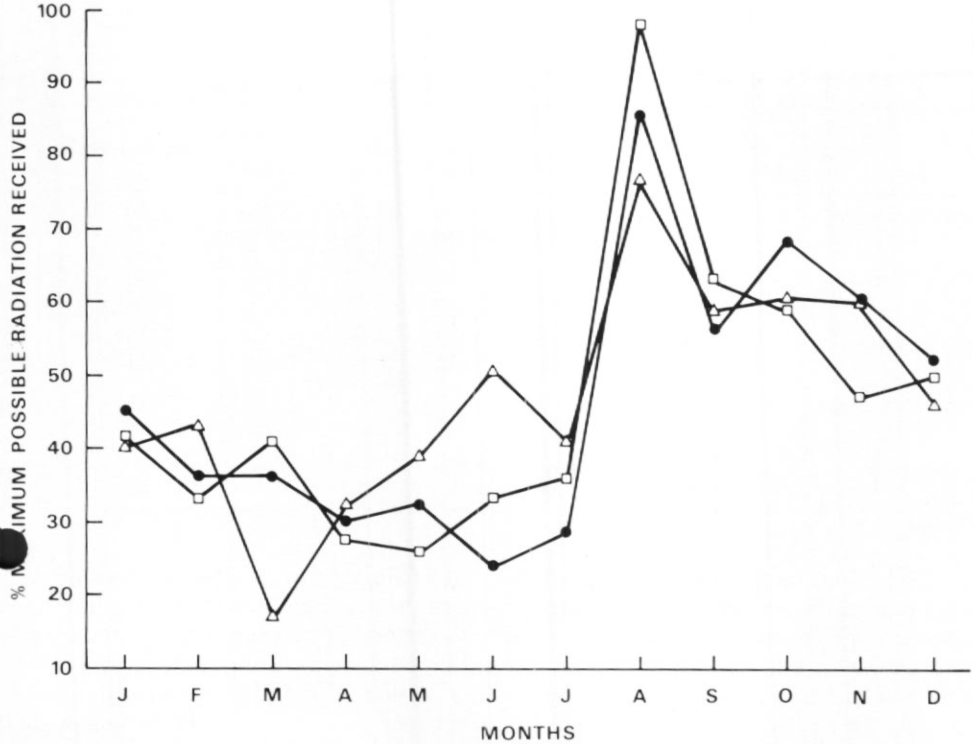

Fig. 3. Radiation received (measured by Kipp and Zonen solarimeter) as a percentage of maximum possible radiation for lat. 60°S (List, 1949).
● 1972; △ 1973; □ 1974.

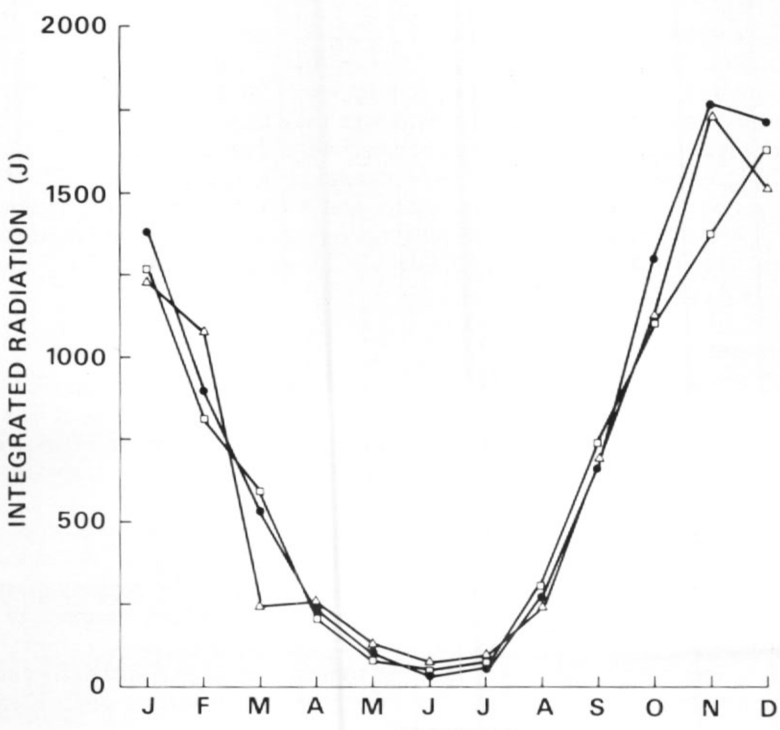

Fig. 4. Mean monthly integrated total radiation received at SIRS, 1972–74.
● 1972; △ 1973; □ 1974.

TABLE I. SEASONAL FREEZE AND THAW EVENTS OF SIRS 1 AND 2, 1972–74

Year	SIRS	Freeze		Thaw			Length of season (d)
		Start	Finish	Start	Zero curtain	Finish	
1972 winter	1	4 Apr	7 May	16 Oct	19 Nov	28 Nov	195
	2	12 Apr	6 May	14 Nov	2 Dec	7 Dec	216
1972–73 summer	1						160
	2						151
1973 winter	1	25 Mar	2 May	8 Oct	3 Nov	26 Nov	197
	2	14 Apr	3 May	8 Oct	20 Nov	23 Dec	177
1973–74 summer	1						186
	2						189
1974 winter	1	12 Apr	30 Apr	19 Oct	2 Nov	4 Nov	190
	2	15 Apr	18 May	20 Oct	4 Nov	8 Nov	189

lichens, winter could be assumed to be from the start of freezing to the start of thawing, since these will occur at the soil surface. For motile organisms retreating down the profile as freezing begins, winter could be taken as the end of freezing to the end of thawing. Clearly, the duration of summer or winter can only be accurately defined in the context of the ecology of particular organisms. On the criteria previously outlined, the duration of the growing season was very similar at both sites, although there were differences between years of 3–4 weeks which might be biologically significant.

Maximum and minimum temperatures

During the 3-year study period the absolute maximum and minimum temperatures in the surface layer at both sites were: SIRS 1, 35.8°, –26.5°C; SIRS 2, 26.5°, –21.5°C. The absolute maximum and minimum temperature profiles were almost isothermal at SIRS 2 but had a marked gradient at SIRS 1 (Fig. 5). This difference may be attributable to the higher water content of SIRS 2 (Goddard, 1979) which dampens change. The maximum surface temperature occurred in mid-December in 1972 and 1974 but in early February in 1973. The surface minimum temperature occurred in May, June, July and August in different years, never on the same day at both sites. The annual range of soil temperatures was greatest at the surface of SIRS 1: 1972, 62.3 deg; 1973, 50.5 deg; 1974, 52.5 deg; and least at 10.5 cm: 1972, 37.1 deg; 1973, 25.2 deg; 1974, 31.3 deg.

Temperature patterns

Goddard (1979) contains values of the 10-day mean, mean maximum and mean minimum temperatures from January 1972 to March 1974 for each of the five depths at SIRS 1, taken from Walton (1977). They show clearly the dampening of response with increasing depth. The depression in mid-summer temperatures in January 1973 was due to a sudden snowfall on 6 January which took 2 weeks to melt.

The tautochrones in Fig. 6 illustrate the seasonal effect on temperature profiles using data from mid-day on the second day of each month in 1972. August was by far the coldest month at both sites. For 5 or 6 months the profiles were virtually isothermal. The January profile at SIRS 1 showed an inversion at 4.5 cm. Inversions occurred at both sites in the summer and were often associated with snowfalls or rain during the day and radiative surface cooling at night.

During the snow-free period, radiation and water content are the principal determinants of the surface temperature, where diurnal variation is greatest. Fig. 7 illustrates surface temperatures

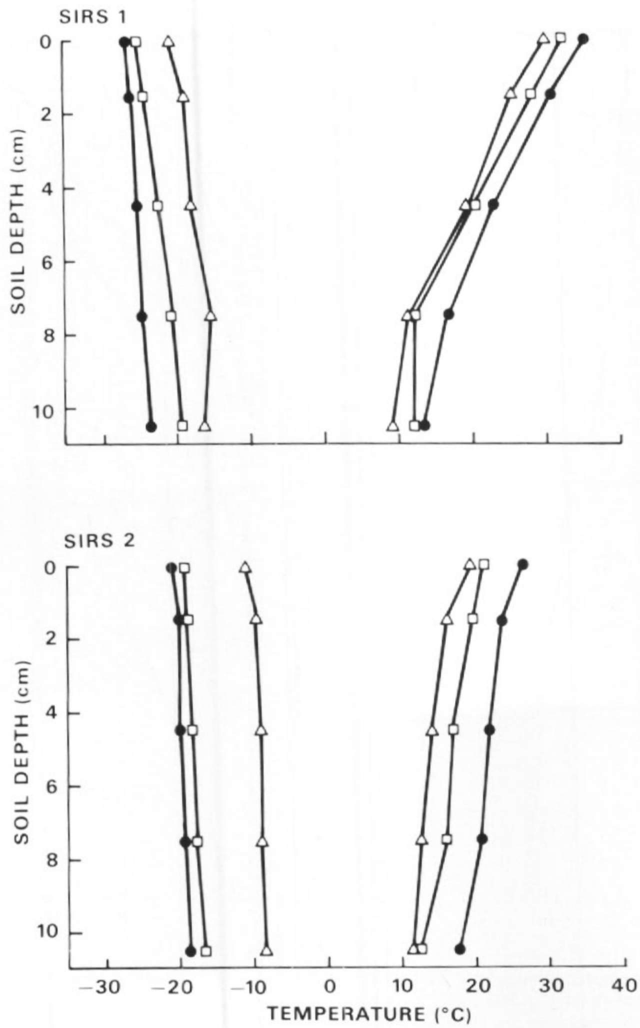

Fig. 5. Absolute maximum and minimum soil temperature profiles at SIRS.
● 1972; △ 1973; □ 1974.

on representative sunny and overcast days for spring, summer and autumn in 1972. The patterns were very similar in the other 2 years. In spring there was little diurnal change at SIRS 2, although at SIRS 1 on a sunny day the diurnal range was about 17 deg. This range increased during the summer to 21.8 deg at SIRS 1. On the overcast summer day the range at SIRS 1 was 10 deg, only 1.7 deg greater than at SIRS 2. In autumn the range under overcast conditions was 5 deg at SIRS 1. High radiation increased this to 15 deg with night temperatures below zero due to radiative cooling. Autumn night temperatures at SIRS 2 remained close to zero probably as a direct result of the buffering action of soil water.

Over the 3-year period, diurnal temperature range at the surface of the two sites showed a maximum of 36 deg at SIRS 1 and of 25.6 deg at SIRS 2 (Fig. 8). Hourly temperature measurements are probably too infrequent to show the true maximum rates of cooling in the field. However, within the limitations of the current data, the maximum cooling rate at the

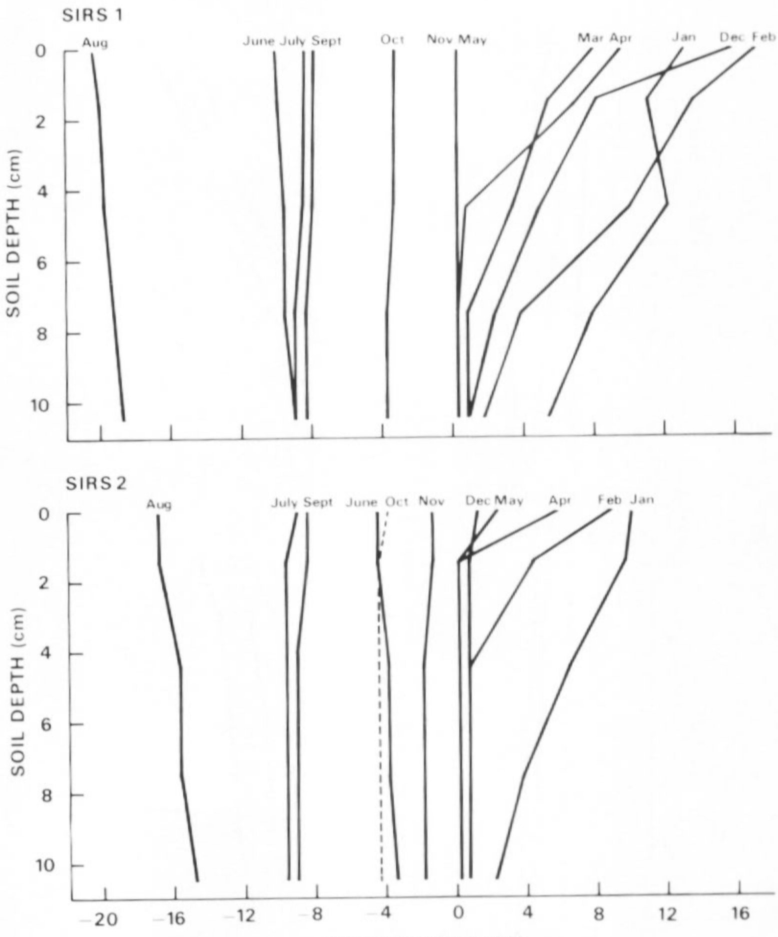

Fig. 6. SIRS soil-temperature profiles at 12.00 h on the second day of each month in 1972 (insufficient data for March tautochrone at SIRS 2).

surface was 16.5 deg h^{-1} at SIRS 1 and 7.8 deg h^{-1} at SIRS 2. The water content of the SIRS 2 soil was generally at least twice that of the SIRS 1 soil (Jennings, 1979) and this markedly decreased the diurnal range at that site throughout the 3 years. The daily range at both sites was very small at both freeze-up and melt. The effect of the zero curtain is especially clear in the data for 1973.

There were marked differences between the two sites in the frequency of freeze-thaw cycles at the surface (Table II). The wet community of SIRS 2 showed little change year by year in the total number of cycles, although there were differences in distribution between months. With only two exceptions, no freeze-thaw cycles occurred from June to September in the 3 years. There is no obvious reason why the total number of cycles at SIRS 1 declined so markedly between 1972 and 1974, the change being due almost entirely to a decrease in the number of cycles in the January–March period.

In order to demonstrate the frequency of occurrence of particular surface temperatures, frequency histograms have been plotted for 5 deg temperature classes (Fig. 9). For all seasons, except winter, the most important temperature class was 0° to +5°C, especially at SIRS 2.

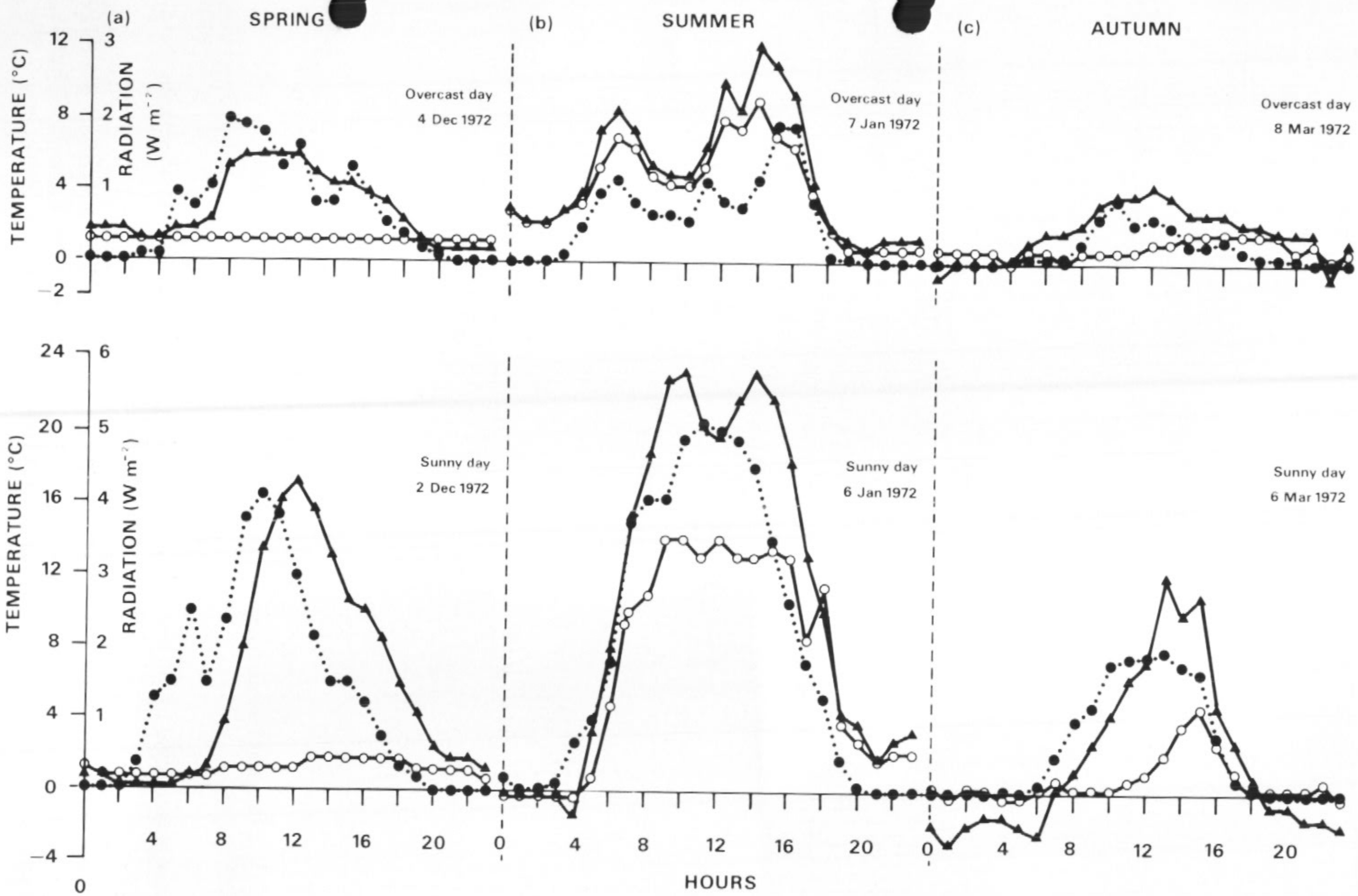

Fig. 7. Seasonal differences in daily temperature patterns at the surface of the SIRS. a. Spring. b. Summer. c. Autumn. ▲ SIRS 1 surface temperature; ○ SIRS 2 surface temperature; ● radiation.

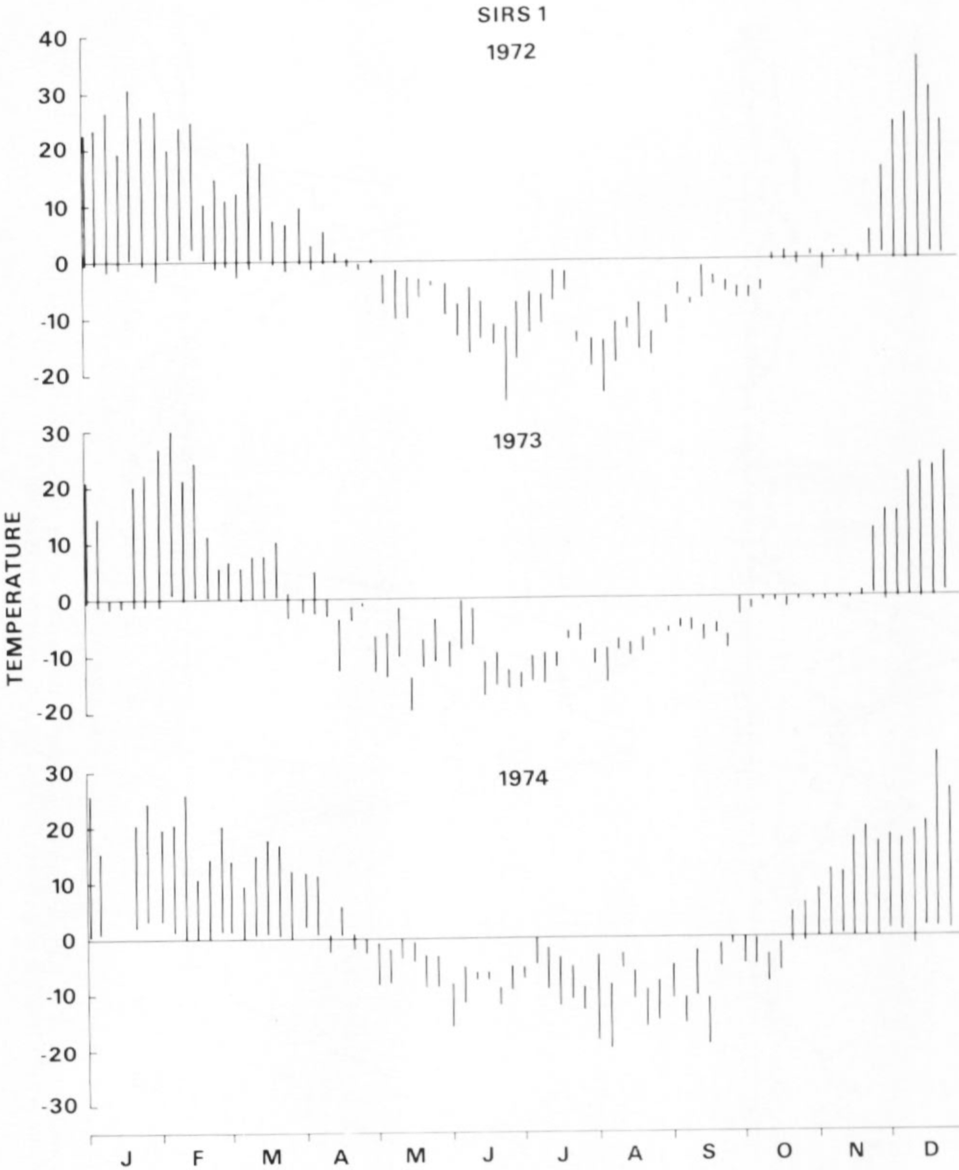

Fig. 8. Maximum diurnal surface temperature range (within each 5-day block) for SIRS, 1972–74.

Distribution was unimodal for all occasions except during winter at SIRS 1. In all seasons there was a greater temperature spread at SIRS 1 than at SIRS 2.

The frequency of particular temperature classes on an annual basis showed important differences over the 3 years (Fig. 10). In 1973 the distribution at SIRS 2 was bimodal due to a shift in temperatures from the 0° to −5°C to the −5° to −10°C class. At both sites in all 3 years very low frequencies were recorded for temperatures above +5°C, 7–12% at SIRS 1 and 5–9% at SIRS 2.

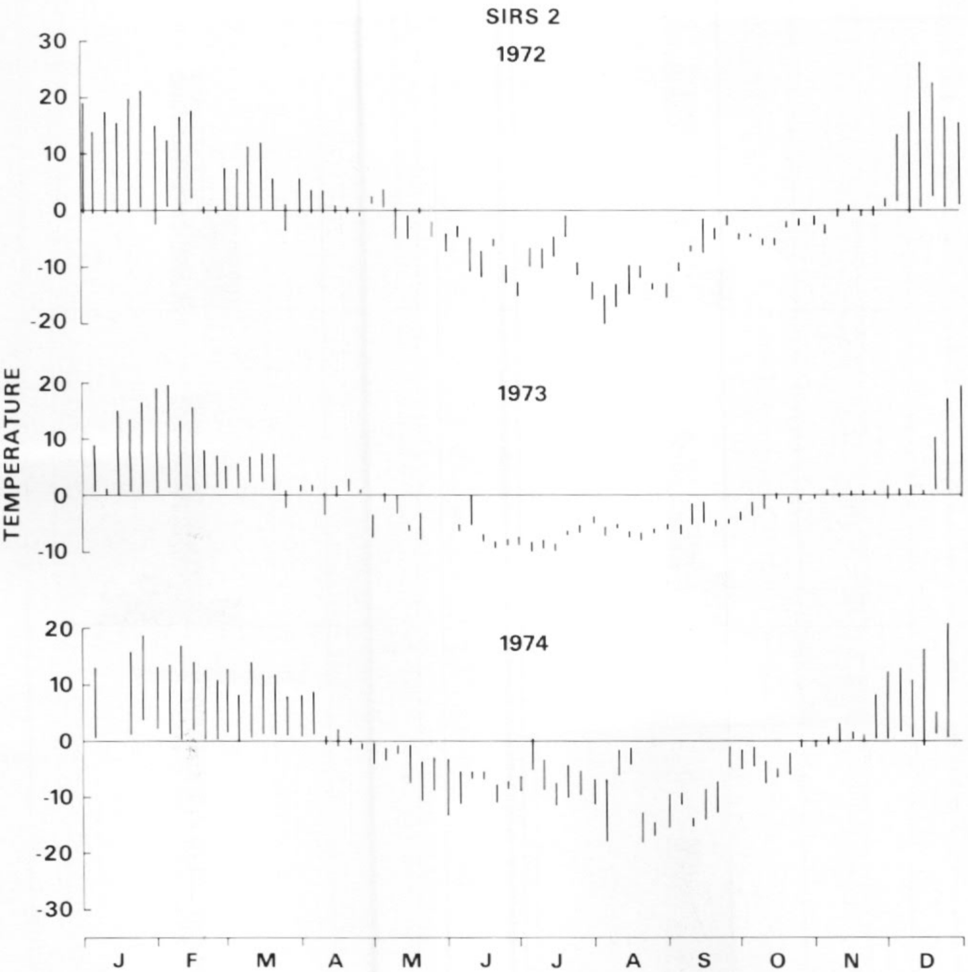

TABLE II. FREEZE-THAW CYCLES AT THE SURFACE OF THE SIRS

SIRS	*1972* 1	2	*1973* 1	2	*1974* 1	2
January	17	1	11			1
February	11	4	8			
March	15	5	9	5	1	
April	8	3	4	3	5	2
May		3		2	3	2
June						
July					1	
August						
September			1			
October	2		2		5	2
November	6	2	1	2	3	1
December	5		2	1	5	5
TOTAL	64	18	38	13	23	13

Cycle criteria: –0.5° to +0.5°C.

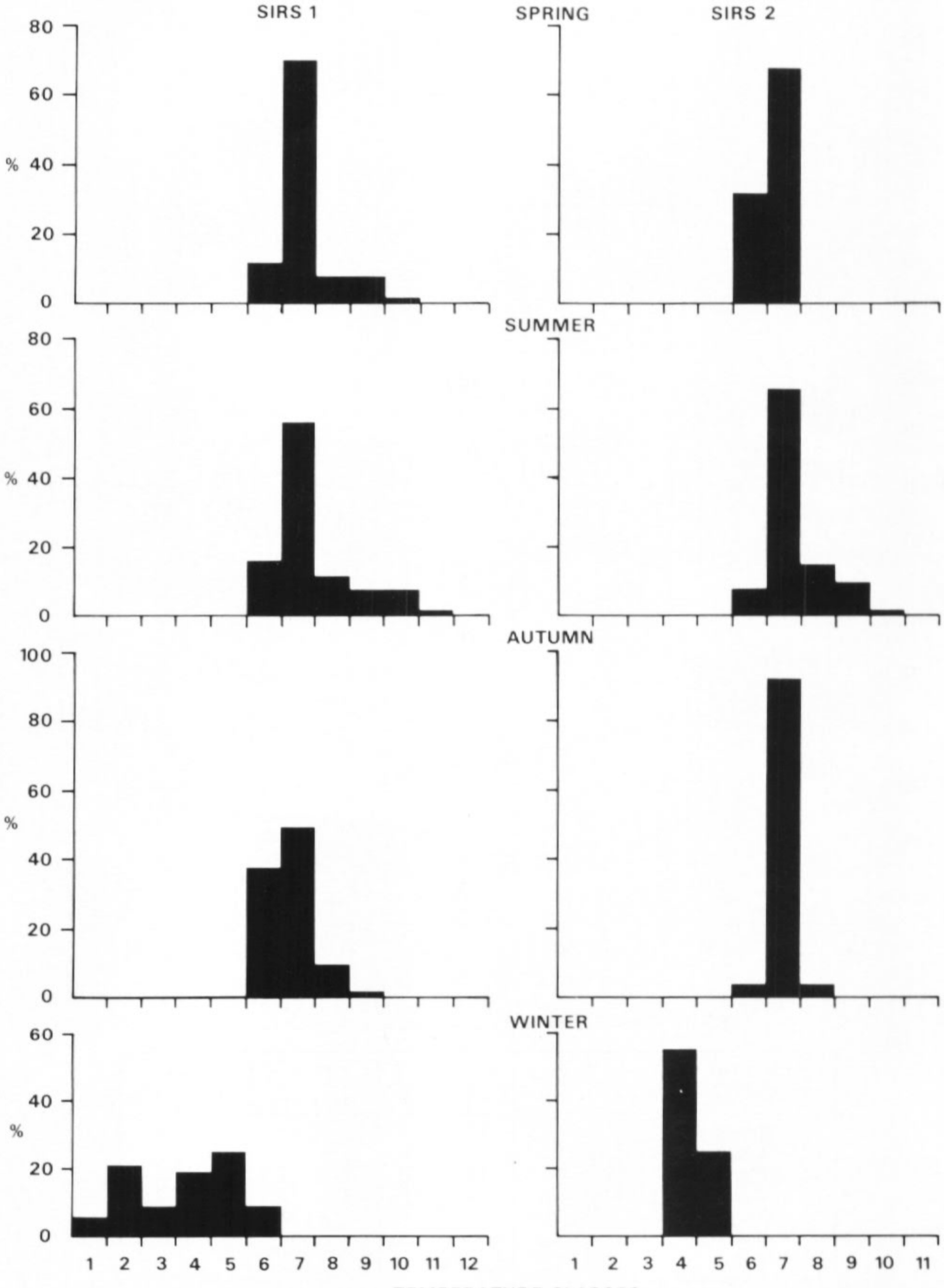

Fig. 9. Histograms of the frequency distributions of hourly surface temperatures at SIRS in four 10-day periods: spring—26 November–5 December 1972; summer—1–10 January 1972; autumn—1–10 March 1972; winter—29 June–8 July 1972.
Temperatures are grouped in 14 5 deg classes:
1. −30° to −25°; 2. −25° to −20°; 3. −20° to −15°; 4. −15° to −10°; 5. −10° to −5°; 6. −5° to 0°; 7. 0° to 5°; 8. 5° to 10°; 9. 10° to 15°; 10. 15° to 20°; 11. 20° to 25°; 12. 25° to 30°; 13. 30° to 35°; 14. 35° to 40°C.

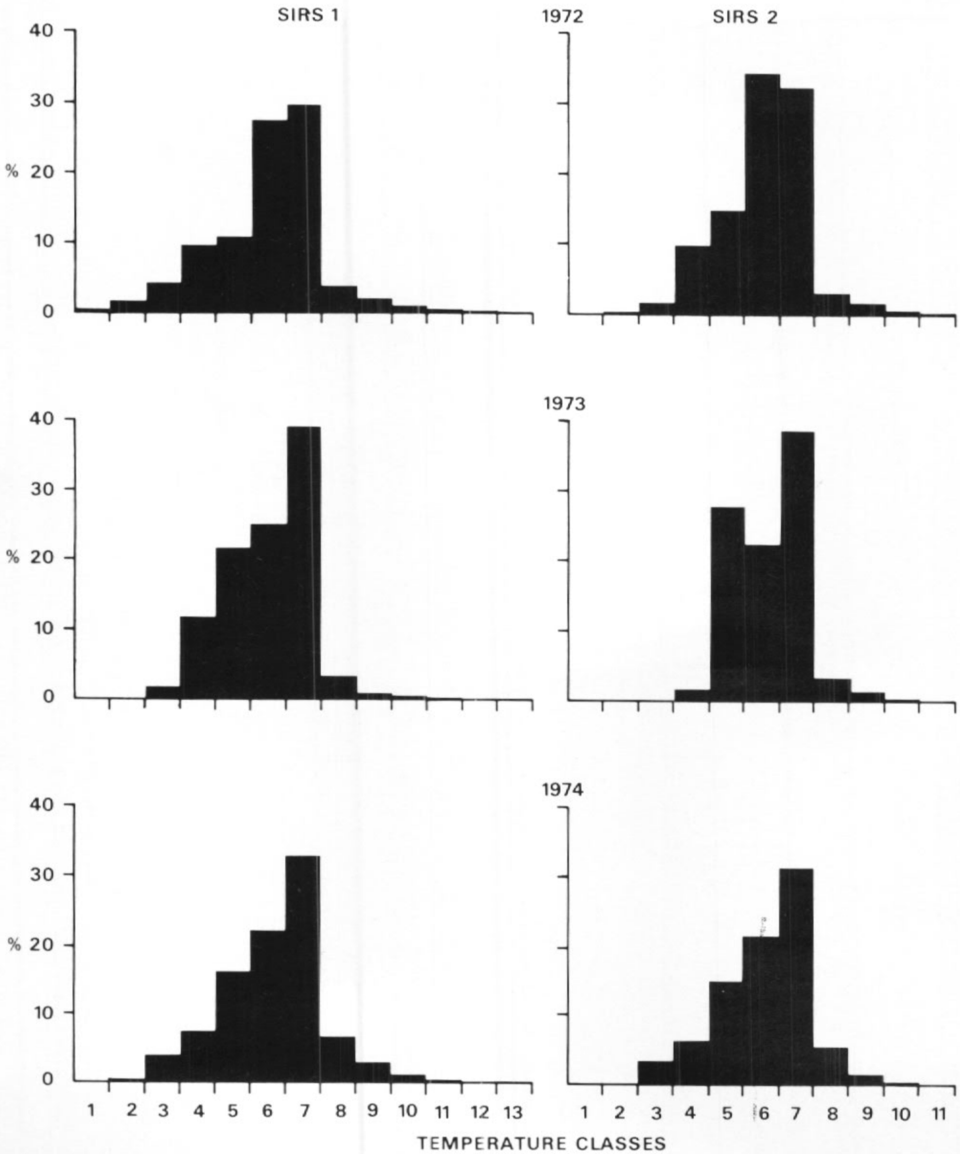

Fig. 10. Histograms of the frequency distribution of all hourly surface temperatures at SIRS, 1972–74, in 14 5 deg temperature classes.

Daily changes in the temperatures throughout the soil profile are influenced by differences in soil conductivity at the two sites. On a very sunny summer day (Fig. 11a), hot spots developed at the surface, exceeding +30°C at SIRS 1. Peat has a lower conductivity than sandy or loam soils, although this is considerably influenced by water content. The rate of penetration of temperature waves in summer is different at the two sites, and is illustrated by the broken lines in Fig. 11a which join the points of highest and lowest temperatures at various depths. In ideal homogeneous ground they would be straight lines. Maximum temperatures usually take 3–4 h dm^{-1} to penetrate at SIRS 1 and at SIRS 2. Minimum temperature waves generally penetrate as quickly

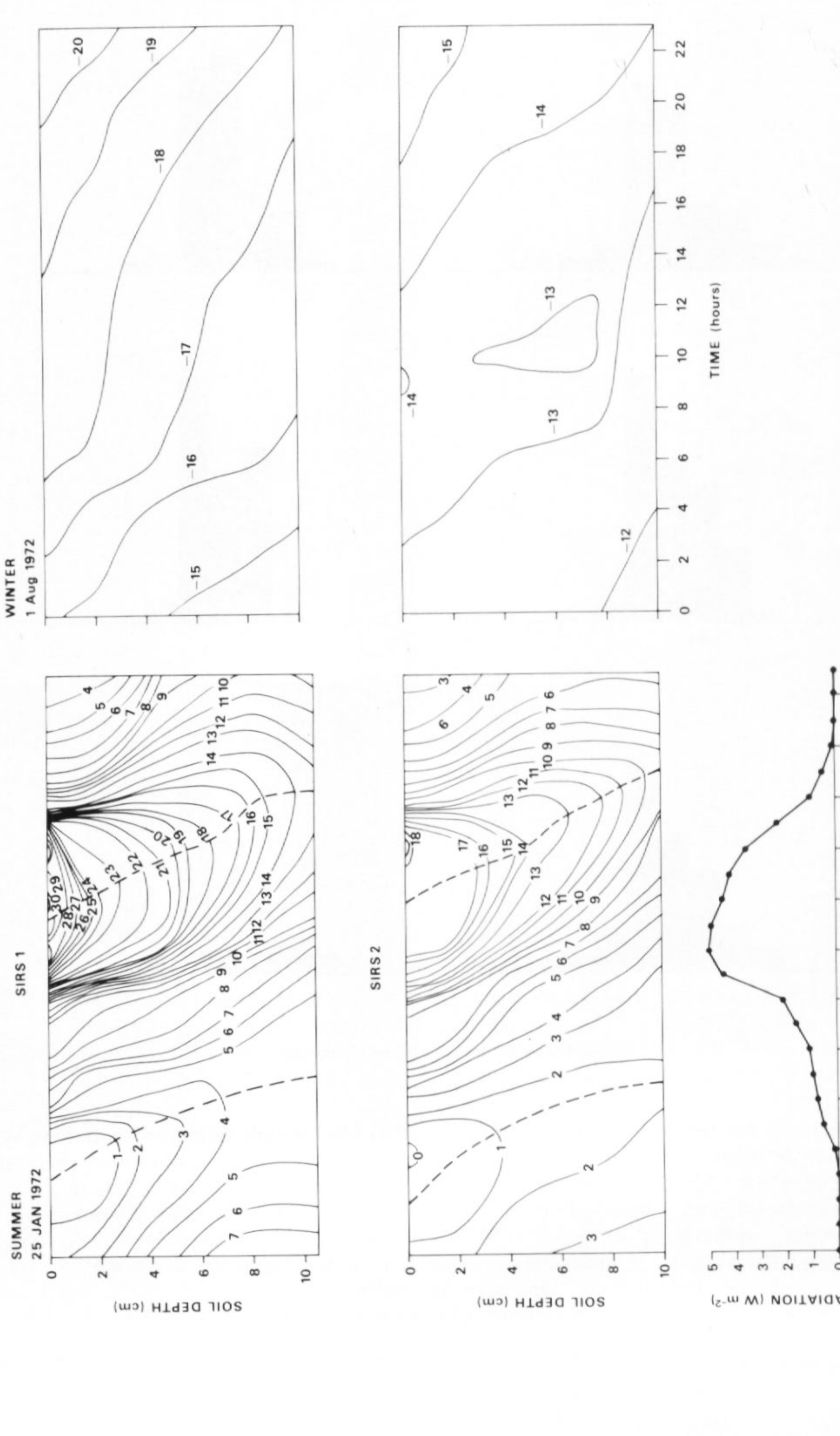

Fig. 11. Isothermal diagrams of soil temperatures for (a) summer day and (b) winter day at SIRS. The heavy broken lines mark the lines of maximum and minimum temperatures down the soil profile. Mean snow-cover on 1 August 1972 was 10.8 cm at SIRS 1 and 27.5 cm at SIRS 2.

at SIRS 1 (3–4 h dm^{-1}) but more rapidly at SIRS 2 (2.5–3.5 h dm^{-1}). At neither site is the peat layer deep enough for permafrost so that it can be assumed that the annual temperature will always penetrate the full soil profile.

The effect of winter snow-cover is shown in Fig. 11b. With a much shallower snow layer, the temperature at SIRS 1 changed at almost twice the rate as at SIRS 2. Snow-cover in summer never persists for long but it can cause rapid changes in surface temperature. Jennings (1979) illustrated this change for 3 days in February 1973 when moss temperature rose from 1° to 24°C after snow melt.

Discussion

The detailed application of the micro-climatic data collected at SIRS will depend on a knowledge of organism physiology and distribution within a given habitat. For example, it is essential to know where in the profile an organism is likely to be found before its tolerances of maximum and minimum field temperatures can be investigated. However, some general comments are possible.

Temperature response is definable in several ways. Absolute maximum and minimum temperatures determine the survival of a species, although in some cases the minimum survival temperature is dependent on acclimatization. Supercooling in invertebrate poikilotherms is another phenomenon related to the absolute minimum survival temperature. The rate of heating and cooling can also be of significance especially if this occurs across a phase-change boundary such as 0°C. Within the absolute temperature band for organism survival there are optimal temperatures for feeding and reproduction. In the case of plants, the closest biological correlation might be between development or other metabolic activity and integrated temperature above a critical base line rather than with mean temperatures.

Previous work on the micro-climates of various Signy Island moss communities has been carried out by Longton (1970, 1972), Longton and Holdgate (1967), and Wright (1975), with additional data by Chambers (1966) based on studies of periglacial activity. Data on snow-cover and water content for the SIRS are contained in Smith (1973), Jennings (1979), Goddard (1979) and Block (1980).

In his detailed account of the temperatures in *Polytrichum* communities in 1965–66, Longton (1972) recorded a similar surface maximum (36°C) but a much higher minimum temperature (−16.5°C). His analysis of short-term freeze-thaw cycles (Longton, 1970) showed 104 cycles in the year. This is in marked contrast to Chambers (1966), who found only 20–22 cycles per year at 1 cm depth in bare ground, and to the present data which show as few as 13 cycles per year at the moss surface. The definition of the cycle obviously affects the number recorded. Chambers (1966) and the present paper used a fall of temperature below −0.5°C and its subsequent rise above +0.5°C. Longton (1970) only defined his minimum temperature. Increase of the band width (+1° to −1°C) for the present data approximately halves the number of cycles recorded.

Both Chambers (1966) and Longton (1972) noted that, in spring, radiation penetration through 4–5 cm of snow or ice would thaw the upper layer of soil on Signy Island. Indeed, Collins and Callaghan (1981) have suggested that up to 11% of the total season's moss growth might take place in spring under shallow snow-cover. Penetration of PAR appears to be sufficient for photosynthesis and temperatures were above −2.5°C for part of the day several weeks before the snow melted and the normal growing season began. Although Longton (1974) found no evidence for a "greenhouse" effect under the snow on Ross Island, he did note that ground temperatures remained within 4 deg of freezing for considerable periods. With water available from snow melt, he suggested that these conditions might be optimal for lichen growth but sub-optimal for mosses.

In the shallow soil profile at both these sites, there was considerable seasonal range of temperature. Even at 10.5 cm depth at SIRS 2, in the most equable year the range was over

20 deg, whilst at the surface of SIRS 1 the annual range reached 62 deg. Even the most rapid rate of change of field temperature was considerably slower than the 1 deg min^{-1} commonly used in laboratory experiments on the physiology of invertebrates and for much of the year was unlikely to exceed 5 deg h^{-1} even at the surface of SIRS 1.

The frequency distributions of temperature show that any organisms in the top 10 cm of soil at both sites were rarely subjected to temperatures above +5°C or below −15°C. This corresponds largely with Longton's (1972) conclusions, although his *Polytrichum* community experienced generally higher winter temperatures due to greater snow depths. Organisms well adapted to this micro-climatic regime could be expected to have physiological optima, e.g. for photosynthesis, close to 5°C with an ability to remain active down to −5°C and a supercooling capacity to remain alive below −25°C (Block, 1980).

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Dr P. J. Tilbrook was responsible for the establishment of micro-climatic recording at the SIRS in 1971–72. J. C. Farman wrote all of the computer programs for converting the digitized data. I am grateful to them, and to I. B. Collinge and D. Friese-Green, for operating the equipment in the field. My thanks are due to Dr W. Block for his constructive criticism of the manuscript.

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