Institute of Hydrology

1992/001

Natural Environment Research Council

T06055 GS

The Detection of Frozen Ground Surfaces Using Satellite Imagery

Report to MAFF

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April 1992

Executive Summary

This report shows how remotely sensed images, together with data from ground instrumentation, have been used to identify areas of frozen ground within the Kennet catchment. There are two aspects to the study:

(i) The analysis of remotely sensed images to provide a temperature distribution over the Kennet.

(ii) The use of this distribution and point values of soil temperatures to generate maps of frozen soil.

The presence of frozen ground in a normally pervious water catchment area will alter the streamflow response to precipitation inputs. The rate of runoff will be accelerated resulting in higher peak flows and an enhanced possibility of downstream flooding. Also, during prolonged periods of frozen ground conditions, precipitation which would normally infiltrate into the soil and augment groundwater stores will be lost as surface runoff. This may have implications for groundwater-fed summer river baseflow levels and for public water supply.

The report begins with a review of operational remote sensors providing images in the appropriate bands for the determination of surface temperatures. It is concluded that, for this particular application, the most suitable sensor, in terms of spatial and temporal resolution, is the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA series of satellites. The problems of converting radiance values, as recorded by the AVHRR, to ground surface temperatures are highlighted.

The catchment of the River Kennet, including its geology, topography, and land use, is illustrated and described. It is particularly well suited for this study, as approximately 70% of its area is composed of a chalk aquifer. There are a number of operational raingauges and streamflow gauging stations within the catchment; the data from these are held on the Surface Water Archive at IH. In addition, there are a number of meteorological stations within and immediately outside the catchment. Data from these have been obtained, via the climatological observers link, to calibrate the results of analysing the remotely sensed images. At three of these sites, soil temperature probes were installed. The data from these were used to determine the extent of frozen ground within the catchment.

The soil temperature data from the three sites are summarized. It is found that good relationships exist between air temperature and soil temperature. These relationships vary with soil type and, in particular, with land cover; soil temperatures under bare soil during cold conditions are significantly lower than those under grass. For the purpose of estimating the extent of frozen ground, the catchment was divided according to soil type, and a different regression of soil temperature to air temperature applied to each soil.

Two suitable cold periods were identified within the duration of the study. Also, a further period prior to the installation of the soil temperature probes was found to be

suitable. AVHRR images for all three periods were analysed, the distribution of air minimum temperature over the catchment established, and the extent of frozen ground estimated. Also, a comparison was made of the distribution of surface temperatures as given by AVHRR (1 km resolution) and Landsat images (30 m resolution).

Finally, the possible use of the areal distribution of frozen ground in hydrological models of streamflow runoff is discussed.

Contents

1. Introduction

The presence of frozen ground within a river catchment area will affect the response of that catchment to rainfall inputs, the magnitude of the effect depending on the extent of frozen ground. Rainfall inputs to frozen areas which, during 'normal' conditions would have been pervious, will now be rapidly converted into surface runoff. This results in more rapid and enhanced peak stream flows. The most obvious and important implication of this is for downstream flooding. Another, lesser consideration is groundwater recharge. During prolonged periods of freezing ground conditions, rainfall inputs which could normally infiltrate the ground and recharge groundwater stores, will be lost to the river system. This may have implications for water supply in following years, particularly for those areas of the country which obtain a high percentage of potable water supply from groundwater sources. Also, such a consideration is particularly relevant at present, with reports of falling summer baseflow levels in many rivers fed by groundwater sources.

General methods for the prediction of streamflow response particularly the magnitude and timing of peak flows, as given in the Flood Study Report (NERC, 1975) depend on the availability of certain catchment characteristics such as topography, vegetation cover and soil types. However, one parameter that is particularly difficult to measure is the condition of the ground surface ie. its permeability. In catchments having a past record of floods, information on the occurrence and, more importantly, the areal extent of frozen, and hence impermeable, ground will be of great value in predicting the extent of flooding for a given rainfall input. The availability of this information in 'real time' would be of additional benefit, as it would then be possible to initialize preventative measures to reduce the extent of damage.

Traditional methods for identifying frozen ground conditions, using recording thermometers or occasional localized ground surveys, lack the spatial and temporal resolutions required for modelling purposes. The information could be obtained by extensive ground surveys. However, these are time consuming and expensive, and would be carried out during periods when such a survey is most hazardous. The analysis of remotely sensed images would seem a sensible alternative. Remotely sensed images, with their spatial attributes would seem ideally suited to extrapolate point values, obtained from ground instruments, over a catchment area. Also, the analysis of sequential images will give some indication of the duration of freezing conditions.

This study investigates the possibilities of using satellite imagery to detect frozen ground conditions within British catchments prone to possible flood risks. The study has been done in three stages:-

(i) The establishment of a network of air, ground surface, and soil thermometers within the area of study. This consists of existing networks of weather stations and recording thermometers installed specifically for the study. The data obtained will be used to identify suitable periods for the acquisition of satellite imagery, for the calibration of the results of the image analysis, and for converting the resulting areal distribution of surface temperatures into soil temperatures at various depths.

(ii) Investigating the feasibility of using satellite imagery for estimating surface temperatures within the area of interest. Satellite imagery for selected periods will be acquired and inspected on the image analysis system at IH. Ground points will be chosen to register the satellite imagery to a base map. Catchment boundaries will be overlain on the images to identify regions of interest. Brightness temperatures will be calculated over the area of interest.

(iii) The *in situ* observations of air and ground temperatures will be used to note differences between observed and the brightness temperatures. These differences will be used for correcting the results from the analysis of the images. Finally, isotherm maps will be produced and, from these, areas of frozen ground identified.

As a sequel to this programme of research, should it be successful, it may be possible to install an 'on-line' system at IH, whereby satellite imagery will be captured using a satellite dish, processed using semi-automated procedures, and the information obtained used for real-time hydrological modelling.

2. Surface Temperatures from Satellite Imagery

There are a number of platform, sensor and waveband combinations that can be used to detect surface temperatures. For the former, the type of platform can range from a moveable tower (Caselles *et al.*, 1988), a vehicle (Thornes, 1989), an aircraft (Birnie *et al.*, 1984) or a satellite (Collier *et al.*, 1989; Byrne *et al.*, 1984). They have been used for a number of applications including the detection of heat loss from urban areas (Birnie *et al.*, 1984), water availability for agricultural purposes (Cihlar, 1980), the detecting of frost hollows in fruit growing areas (Caselles and Sobrino, 1989), areal estimates of evaporation (Carson and Buffum, 1989), the detection of icy road conditions (Thornes, 1989), and the mapping of very low temperatures (Collier *et al.*, 1989).

The best combination to be adopted depends on the application. For the detection of frozen ground conditions over relatively large areas, the use of moveable towers and vehicles is clearly impractical. Also, the use of an aircraft would become prohibitively expensive on a routine basis. This suggests that satellite imagery is likely to prove the most suitable for this application. Even then, a compromise has to be made between the frequency of observation and the spatial resolution achieved for a particular satellite.

Two regions of the electromagnetic spectrum have been used operationally for the determination of surface temperatures: passive microwave and thermal infrared. The former method can be used during periods of cloud cover, whereas thermal infrared radiation cannot penetrate clouds and the method can only be used during periods of clear skies. However, the presence of snow and water bodies limits the applicability of the microwave method (McFarland *et al.*, 1990), particularly for the detection of frozen ground conditions. Also, the ground resolution associated with passive microwave imagery, typical pixel size 50 km limits its application to global studies.

Given all the above constraints, it seems that thermal infrared imagery obtained from a satellite system is the most appropriate for the particular application described in this report. There are three satellite/sensor combinations from which suitable imagery may be obtained on a routine basis. These are the Meteosat and Landsat series of satellites (Fig. 2.1) and the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA series of satellites (Fig. 2.2). All three satellites acquire images in the thermal infrared region, 10.5 - 12.5 micron wavelength range.

The Meteosat and Landsat series of satellites (Fig. 2.1) provide the two extremes in terms of image acquisition and ground resolution. For the former, images are obtained every 30 minutes at a ground resolution of 5 km for the thermal infrared band. In contrast, the Thematic Mapper sensor on board Landsat produces a 120 m ground resolution thermal infrared image every 16 days. Neither satellite is ideally suited for this particular application, the ground resolution associated with the Meteosat images is too coarse whereas the repeat cycle of Landsat would not give the temporal resolution required even if clear sky conditions could be guaranteed.

The AVHRR sensor on the NOAA series of satellites (Fig. 2.2) is a good compromise. The two operational NOAA satellites provide 4 images a day with a ground resolution of 1.1 km at nadir. Also, in the latest NOAA satellites, the thermal band has been split into two, this simplifies the correction for atmospheric effects (see below). Images from this sensor have been used extensively, in particular, for mapping sea surface temperature.

For this, it is generally only necessary to correct the sea surface brightness temperature, as given by the sensors on board the satellite, for atmospheric effects. These are caused by absorbtion and scattering of radiation by particulate matter or gases within the layer of atmosphere between the emitting surface and the sensor. The method of correction is based on the fact that these atmospheric effects vary with wavelength. By obtaining images in more than one wavelength, and expressing the surface temperature as a combination of observed temperatures in the various wavelengths, the problem can be minimized. As indicated above, in the AVHRR sensor on the latest NOAA satellites, the original 10.5-12.5 micron channel has been separated into a 10.5-11.5 and a 11.5-12.5 micron channel. Atmospheric correction by the use of images in two such bands is known as the 'split-window' technique (Prabhakara *et al.*, 1975).

A major problem when attempting to determine land surface temperatures from remotely sensed images is the effect of emissivity. Unlike water bodies, for which the emissivity is close to 1.00 with little variation, land surfaces exhibit large variations in emissivity (Griggs, 1968). Neglecting this variation may result in appreciable errors in the estimates of land surface temperatures (Becker, 1987). A number of theoretical formulations have been developed to solve the problem (see, for example, Becker and Li, 1990; Wan and Dozier, 1989). Alternatively, derived emissivity values from ground-based radiometers for different land surfaces may be used to correct the observed brightness temperatures over the area of interest according to the distribution of land cover. Another approach is to correct the brightness temperatures observed by the satellite using measured ground or air temperatures (McClatchey *et al.*, 1987). Both of the latter techniques suffer from the fact that, whilst the ground observations are point values, the brightness temperatures are averaged over a considerable area (1 km^2 in the case of the AVHRR sensor). In spite of this, satellite derived temperatures are generally verified by ground (or sea) temperature data (McClatchey, 1992), and it is the method employed in this particular study.

Fortunately, the lowest land surface temperatures and, hence frozen conditions are likely to occur during conditions which favour the use of remotely sensed images for the detection of ground temperatures (Roach and Brownscombe, 1984). These conditions include clear skies (no problems with clouds), a very dry troposphere (little atmospheric correction required), and the land surface covered with fresh snow of moderate depth (uniform emissivity can be assumed).

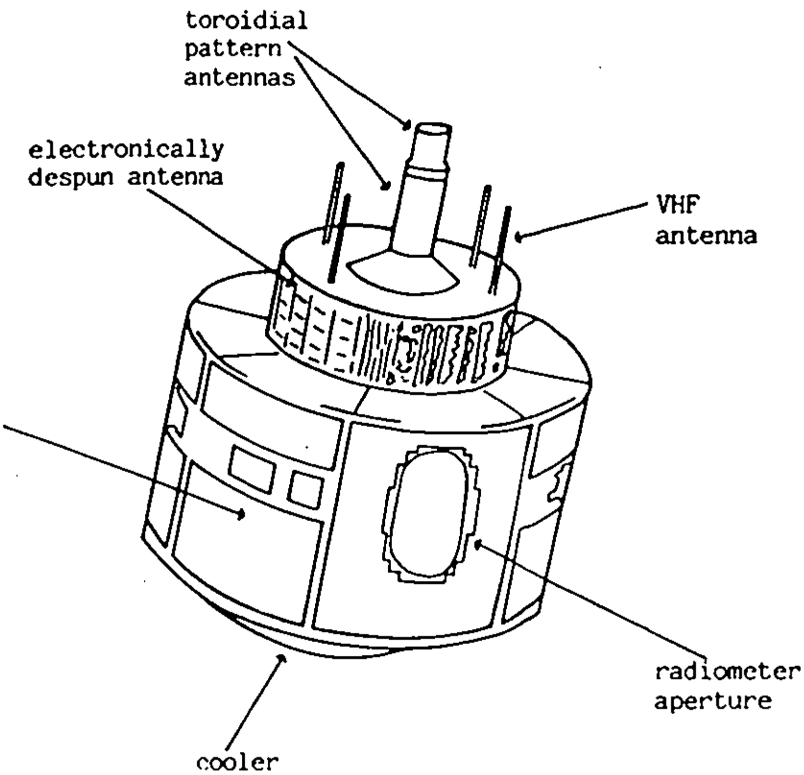
The most appropriate study to the one reported on here was carried out in the Central Highlands of Scotland. NOAA-AVHRR images taken on four dates during winter months were analysed to determine the distribution of very low surface temperatures (Collier *et al.*, 1989; McClatchey *et al.*, 1987). Brightness temperatures derived from the images were compared with minimum air temperatures measured at

METEOSAT

Launch:
Meteosat-1: November 1977
retired: November 1979
Meteosat-2: June 1981

Orbital parameters:
Orbit: geostationary
Altitude: 35,900 km
Position: 0° latitude, 0° longitude

Sensors
Wavebands (μm): 0.4- 1.1
5.7- 7.1
10.5-12.5
Resolution (at nadir):
visible: 2.4 km
infra-red: 5.0 km
Data acquisition: every 30 minutes.



LANDSATS 4 and 5

Launch:
Landsat 4: 16 July 1982
Landsat 5: 1 March 1984

Orbital parameters:
Orbit: near polar
sun synchronous
Altitude: 705 km
Inclination: 98.2°.
Coverage: 81°N to 81°S.
Period: 99 minutes, crossing the equator at 9.45hrs local time.
Repeat cycle: 16 days.

Thematic Mapper

	Wavelength (μm)	Resolution
Band 1	0.45 - 0.52	30m
Band 2	0.52 - 0.60	30m
Band 3	0.63 - 0.69	30m
Band 4	0.76 - 0.90	30m
Band 5	1.55 - 1.75	30m
Band 6	10.40 - 12.50	120m
Band 7	2.08 - 2.35	30m

Both sensors provide image data with 185 x 185km coverage, with 5.4% forward overlap and 7.3% side overlap at the equator increasing at higher latitudes.

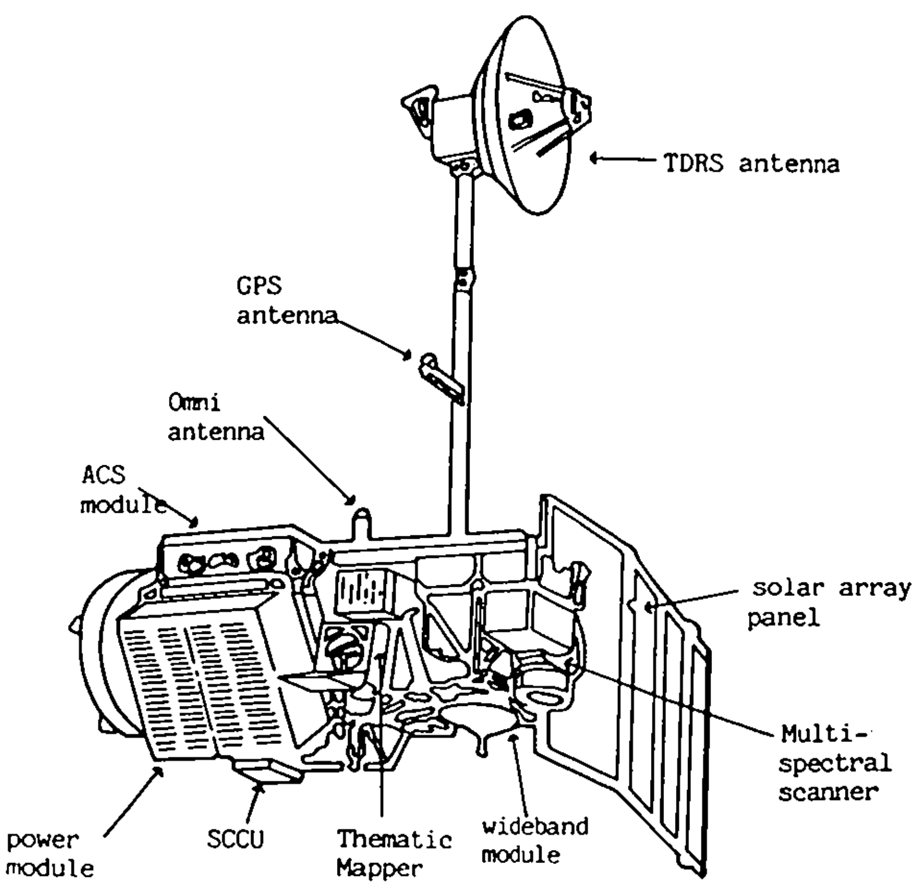
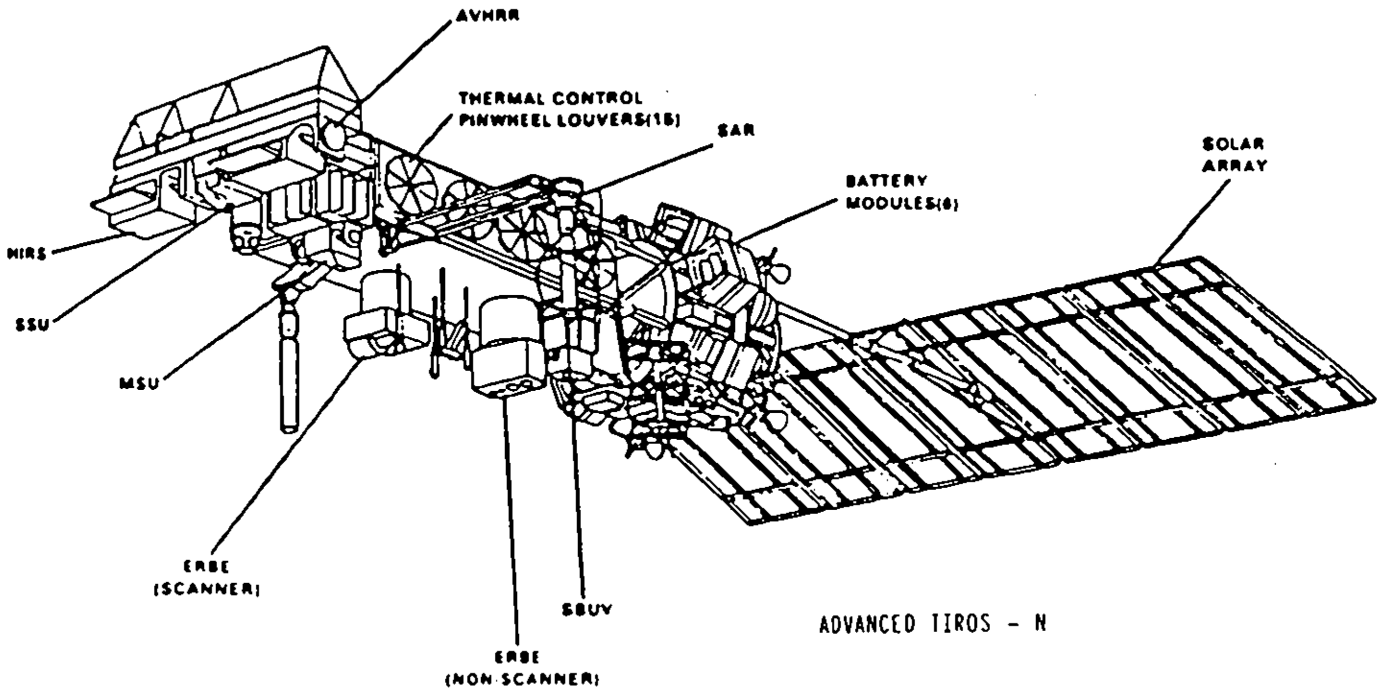


Fig. 2.1 Details of the Meteosat and Landsat satellites

NOAA POLAR ORBITING SATELLITES



Launch:
TIROS-N series
NOAA-6: 27 June 1979
NOAA-7: 23 June 1981

Advanced TIROS-N (ATN)
NOAA-8: 28 March 1983
NOAA-9: 12 December 1984

Orbital parameters:
Orbit: near polar
sun synchronous
Equatorial crossing
1) 0730 and 1930
2) 1400 and 0200
local sun time
Altitude: 833-870 km
Inclination: 98.7°-98.9°
Period: 101.6-102.4 minutes
Repeat cycle: 12 hours per satellite

Primary instruments

Advanced Very High Resolution Radiometer (AVHRR)

1.1 km resolution

Channel	Wavelengths (μm)	Primary uses
1	0.58 - 0.68	weather forecasting, cloud delineation snow and ice monitoring
2	0.725- 1.10	location of water bodies, ice and snow melt, vegetation and agriculture assessments, rangeland surveys
3	3.55 - 3.93	sea surface temperature, night clouds, land/water delineation, volcanic activity, forest fire, monitoring, straw burning
4	10.30 -11.30	sea surface temperature, day/night clouds, soil moisture
5	11.50 -12.50	sea surface temperature, day/night clouds, soil moisture

Fig. 2.2 Details of the AVHRR sensor on the NOAA series of satellites

meteorological stations. Differences of up to 3.5°C were observed; those were attributed to differences between the timing of the satellite overpass and the minimum air temperature. Isotherm maps produced from the derived brightness temperatures showed good correlation with topography, with the lowest temperatures being generally found in the lower lying areas.

3. Study Area

The area chosen for the study is the catchment of the River Kennet, the largest single tributary of the River Thames (Fig. 3.1). Its catchment area is approximately 1156 km^2 covering much of the counties of Wiltshire and Berkshire (Fig. 3.2).

This catchment is particularly suited to this study. Approximately three quarters of its area is composed of a chalk aquifer (Fig. 3.3) which generally absorbs winter rainfall with a subsequent release in the spring and summer to provide the streamflow necessary to maintain a wide diversity of natural flora and fauna and a thriving fisheries industry. In addition, an increased demand is made on groundwater sources for agricultural and industrial use, and for domestic water supply. Much concern has been expressed in recent years that the succession of relatively dry winters and increased demand for groundwater has resulted in reduced summer baseflow levels. Any reduction in winter groundwater recharge as a result of frozen ground will exacerbate the problem.

The altitude in the catchment ranges from 43 m at its outfall to a maximum of 297 m in the chalk outcrop of the Marlborough Downs (Fig. 3.4). The Kennet itself rises at Broad Hinton, some 12 km to the northwest of Marlborough and flows due south to Silbury Hill, and then eastwards some 98 km to its confluence with the Thames at Theale.

The chalk is a soft microporous limestone in which movement is dominated by fissure flow. Three major units are recognized - upper chalk, middle chalk and lower chalk - with permeabilities and hence yields, decreasing from the upper to lower. The Chalk aquifer is mainly unconfined but confined conditions occur along the valley bottom and flood plains in the lower reaches. In some areas of the catchment, notably along the northern edge of the Marlborough and Berkshire Downs, the chalk outcrops giving rise to prominent escarpments. Most of the catchment is covered by drift deposits, and thickness and type being determined principally by the topography (Fig. 3.5 and 3.4).

In the flatter, interfluve areas of the catchment, brown calcareous earths dominate. These are well drained shallow chalky soils, associated with deeper, loamy or clayey, flinty soils. The steeper valley sides are mainly drift free whilst the lower slopes are associated with well drained loamy-over-clayey soils. The floodplain terrace consists of clayey soils having impeded drainage, whereas the river valley is composed of poorly drained loamy and clayey soils with high groundwater. Generally speaking, permeability decreases with decreasing altitude.

The main land use in the catchment is agriculture. A MAFF agricultural census of the catchment carried out in June 1965 separated the catchment into 39% arable land, 33% grassland (both temporary and permanent), and 28% other land, including woodland, common land/unproductive heathland, open water, and urban areas. As part of this present study, a Landsat 7-band satellite image taken on the 9th August

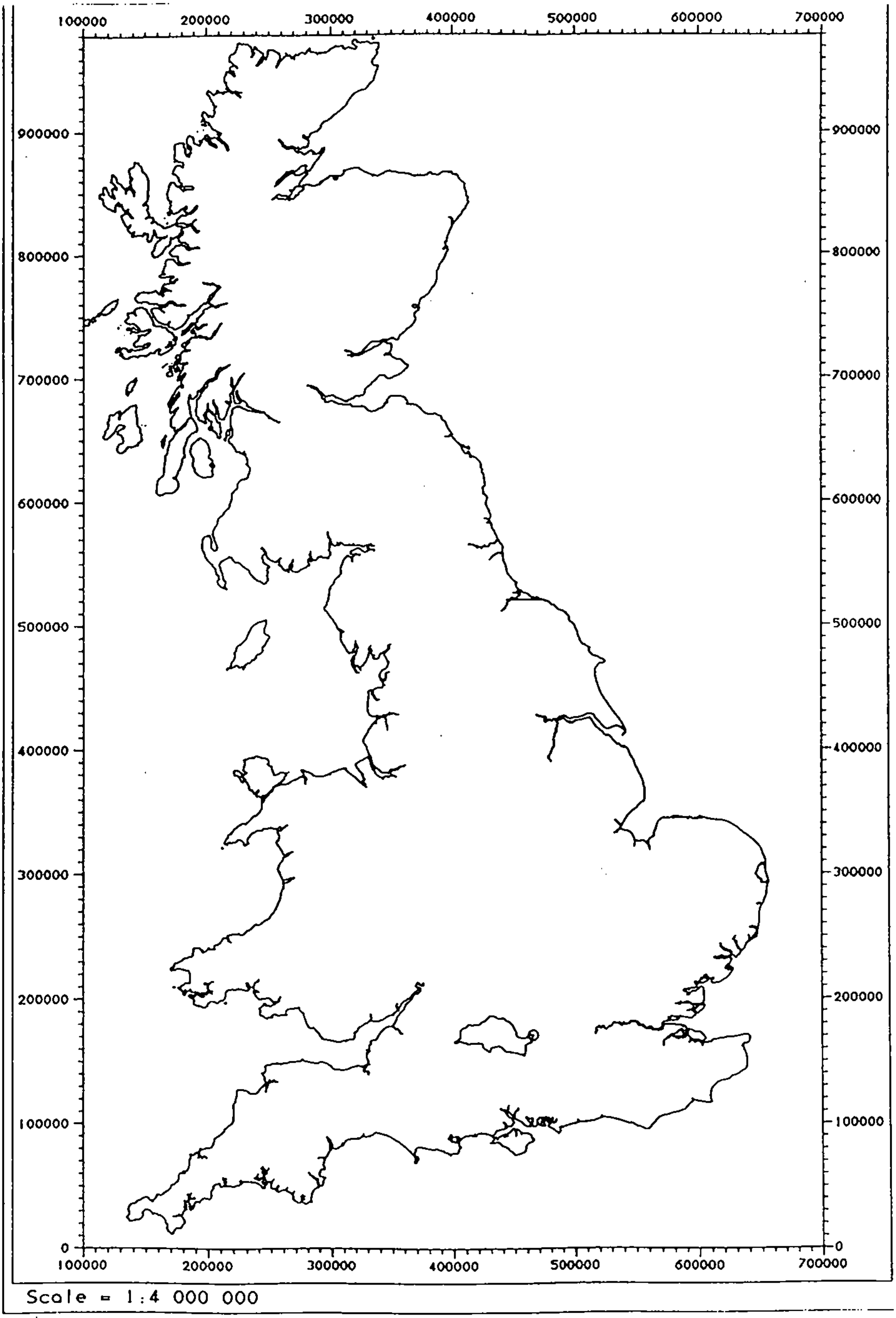


Fig. 3.1 Location of the catchment of the River Kennet

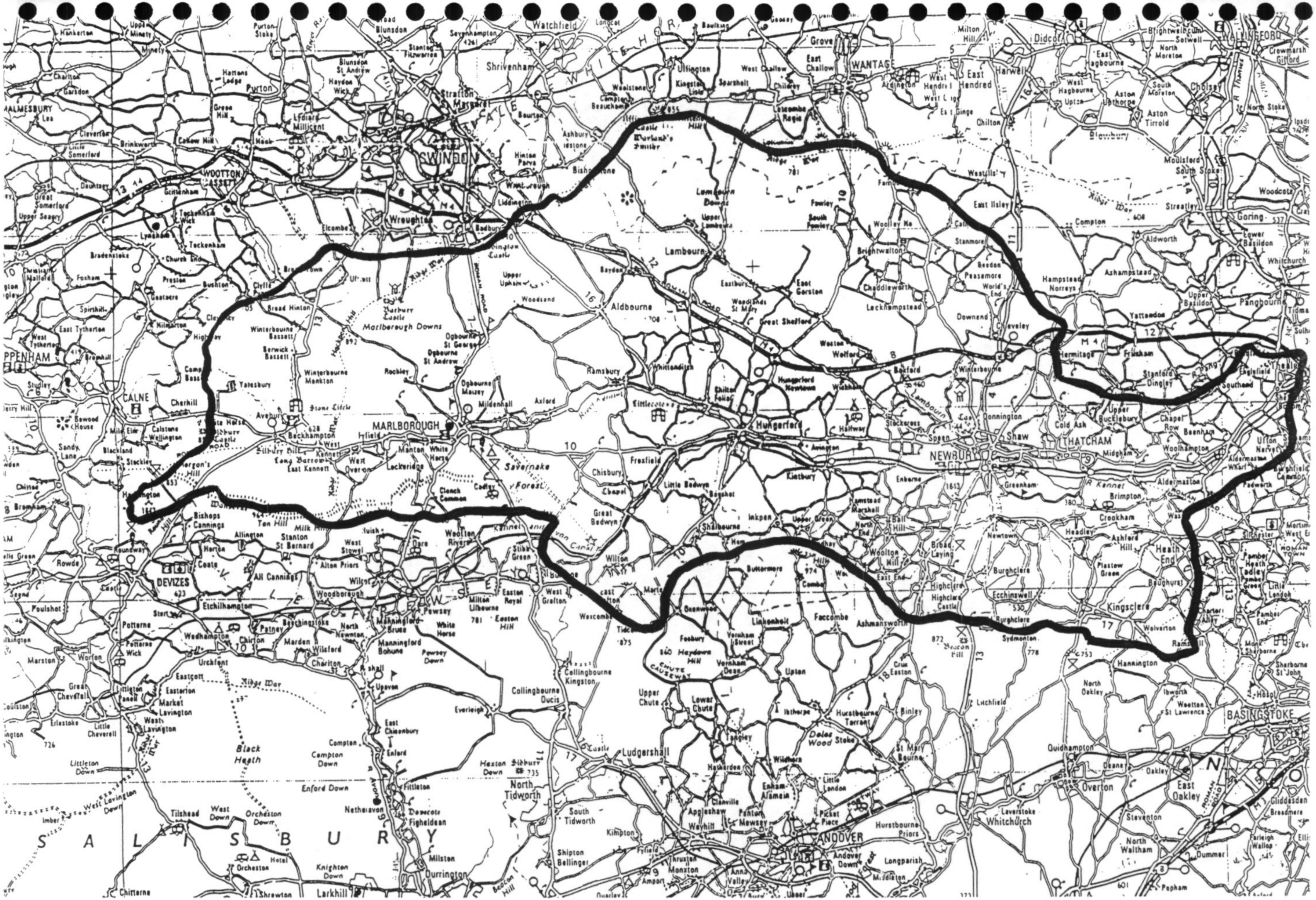


Fig. 3.2 The catchment area of the River Kennet

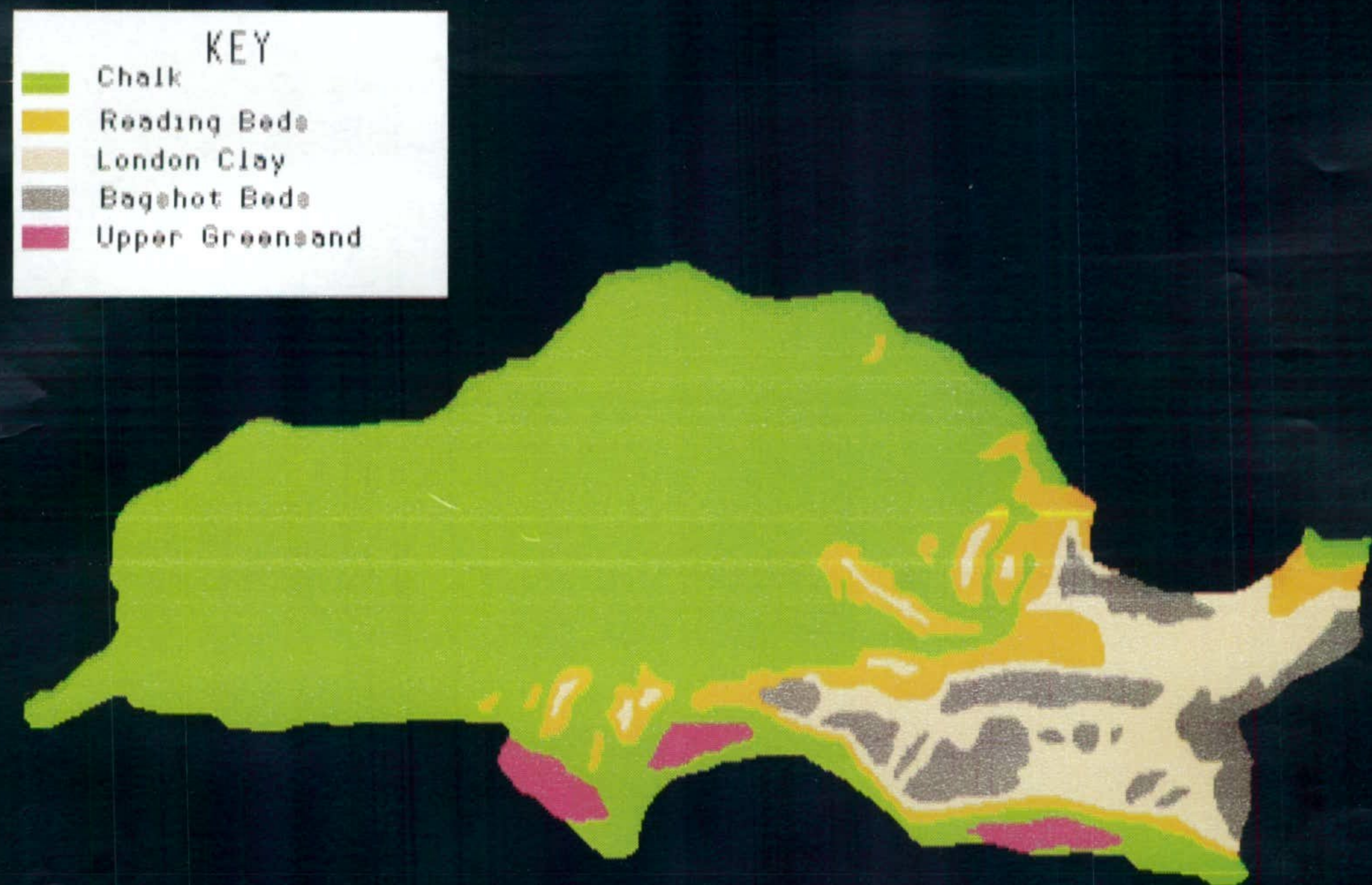


Fig. 3.3 Kennet Catchment - Geology

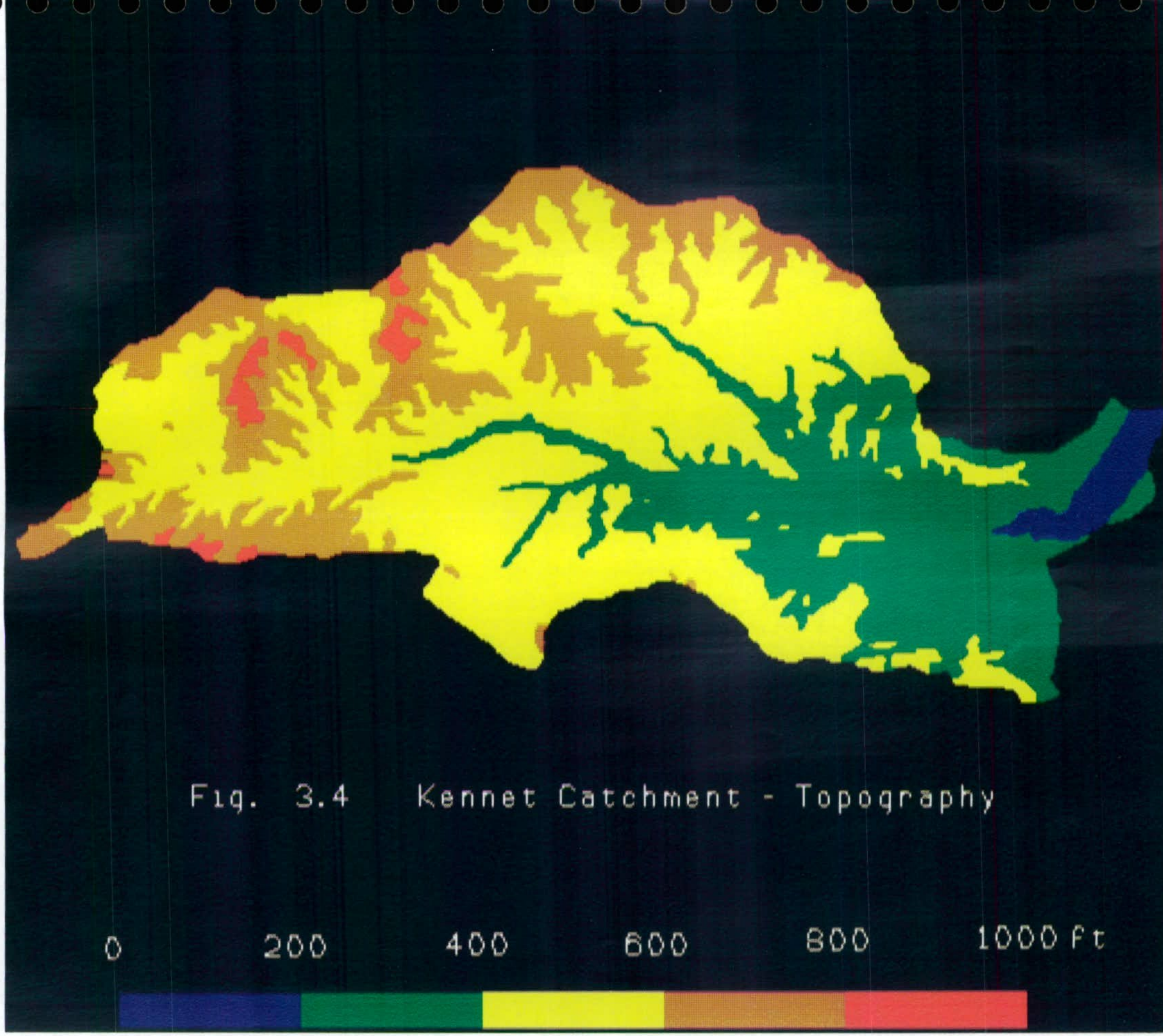


Fig. 3.4 Kennet Catchment - Topography

Fig. 3.5 Kennet catchment - Generalized Soils Map

1984 was analysed to produce a land use map of the catchment (Fig. 3.6). The analysis suggested that 52% was arable, 38% was grassland, and 9% forested. Most of the arable crops are grown in the well drained soils on the interfluve areas and valley sides, whilst the grassland areas occur in the less well-drained valley bottoms.

The two major tributaries are the Lambourn and the Enborne which meet the Kennet at Newbury and Aldermaston respectively. In addition, there are a number of other tributaries, many of which have flow gauging stations (Fig. 3.7) from which flow records have been obtained over variable length periods. These records, given as mean daily flows, are held on the surface water archive at the Institute of Hydrology. Appendix I gives details of all the flow gauging stations within the Kennet. The outfall of the Kennet at Theale has been monitored since 1961. The mean flow is 9.5 cubic metres per second (cumecs) with a lowest recorded flow of 2.9 cumecs and a highest of 40.9 cumecs. Much of this flow is derived from the Chalk aquifer, as suggested by the high base flow index of 0.87. Because of this, summer baseflow levels are highly dependent on the amount of groundwater recharge during the previous winter.

There are a number of operational raingauges within the catchment and the records are again held on the surface water archive at IH. The 1961-1990 mean annual rainfall is 767 mm, with a range of 579 to 940 mm. There are a number of meteorological stations within and immediately outside the catchment area. These are described in the following section.

4. Ground Instrumentation

As indicated previously in Chapter 2, variations in the emissivities of ground surfaces renders the estimation of land temperatures by remote sensing a difficult proposition. Although a number of theoretical formulations are available, it was decided that, for this particular application, it would be more appropriate to calibrate the remotely sensed data using temperatures recorded at a number of meteorological stations within and immediately outside the Kennet catchment. The locations of these stations are shown in Figure 4.1 and their details tabulated in Table 4.1.

Table 4.1 Meteorological Stations used in the Study

Location	Grid Ref.	Alt (m)	Air min.	Grass min.	Soil Thermometers
Boscombe Down	SU172403	126	✓	✓	x
Lackam College	ST920710	49	✓	✓	✓
Larkhill	SU137447	132	x	✓	x
Lyneham	SU020780	145	✓	✓	x
Marlborough	SU185686	129	✓	✓	x
Netheravon	SU164495	129	✓	✓	x
Aborfield	SU757685	49	✓	✓	x
Easthampstead	SU846664	74	✓	✓	x
Hurley	SU823829	43	✓	✓	x
Lambourn	SU355845	192	✓	x	✓
Reading	SU739719	66	✓	✓	x
Wallingford	SU618898	48	✓	✓	✓
Greenham Common	SU481653	80	✓	x	x

The most useful variables measured at these Meteorological stations are the air minimum and grass minimum temperatures. These are the minimum temperatures recorded in a 24 hour period (0900-0900 GMT) in a Stevenson screen and at ground level within a grass sward. Most of the stations record both variables. Whilst these variables give a good general indication of the temperature, the time of satellite overpass would not normally coincide with the time of air or grass minimum temperature. Also, as well as gaining some insight into the extent and areal distribution of frozen ground surface over the catchment, it would be desirable to obtain information on the depth of frozen soil. For these two reasons, a number of

Fig. 3.6 Kennet Catchment - Land Use

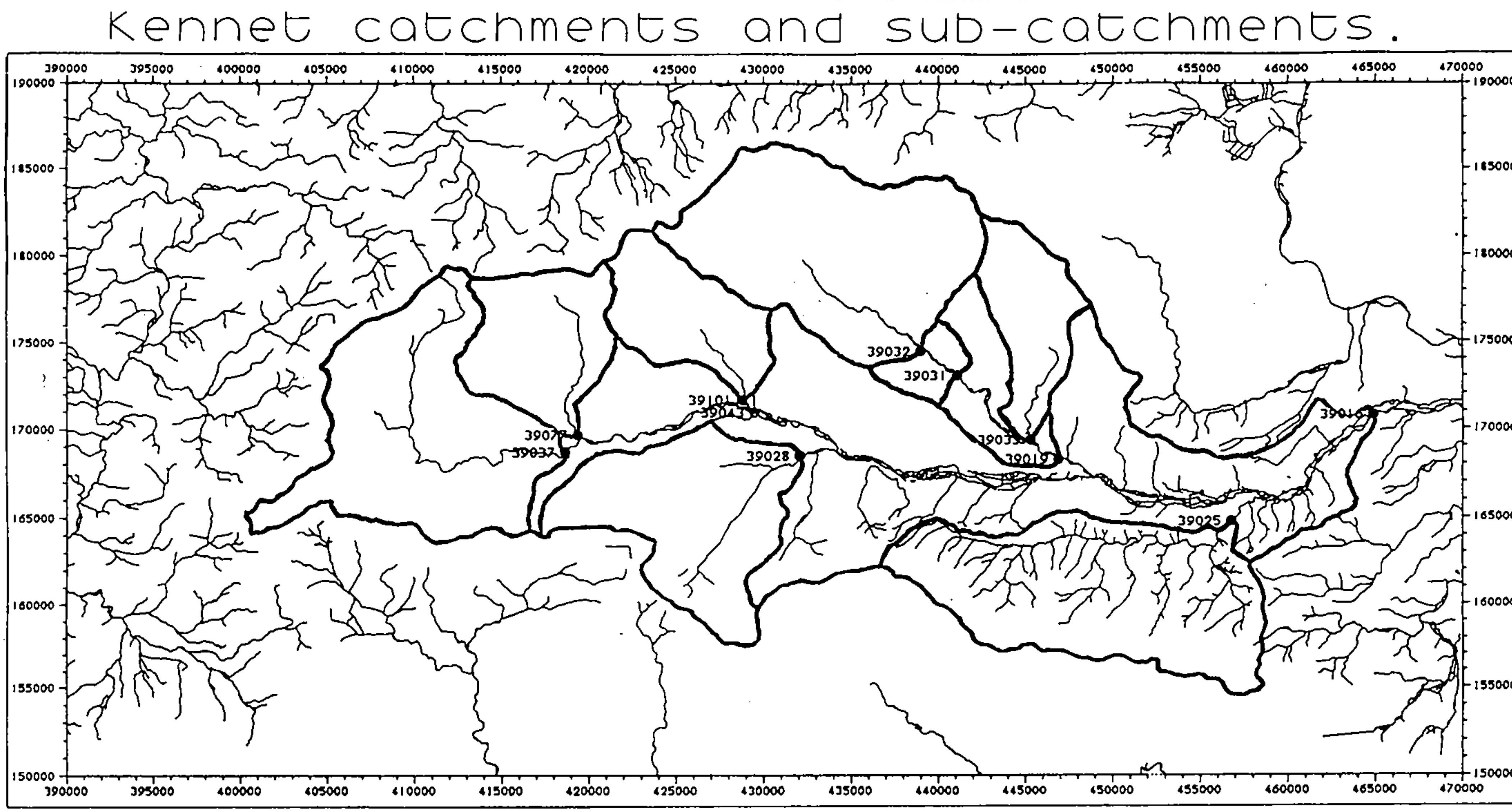


Fig. 3.7 Kennet catchment - Flow Gauging Stations

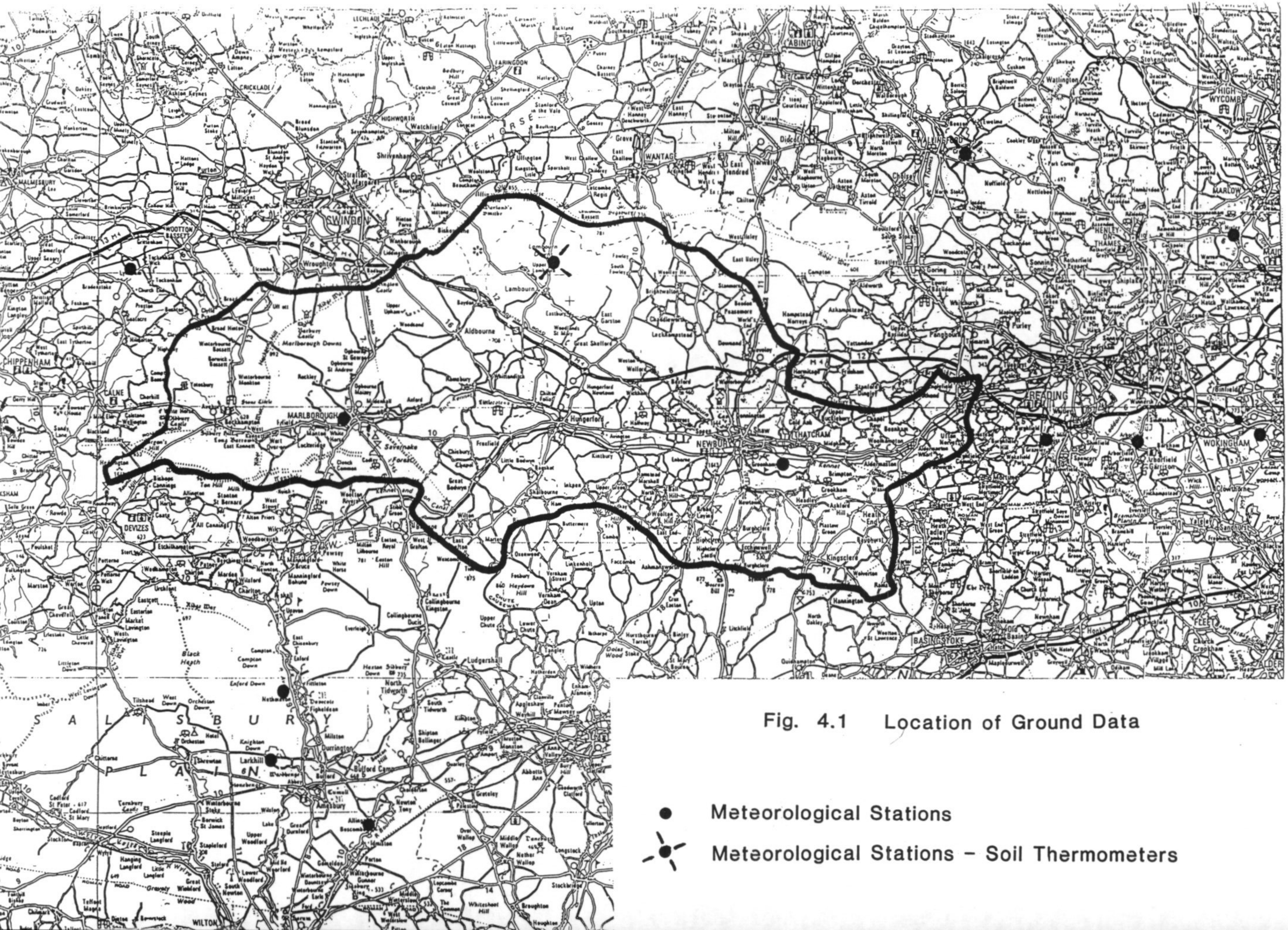


Fig. 4.1 Location of Ground Data

● Meteorological Stations

Meteorological Stations - Soil Thermometers recording grass and soil thermometers were installed at three of the meteorological sites.

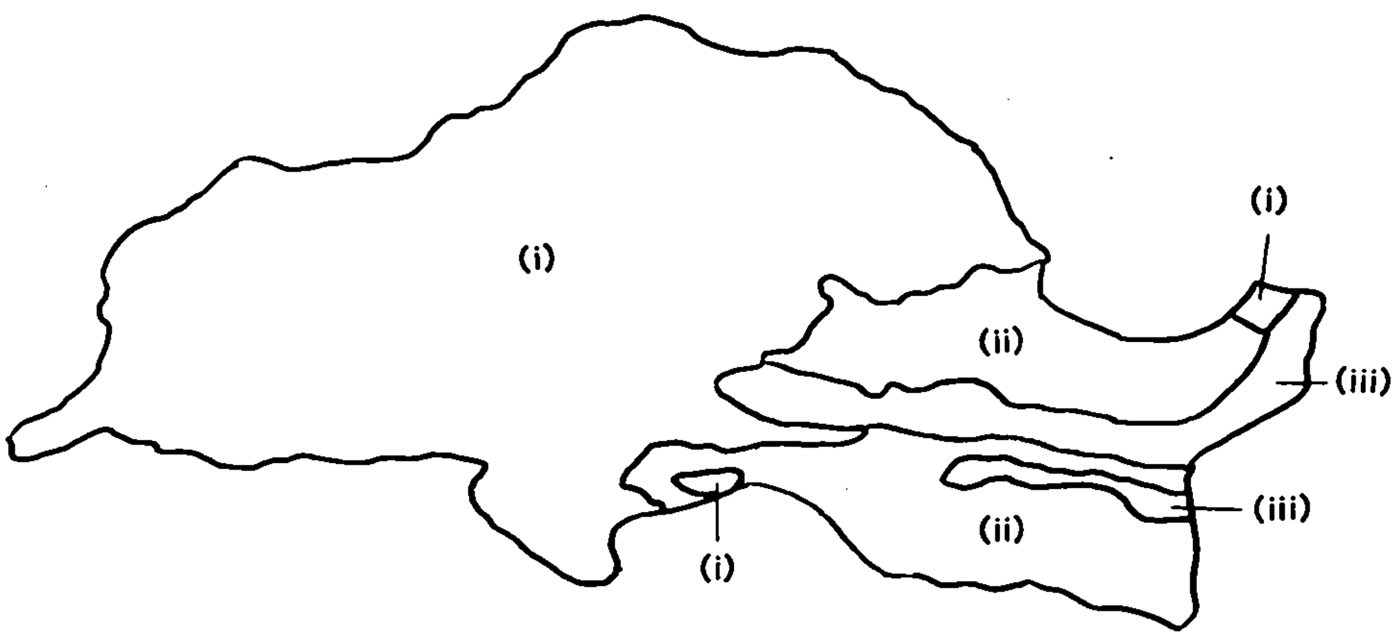
A brief description of each site and the data recorded is given in Table 4.2. Originally, the three sites were chosen for their ease of access and geographical position i.e. it was envisaged that the site at Lackam College would be representative of the western end of the catchment, the site at Wallingford would represent the eastern portion, with Lambourn representing the middle portion. However, an inspection of the altitudes and soil types at each site suggested a more sensible representation. Thus the site at upper Lambourn is typical of much of the higher altitude areas of the catchment and, for the purpose of this study, is taken to represent approximately 70% of the catchment, comprising the first four soil types depicted in Fig. 3.5. Similarly, the site at Lackam College represents the floodplain terrace (the Brown Earths in Fig. 3.5), whilst the Wallingford site represents the river valley (the Alluvial Gley Soils and Paleoargillic Brown Earths in Fig. 3.5). Whilst it is appreciated that such a representation is somewhat general, it is inevitable given the amount of instrumentation. Figure 4.2 shows how the catchment has been divided in terms of the representivity of the three sites.

The main reason for installing the soil thermometers was to investigate the depth to which the ground was likely to be frozen. Most attention was given to soil profiles under grass because, even in arable areas, the main emphasis is on autumn sown cereals, and these are likely to provide at least a sparse covering of green vegetation during the winter months. At the Wallingford site it was decided to monitor also the soil profile under bare earth, whilst at Lackam College, duplicate soil depths were monitored for comparison purposes. At upper Lambourn, intermediate depths were monitored in addition to the normal 1, 5 and 10 cm depths.

Campbell Scientific Ltd. Model 107B Temperature Probes were used to monitor ground surface and soil temperatures. Each probe consists of a 40 mm x 4 mm diameter metal rod connected to a solid state logger. Average hourly temperatures were recorded. The probes were inserted into the soil profile by digging a pit and carefully inserting the probes horizontally into the wall of the pit at the appropriate depths. The pit was infilled with the excavated soil and the grass sod replaced. The ground surface probes were simply inserted inside the grass sward.

Table 4.2 Soil Thermometer Sites

Location	Relief	Soil Type		Soil Depths Monitored
Warren Farm	Gently sloping	Brown Rendzina	GRASS	1.0 cm
Upper Lambourn	Interfluve Area	Well drained shallow		2.5 cm
		flinty soil over chalk		5.0 cm
				7.5 cm
				10.0 cm
Lackam College	Gently Sloping	Surface water gley soil	GRASS	1.0 cm
	River Terrace	Fine loamy soil over clay		5.0 cm
				10.0 cm
				1.0 cm
				5.0 cm
				10.0 cm
Institute of	Flat	Argillic brown earth	GRASS	1.0 cm
Hydrology	Thames floodplain	Loamy soil over sand		5.0 cm
				10.0 cm
Crowmarsh Gifford			SOIL	1.0 cm
Wallingford				5.0 cm
				10.0 cm



(i) Lambourn

(ii) Lackam

(iii) Wallingford

Fig. 4.2 The division of the Kennet catchment

for soil/air temperature calibration purposes

5. Data Analysis

This chapter begins with a brief description of the main trends found in the soil temperature data at the three monitored sites. The criteria for selecting suitable periods for analysis are then investigated, and the processing of the remotely sensed images described. Finally, the use of the results in determining the extent, duration, and depth of freezing within the Kennet catchment is examined.

5.1 SOIL TEMPERATURE DATA

The soil temperature probes were installed at the three sites at different dates:

Upper Lambourn	1200 GMT	30.10.91
Lackam College	1130 GMT	23.10.91
Wallingford	1200 GMT	20.06.91

For comparing data from the three sites, a common starting date of 1st November 1991 has been assumed. As the main interest is in minimum temperatures, this assumption will not be significant. Unfortunately, there were periods when the data were suspect. These periods related more to the movement of the temperature probes due to, for example, frost action than to instrument malfunction. This affected in particular the surface probes.

i) Upper Lambourn

Six temperature probes were installed at the Meteorological site at Warren Farm, upper Lambourn. These were at the ground surface (grass), and at depths of 1, 2.5, 5, 7.5 and 10 cm below grass. The range of values for each probe between the starting date and the end of February 1992 is given below.

		Minimum Temperature	Maximum Temperature
Grass surface		-3.6°C	+12.8°C
Grass :	1.0 cm	-1.4°C	+12.0°C
Grass :	2.5 cm	-0.2°C	+11.8°C
Grass :	5.0 cm	+0.2°C	+11.6°C
Grass :	7.5 cm	+0.7°C	+11.3°C
Grass :	10.0 cm	+1.0°C	+11.2°C

The time series graphs in Appendix II(a) show maximum and minimum daily temperatures for the 1, 5, and 10 cm soil temperature probes for the period of observation.

Both the surface and 1 cm depth probe suffered from displacement problems described above. For the 1 cm depth probe, the minimum and maximum temperatures shown above are probably correct; for the grass surface probe the minimum temperature is almost certainly underestimated. Figures 3 and 4 in Appendix II(a) show clearly the period when the 1 cm soil temperature probe became displaced. This period has been ignored for all data analysis purposes.

The patterns of soil temperatures are as expected, with higher minimum and lower maximum temperatures with increasing depth. The data suggest that the greatest depth of freezing is approximately 3 to 4 cm.

ii) Lackam College

Seven temperature probes were installed at the meteorological site at Lackam College. These were at the ground surface (grass) and duplicate probes at depths of 1, 5, and 10 cm below grass. The range of values for each probe between the starting date and the end of February 1992 is given below.

		Minimum Temperature	Maximum Temperature
Grass surface		-1.4°C	+12.9°C
Grass :	1.0 cm	-0.7°C	+12.7°C
Grass :	5.0 cm	-0.1°C	+12.4°C
Grass :	10.0 cm	+0.8°C	+12.2°C
Grass :	1.0 cm	-0.2°C	+12.6°C
Grass :	5.0 cm	+0.4°C	+12.2°C
Grass :	10.0 cm	+0.9°C	+12.0°C

The time series graphs in Appendix II(b) show maximum and minimum daily soil temperatures for the period of observation; average values from the duplicate probes have been taken.

The grass surface temperature probe suffered from displacement problems and the minimum temperature shown above is certainly an underestimate. Comparisons of the maximum temperatures between the two sets of thermometers is good, though there are differences, up to ±0.5°C, in the minimum temperatures. As each probe is individually calibrated to ±0.1°C in the laboratory prior to installation, this difference is probably due either to installation at slightly different depths or to heterogeneity in the soil profile.

Again the patterns of soil temperature with depth are as expected, with the greatest depth of freezing being approximately 3 to 4 cm.

iii) Wallingford

Seven temperature probes were installed at the meteorological site at the Institute of Hydrology. These were at the ground surface (grass) and at depths of 1, 5 and 10 cm below both grass and bare earth. The range of temperatures recorded by each probe was as follows:

		Minimum Temperature	Maximum Temperature
Grass surface		-11.8°C	+15.1°C
Grass :	1.0 cm	-1.3°C	+12.4°C
Grass :	5.0 cm	-0.1°C	+12.0°C
Grass :	10.0 cm	+1.3°C	+11.7°C
Soil :	1.0 cm	-6.4°C	+14.3°C
Soil :	5.0 cm	-3.4°C	+12.8°C
Soil :	10.0 cm	-1.4°C	+12.2°C

Appendix II(c) gives time series graphs of maximum and minimum daily temperatures for the soil temperature probes at IH over the period of observation.

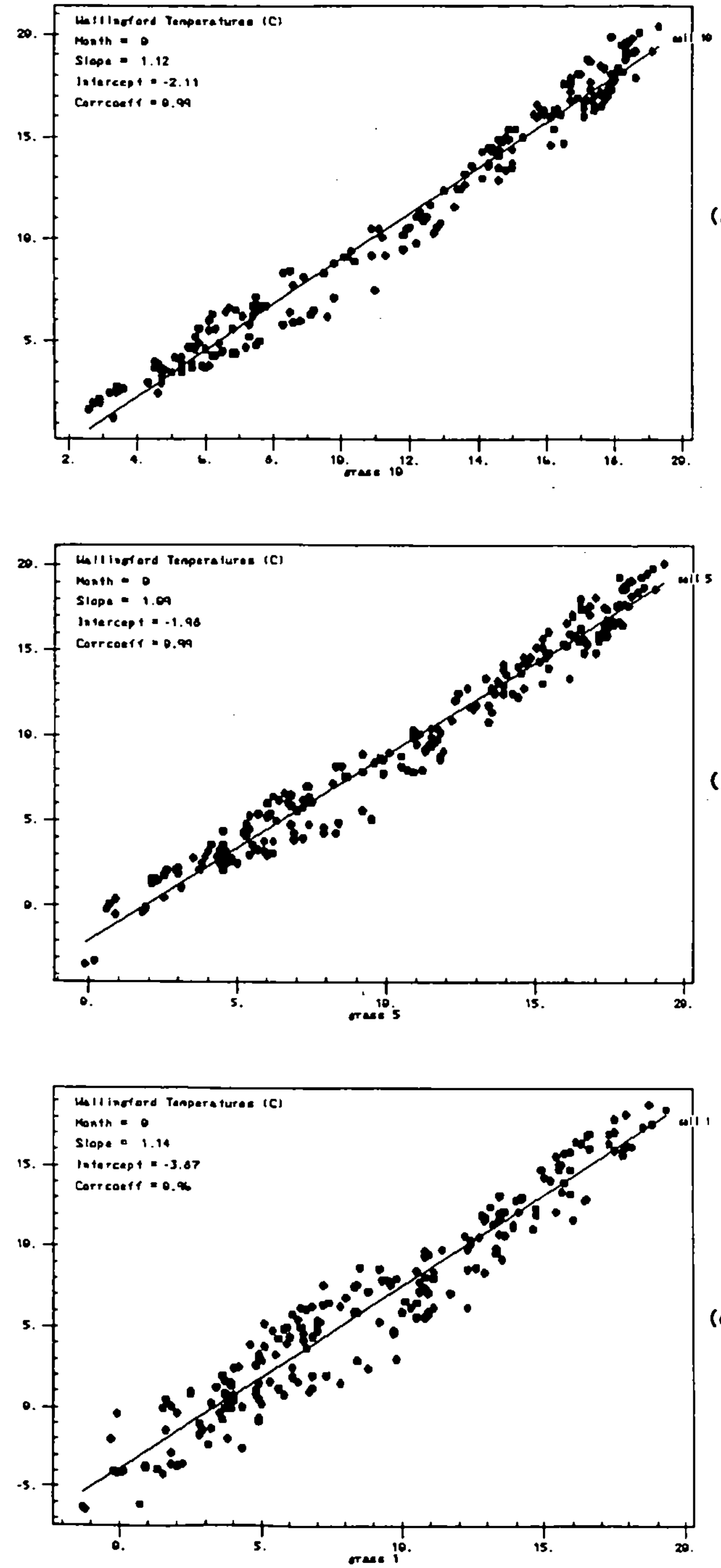
In this case, all the probes worked satisfactorily except for the 1 cm probe under bare soil which became uncovered for approximately 10 days in March 1992 (see Fig. 5, Appendix II(c)(ii)). In particular, the minimum grass temperatures given by the surface probe were generally close to those given by the standard grass minimum thermometer.

The range of temperatures for the soil probes under grass were similar to those at Lambourn and Lackam College. However the soil temperatures under bare earth were very different. Here, maximum temperatures were greater and, in particular, minimum temperatures were significantly less than those under grass. This is demonstrated in Figures 5.1 (a) - (c), where daily minimum temperatures at, respectively, 10, 5 and 1 cm depth under bare earth are plotted against those under grass for the period 20.06.91 to 01.03.92. These graphs show that excellent relationships exist between soil temperatures under bare earth and grass. Also, they demonstrate the buffering effect of vegetation in 'damping' variations in soil temperatures. Of particular significance to this study, is the fact that at a soil temperature of 0°C under grass, temperatures under bare earth at 10 cm, 5 cm and 1 cm depth will be depressed, respectively, by approximately 2°C, 2°C, and 4°C. Similar observations have been made by Kalma *et al.*, 1986.

Figures 5.2 and 5.3 show soil temperatures at various depths plotted against surface (grass) temperatures for grass and soil, respectively. As for Figure 5.1, daily minimum temperatures for the period 20.06.91 to 01.03.92. at the Wallingford site have been used. Unfortunately, problems with the surface probes at Lambourn and Lackam prevented a similar analysis of the data at these sites.

Good general relationships were obtained between soil minimum temperatures and surface minimum temperatures though, as Figures 5.2 and 5.3 show, there was a great deal of scatter. In general, the relationships are better for bare soil than grass, and improve with decreasing depth i.e. as the soil becomes more responsive to changes in surface temperature. If the relationships are examined on a monthly basis (Table 5.1), then it can be seen that the slopes and intercepts (and, in fact, correlations) are temperature dependent, with the relationships generally improving with decreasing temperature. Because of this, it was decided to restrict the range of temperatures used when correlating soil temperatures to surface temperatures (see Section 5.4).

Finally, daily grass minimum temperatures are plotted against air minimum temperatures for the Wallingford site in Figure 5.4. A good relationship is obtained with ground temperature being a degree or so less than air temperature.

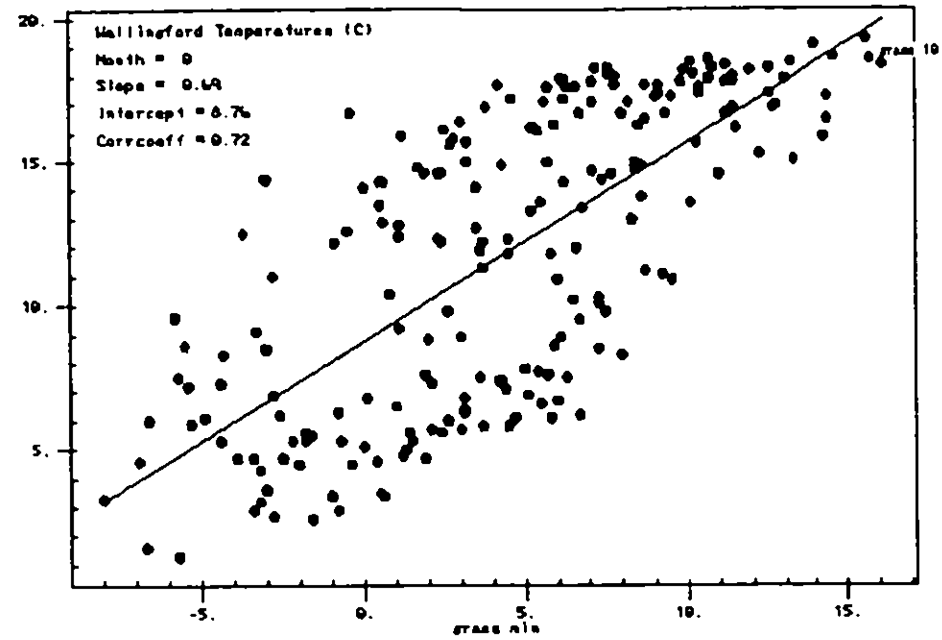


(a) 10 cm depth

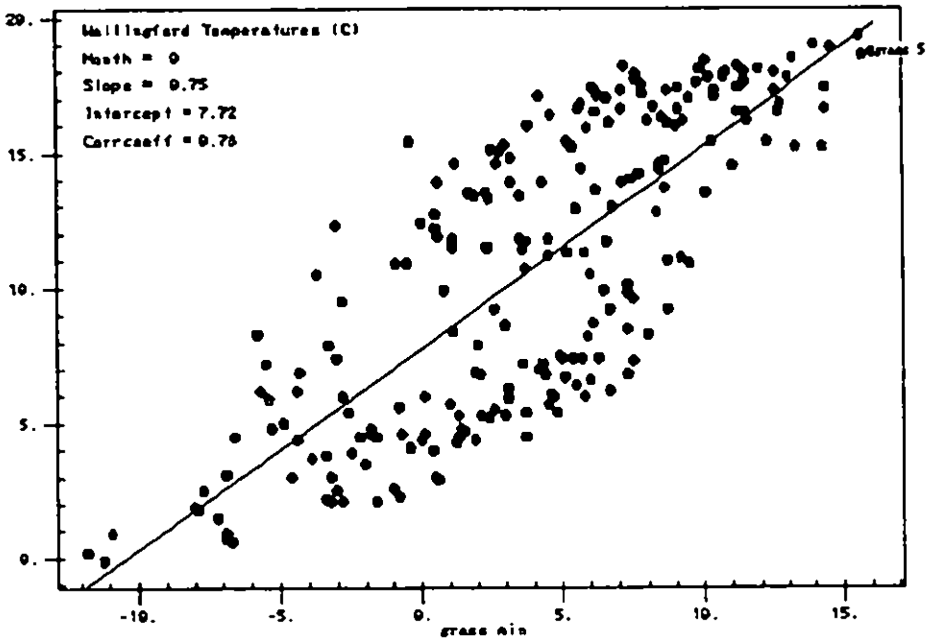
(b) 5 cm depth

(c) 1 cm depth

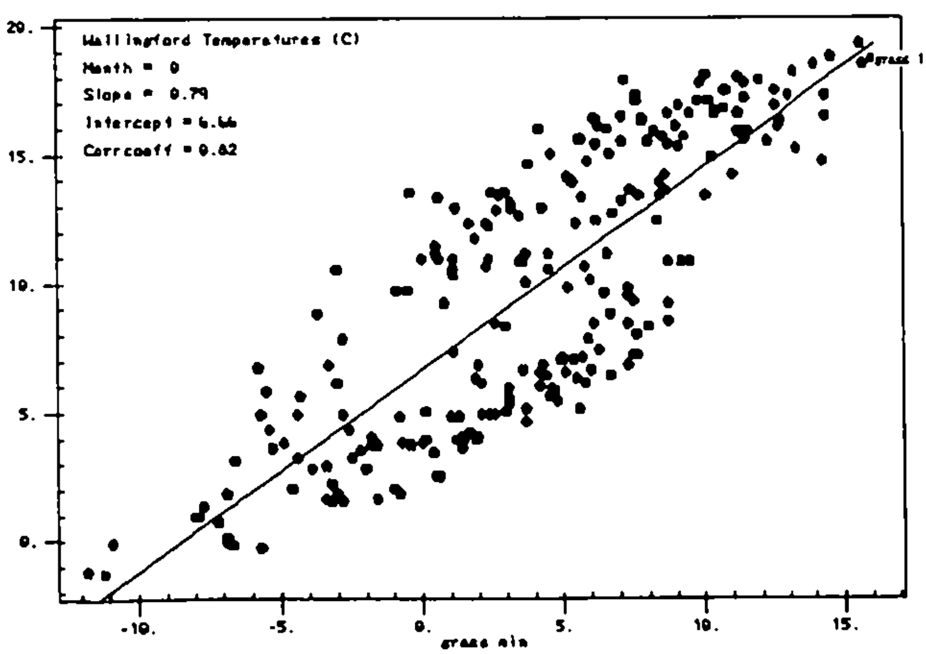
Fig. 5.1 Daily minimum temperatures under bare earth and grass at Wallingford



(a) 10 cm depth

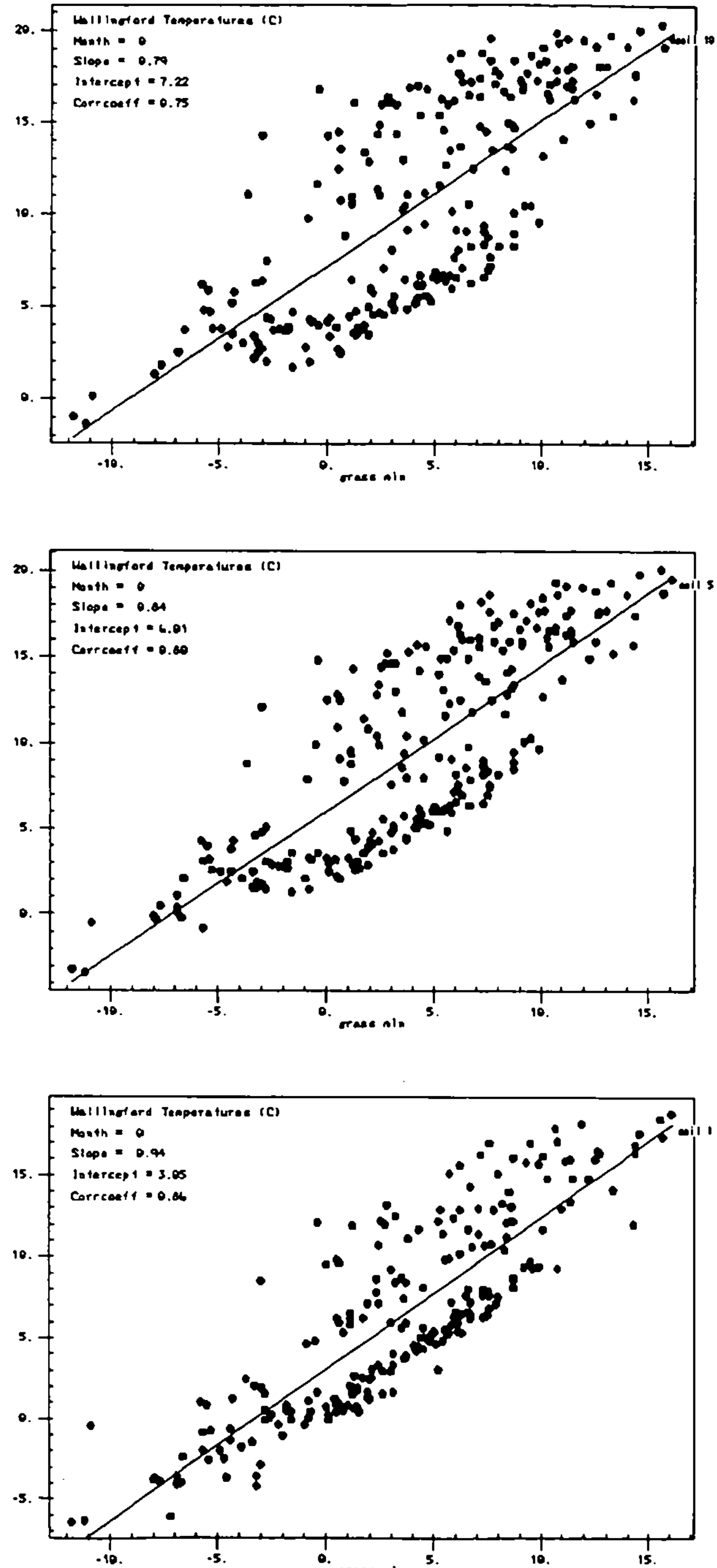


(b) 5 cm depth



(c) 1 cm depth

Fig. 5.2 Daily minimum soil temperatures under grass against surface temperatures at Wallingford



(a) 10 cm depth

(b) 5 cm depth

(c) 1 cm depth

Fig. 5.3 Daily minimum soil temperatures under bare earth against surface temperatures at Wallingford

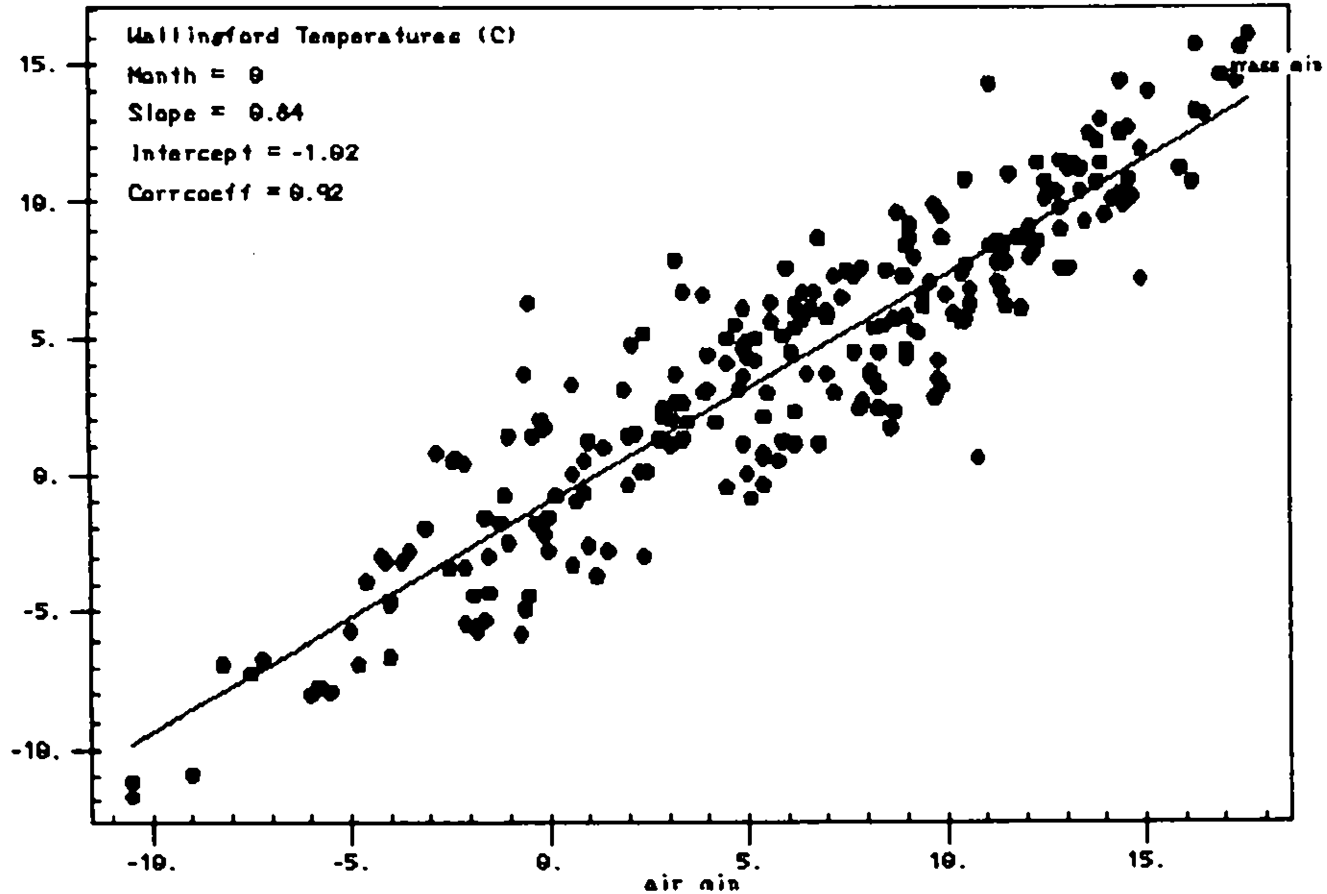


Fig. 5.4 Daily grass minimum temperatures against air minimum temperatures for Wallingford

Table 5.1 Monthly Regressions of Daily Minimum Soil Temperatures Against Ground Temperatures at Wallingford

		Mean Values		Slope	Intercept	Corr. Coeff.
GRASS 10		GRASS 10	SURFACE			
July	1991	17.7	9.7	0.12	16.5	0.56
August	1991	17.3	7.5	0.19	16.0	0.78
September	1991	14.8	5.1	0.20	13.8	0.77
October	1991	11.2	3.4	0.17	10.7	0.51
November	1991	7.4	1.3	0.21	7.6	0.65
December	1991	5.4	-1.6	0.28	5.9	0.66
January	1992	5.3	0.8	0.43	5.0	0.88
February	1992	5.1	1.2	0.33	4.7	0.80

		Mean Values		Slope	Intercept	Corr. Coeff.
GRASS 5		GRASS 5	SURFACE			
July	1991	17.3	9.7	0.19	15.4	0.71
August	1991	16.8	7.5	0.28	14.7	0.86
September	1991	13.8	5.1	0.29	12.4	0.85
October	1991	10.6	3.4	0.26	9.7	0.69
November	1991	7.3	1.6	0.29	6.9	0.80
December	1991	4.2	-2.6	0.38	5.2	0.91
January	1992	4.4	0.2	0.46	4.4	0.94
February	1992	4.5	1.4	0.40	3.9	0.87

		Mean Values		Slope	Intercept	Corr. Coeff.
GRASS 1		GRASS 1	SURFACE			
July	1991	16.6	9.7	0.31	13.7	0.81
August	1991	16.0	7.5	0.41	12.9	0.90
September	1991	12.9	5.1	0.37	11.1	0.89
October	1991	9.9	3.4	0.35	8.7	0.80
November	1991	6.6	2.0	0.36	5.9	0.86
December	1991	3.5	-2.1	0.44	4.4	0.93
January	1992	4.0	0.6	0.51	3.8	0.96
February	1992	4.2	1.6	0.49	3.3	0.94

Table 5.1 Continued

		Mean Values		Slope	Intercept	Corr. Coeff.
SOIL 10		SOIL 10	SURFACE			
July	1991	17.6	9.7	0.22	15.4	0.60
August	1991	17.6	7.5	0.28	15.6	0.69
September	1991	14.6	5.1	0.32	13.0	0.75
October	1991	9.7	3.4	0.33	8.6	0.73
November	1991	6.3	2.3	0.34	5.6	0.86
December	1991	3.7	-2.0	0.40	4.5	0.91
January	1992	4.8	1.9	0.44	4.0	0.93
February	1992	4.4	1.6	0.40	3.6	0.89

		Mean Values		Slope	Intercept	Corr. Coeff.
SOIL 5		SOIL 5	SURFACE			
July	1991	16.8	9.7	0.30	13.9	0.70
August	1991	16.5	7.5	0.38	13.7	0.76
September	1991	13.4	5.1	0.43	11.2	0.81
October	1991	8.6	3.4	0.44	7.1	0.83
November	1991	5.5	2.3	0.43	4.5	0.91
December	1991	2.8	-1.7	0.48	3.6	0.93
January	1992	3.9	1.0	0.50	3.4	0.97
February	1992	3.9	1.8	0.50	2.8	0.93

		Mean Values		Slope	Intercept	Corr. Coeff.
SOIL 1		SOIL 1	SURFACE			
July	1991	14.5	10.3	0.64	7.9	0.95
August	1991	14.5	7.5	0.48	10.9	0.80
September	1991	10.4	5.1	0.63	7.2	0.81
October	1991	6.6	3.4	0.63	4.4	0.93
November	1991	3.7	2.9	0.71	1.7	0.97
December	1991	1.0	1.0	0.64	1.6	0.95
January	1992	1.6	0.7	0.79	1.0	0.99
February	1992	2.0	2.0	0.96	0.0	0.97

5.2 CLIMATOLOGICAL DATA

The climatological data, particularly the air and grass minimum temperatures, recorded daily at 0900 GMT at the Institute of Hydrology Meteorological site were inspected, so that appropriate conditions could be identified to test the suitability of AVHRR images in detecting frozen ground conditions. The period considered was governed by the availability of AVHRR images from the receiving station at the University of Dundee (August 1976 to the present). The main consideration was to identify suitable periods during the winter 1991/92, so that the images acquired could be calibrated using the instrumentation described above. However, it was decided to consider also suitable periods prior to the installation of the instrumentation.

A number of climatologically suitable (cold temperature) periods were identified prior to winter 1991/92, and a number of 'quick-look' hard copy images of the UK ordered. Of these the most suitable for analysis was found to be an image taken at 0430 on the 30th January 1987. On the day of image recording, an air minimum temperature of -2.8°C and a grass minimum temperature of -10.7°C was observed at IH met. site, with similar values being observed at the other met. sites within and immediately outside the Kennet catchment. It was decided to use this image to investigate the feasibility of using AVHRR images to estimate the distribution of surface temperatures over the Kennet catchment.

The winter of 1991/92 has proved to be a disappointing one in the context of this study. Periods of very low temperatures, producing significant ground frost, have been rare. Only two such periods have been identified - the 11th to the 14th December 1991 and the 21st to the 24th January 1992. 'Quick look' photographs for the two periods were inspected to determine whether the UK was cloud free. For the first period, an image taken at 0440 GMT on the 12th December was acquired and analysed, in spite of the existence of substantial cloud cover. For the second period, an image taken at 0310 GMT on the 23rd January has been analysed

In addition, it was decided to compare land surface temperatures over the Kennet using a Landsat image and an AVHRR image taken at approximately the same time. The Landsat image was the one used to provide the land classification (see section 3); this was taken at 1015 GMT on the 9th August 1984. An AVHRR image taken at 0900 GMT on the same date was obtained for comparison purposes. Although the temperatures experienced at this time were much higher than those of interest to this particular study, nevertheless such a comparison may be of general interest.

5.3 REMOTELY SENSED IMAGES

This section describes the characteristics of AVHRR and Landsat images, and the steps taken to produce the ground surface temperatures over the Kennet catchment.

(i) AVHRR images

The characteristics of the AVHRR sensor on board the NOAA Polar Orbiting Satellites are given in Fig. 2.2. At present, two NOAA satellites are operational; these provide four images per day. These images are captured by a receiving station at the University of Dundee; these are then processed to provide a number of products (University of Dundee, unpublished).

For this particular application, the products utilized are 'quick-look' photographs, to determine whether the area of interest is cloud free and, if so, a multi-band sub-image covering Southern England. One of the NOAA satellites records images in four bands, whilst the other records in five bands (the thermal band is split into two to enable an atmospheric correction to be performed). Only the thermal band(s) are used for this study. All of the processing of the images was done on the image analysis system at the Institute of Hydrology.

The first step in processing the images involves registering the image to a base map. The routine used is based on a geolocation algorithm originally developed in the United States for the Coastal Zone Colour Scanner (Wilson *et al.*, 1981). This algorithm has subsequently been modified at the Plymouth Marine Laboratory to cope with AVHRR images. The algorithm requires the pixel coordinates of one reference point (normally a prominent part of the coastline is chosen), together with its map coordinates. The algorithm then uses these values together with information relating to the altitude and aspect of the satellite to register the image.

The conversion of radiance values (digital numbers, DN) as observed by the AVHRR thermal sensors to brightness temperatures is done using calibrations derived using laboratory standards (Lauritson *et al.*, 1979). The resulting 'brightness' temperatures may be different from actual surface temperatures because of atmospheric effects and varying emissivities from different surfaces.

For the NOAA satellite (NOAA 11) having two thermal bands, the atmospheric effects may be eliminated using the 'split-window' technique (Prabhakara *et al.*, 1975). Basically, this technique utilizes the fact that these atmospheric effects vary with wavelength, so that a brightness temperature expressed as a combination of the brightness temperatures in the two individual bands will be free from error due to atmospheric effects. Typically, relationships of the form

$$T^{BB} = T_4 + A\,(T_4 - T_5) + B$$

are used,

where T^{BB} is the satellite temperature corrected for atmospheric effects,
T_4 and T_5 are the brightness temperatures measured in NOAA bands 4 and 5,
A is a constant associated with the absorbtion coefficients of water vapour in NOAA bands 4 and 5,

B is a constant that takes into account the influence of surface reflection and carbon dioxide emission.

The values of A and B are derived from regressions between actual sea surface temperatures and brightness temperatures in NOAA bands 4 and 5. For the north-east Atlantic Ocean and the Mediterranean sea, it has been found (Castagné *et al.*, 1986) that the following relationship applies:-

$$T^{BB} = T_4 + 2.0\,(T_4 - T_5) + 0.5$$

where T^{BB}, T_4, T_5 are in °C.

For NOAA10, which only has one thermal band, such a correction is not possible.

The biggest problem with determining land surface temperatures from AVHRR images is that of emissivity. Whilst the sea surface has an almost constant emissivity close to unity, different land surfaces have widely varying emissivities (Griggs, 1968). A knowledge of these emissivities plus a land cover map at the time of satellite overpass would be required to convert the atmospherically corrected brightness temperatures to 'true' temperatures. Alternatively, a number of theoretical formulations could be applied. For this particular application, it was decided to use the data from the meteorological stations described previously (chapter 4).

In theory, the most appropriate parameter to use for calibrating the AVHRR images is the grass minimum temperature, as this is probably closest to what the remote sensing sensor 'sees'. However, this parameter is known to vary considerably over short distances according to topography and is very dependent on how the temperature probe has been inserted within the grass sward. The first point is very relevant to AVHRR imagery, as each 'pixel' (picture element) is an average over an area of 1 km^2. Using a point value from an unrepresentative location as an average for a 1 km^2 area could be very misleading. The second point became very apparent when comparing recorded and manually-read grass minimum temperatures at Lackam and Lambourn; large differences were observed, often up to 10°C.

Minimum air temperature, recorded in a Stevenson screen approximately 1.25 m above ground level, is also dependant on the positioning of the meteorological site, but to a lesser degree than is minimum grass temperature. Also, the recorded air temperature does not depend on the installation of the thermometer as does grass temperature. For these reasons, it was decided to use the mean air temperature at the various meteorological sites (Fig. 4.1) as one point to calibrate the AVHRR images. A similar conclusion was reached by McClatchey, 1992 in this study of low temperatures over Scotland.

(ii) Landsat images

The characteristics of the Thematic Mapper sensor on board the Landsat series of satellites are given in Fig. 2.1. Full scenes cover an area of 185 x 185 km and may be purchased from a number of agencies. For this particular study, the Landsat scene utilized had already been purchased by NERC for a previous application.

The first step in the processing involves registering the image to a base map. This is done by selecting suitable reference points - major road junctions, bends in rivers etc., on both the Landsat image and the base map, normally 1 to 50,000 scale, and using a warping routine on the image analysis system to register the image to the map coordinates. Normally, a mean error of registration of 1 pixel (30 m) can be achieved for Landsat images. At the same time the area of interest, in this case the catchment boundary of the River Kennet, is digitized from the base map and registered to the image.

The land classification shown in Fig. 3.6 was obtained using a supervised classification (Schowengerdt, 1983). For this, areas of known, homogeneous vegetation are used as 'training' areas for the classification of the whole image or, in this case, the Kennet catchment. Fortunately, many areas within and immediately outside the Kennet have been the subject of a long-term vegetation survey. Also, the relative spectral responses of the various vegetation types are reasonably well known, and a land classification using a satellite image even eight years old can be done with some confidence. Six bands, the maximum permitted, was used for the classification. Band 6, the thermal band, was omitted as this was likely to yield the least information.

For the temperature distribution, the thermal band, 10.4 to 12.5 microns, was utilized. The thermal sensor on board the Landsat series of satellites is calibrated against sources of known temperature.

The relationships between the values recorded by the sensor and uncorrected temperatures are given in Wukelic *et al.*, 1989. These uncorrected temperatures are also subject to modification by the atmosphere and to variations in the surface emissivity. In a similar manner to the AVHRR images, the uncorrected temperatures from the Landsat image have been calibrated using sea surface and ground temperatures.

5.4 IMAGE ANALYSIS

This section describes the results of analysing the various remotely sensed images. It begins with a comparison of surface temperatures obtained from a Landsat and AVHRR image, and then presents the results from the AVHRR images of January 1987, December 1991, and of January 1992. The use of the results of the image analysis in determining the extent and depth of frozen ground within the Kennet catchment will be described in section 5.5.

(i) Landsat vs AVHRR surface temperatures

The Landsat image was taken at approximately 1015 GMT on the 9th August 1984. The characteristics of the image are shown in Fig. 2.1 and a description of the way the image is analysed given in section 5.3 (ii). The AVHRR image used for comparison was obtained at approximately 0900 GMT on the same date. Since the AVHRR image was recorded over an hour before the Landsat image, it has been assumed that the distribution of surface temperature did not change appreciably during this period, and that ground data taken at the time of Landsat overpass could be used to calibrate the AVHRR image.

'Ground' data for calibrating the results of analysing the images were given by the sea surface temperature (13.5°C) in the English Channel and by soil temperatures recorded at 1020 GMT at the meteorological site at IH. Two relevant soil temperatures were employed; values at 0.5 cm depth under bare soil (30.4°C) and under short grass (20.6°C). For the Landsat image, it was possible, using the visible bands, to identify almost precisely the location of the meteorological site. For this reason, grass temperatures, as given by the Landsat image, have been corrected using the soil temperature under grass. This was not possible using the AVHRR image because of its coarser spatial resolution. For this, it has been assumed that the 1 km^2 surrounding the meteorological site at IH is 50% grassland and 50% arable land, or bare earth at that particular time of year. Inspection of the land classification in the Wallingford area (Fig. 3.6) suggests that such an assumption is not unreasonable, though it is appreciated that there are a number of concrete surfaces - roads, buildings etc., that will obviously affect the radiance temperature observed by the AVHRR sensor.

A comparison of the 'uncorrected' surface temperatures from the Landsat classification and the ground values showed that, as expected, the former were higher than the latter. The differences were as follows:

	Landsat	Ground values	Difference
Sea Surface	16.2°C	13.5°C	2.7°C
IH short grass	24.0°C	20.6°C	3.4°C

These differences are caused by attenuation of the surface temperatures by the atmosphere, and are of the same order of magnitude quoted in the literature (Wukelic *et al.*, 1989). A correction of -3.0°C was applied to the Landsat temperatures.

For the AVHRR, only one thermal band was recorded, and no atmospheric correction was possible. For this reason, no brightness temperatures were calculated, and a linear regression applied between the ground values and the radiances measured by the thermal channel of the AVHRR. The values were as follows:

	AVHRR (Radiances)	Ground values
Sea Surface	100	13.5°C
IH Short grass/Bare earth	110	25.5°C

The resulting regression was:

$$\text{Temp } (^\circ C) = 1.2 \times \text{Radiance} - 106.5;$$

this was applied to the whole of the Kennet.

The resulting temperature distributions in the Kennet are shown in Fig. 5.5. Although the range of temperatures are similar, the distributions are different. A number of factors are involved:

(a) The time difference between the satellite overpasses.

(b) The occurrence of haze in the Landsat image. This is shown as the colder areas to the west and north of the catchment. A similar effect can be seen for the aircraft vapour trail bisecting the catchment.

(c) The difference in ground resolution of the two images. The net effect of this will be to reduce the range of surface temperatures given by the AVHRR image compared to the Landsat image. This also results in the 'block' nature of AVHRR classifications, compared with Landsat classifications.

In spite of these differences, such a comparison is interesting, and highlights the uncertainties in estimating surface temperatures from the various satellite images.

(ii) January 1987 AVHRR image

The image was recorded at 0430 GMT on the 30th January 1987. It is particularly suitable for this application. Figure 5.6 is a Band 4 (thermal) image of southern UK showing the location of the Kennet catchment. Apart from an area in the West Midlands, the area is cloud free.

Table 5.2 gives the AVHRR Bands 4 and 5 combined radiance values, corrected for atmospheric effects, and air temperatures, at 0900 GMT, for the meteorological sites chosen for calibration purposes (Fig. 4.1). Sea surface radiance and temperature are also shown. For calibration purposes, this latter value was used as one extreme, whilst the average of the land values in Table 5.2 provide the other. Air temperatures in brackets at each site are the 'corrected' air temperature values from the AVHRR imagery. In general, these agree reasonably well with the observed values.

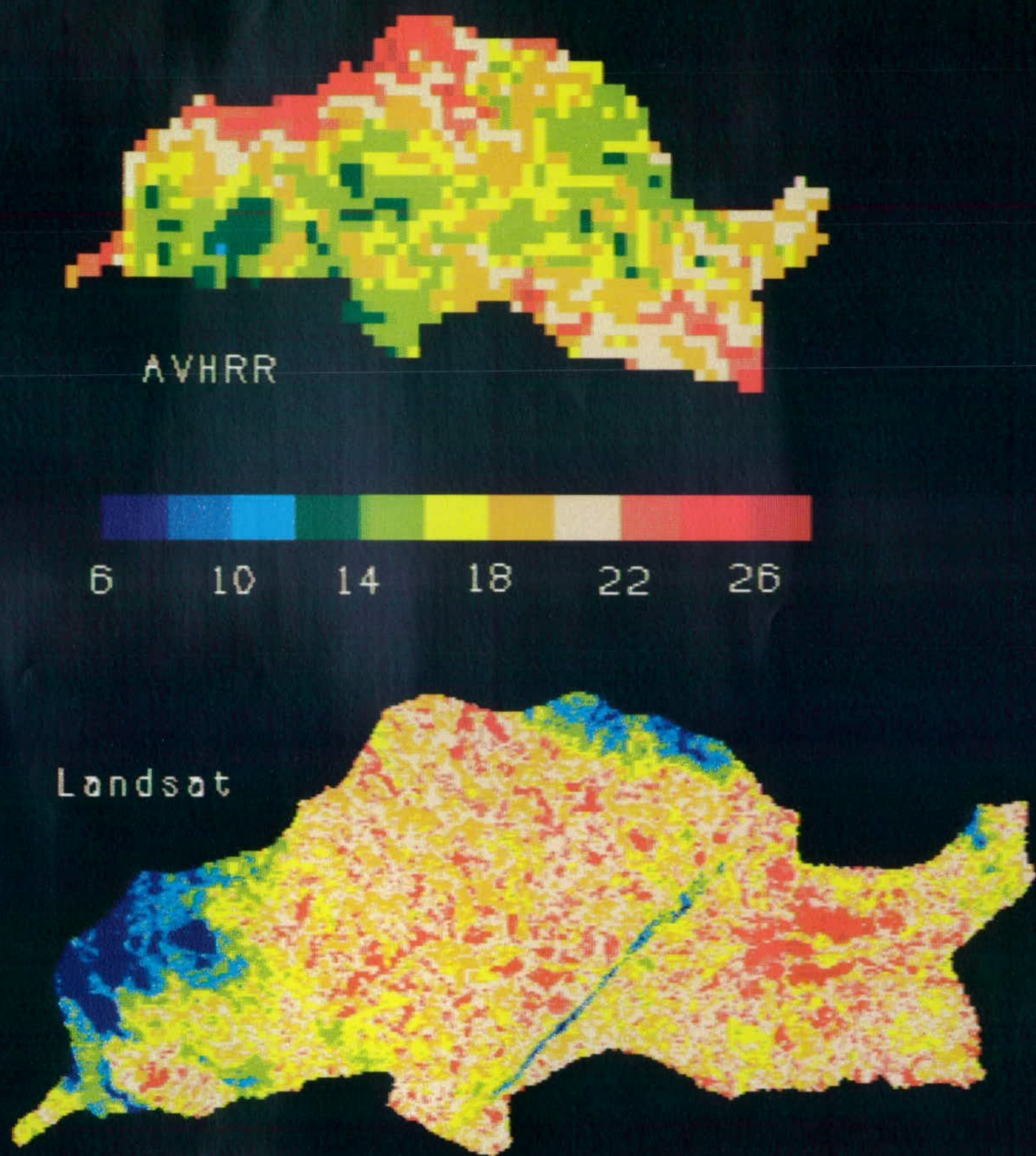


Fig. 5.5 AVHRR and Landsat Temperatures

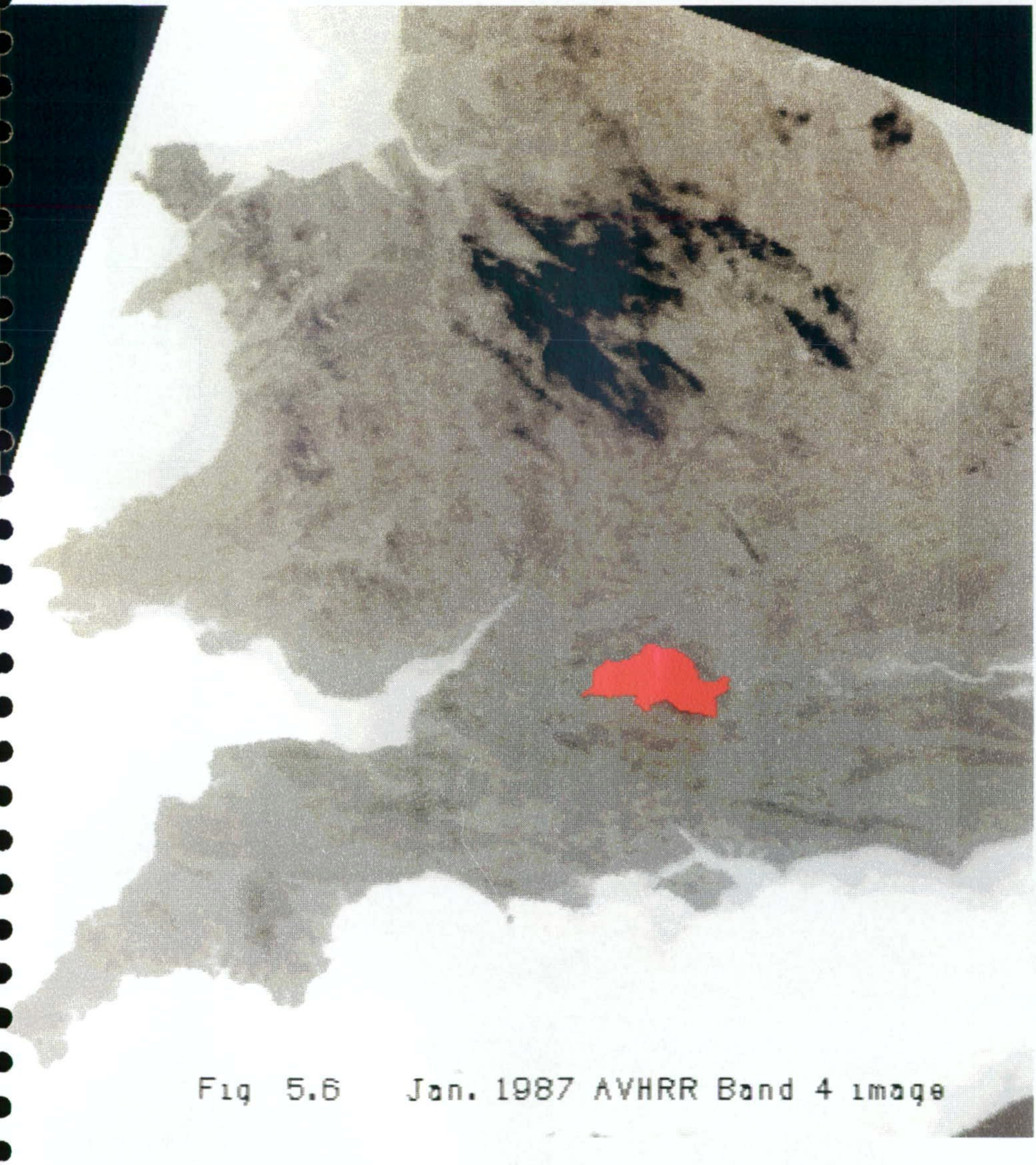


Fig 5.6 Jan. 1987 AVHRR Band 4 image

Table 5.2 Calibration of the January 1987 AVHRR image

Location	AVHRR Radiance	Air Temperature °C
Lyneham	105	-4.4 (-4.5)
Marlborough	117	-3.8 (-3.7)
Lambourn	107	-4.4 (-4.3)
Netheravon	120	-4.2 (-3.7)
Boscombe	119	-4.3 (-3.6)
Wallingford	121	-4.8 (-3.4)
Benson	120	-3.6 (-3.5)
Reading	131	-2.1 (-2.8)
Aborfield	119	-0.3 (-3.6)
Easthampsted	121	-3.8 (-3.4)
Average	118	-3.6
Sea surface	255	+5.0

The derived regression was:

Temperature = 0.063 x Radiance -11.07;

this was applied to the whole of southern UK; Fig. 5.7 shows the results obtained. The temperatures vary between less than -8°C and greater than +5°C. There are two main points of interest in this temperature distribution:

(a) The reduction in sea surface temperature in the coastal areas. This is particularly evident in the Severn estuary, the Wash and in the south and west coasts.

(b) The higher land surface temperatures in Cornwall, part of Devon and south-west Wales.

Figure 5.8 shows the temperature distribution in the Kennet catchment. In this case, the temperatures have been adjusted by approximately +1.5°C to compensate for the fact that there was a temperature difference, as recorded by an automatic weather station at IH, between 0430 GMT and 0900 GMT. The observed temperature range was -2.5°C to -5.0°C. The temperature pattern suggests that the 'higher' temperatures are generally found in the valley bottoms, with the colder values confined to the higher interfluve area. However, a poor correlation was obtained between temperature and altitude, as obtained from Fig. 3.4. This is also evident for the measured temperatures at the met. sites. Possible reasons for this will be discussed later. Implications for frozen ground conditions will be described in

Section 5.5.

(iii) December 1991 AVHRR image

The image was recorded at 0442 GMT on the 12th December 1991. Unfortunately, although the air temperatures recorded on the ground were much colder than those for the January 1987 image, much of the UK was covered by cloud. Over the Kennet catchment, the cloud was very thin and it was decided to analyse the image. As a result of the cloud cover, the analysis was confined to the Kennet catchment. Also, thermal band 4 was particularly affected, and the analysis was done with band 5 radiances only, uncorrected for atmospheric effects.

Table 5.3 gives the AVHRR Band 5 radiance values and air temperatures at 0900 GMT for the meteorological sites. Sea surface radiance and temperature are also shown. In this case, temperatures at the three intensively instrumented sites suggested that no correction was required between the 0440 and 0900 GMT temperatures. As before, the calibration is done on the sea surface and average land temperatures, and the temperatures in brackets in Table 5.3 are the 'corrected' AVHRR temperatures. As for the January 1987 image, the agreement is reasonable.

Table 5.3 Calibration of the December 1991 AVHRR image

Location	AVHRR B5	Air Temperature °C
Lyneham	81	-9.2 (-9.2)
Marlborough	77	-10.6 (-9.6)
Lambourn	77	-7.5 (-9.6)
Netheravon	72	-8.9 (-10.0)
Larkhill	61	-8.2 (-11.0)
Boscombe	58	-11.4 (-11.3)
Wallingford	74	-10.5 (-9.9)
Reading	80	-8.9 (-9.3)
Easthampsted	72	-12.8 (-10.0)
Average	73	-9.9
Sea surface	241	+5.0

The derived regression was:

Temperature = 0.089 x Radiance -16.45;

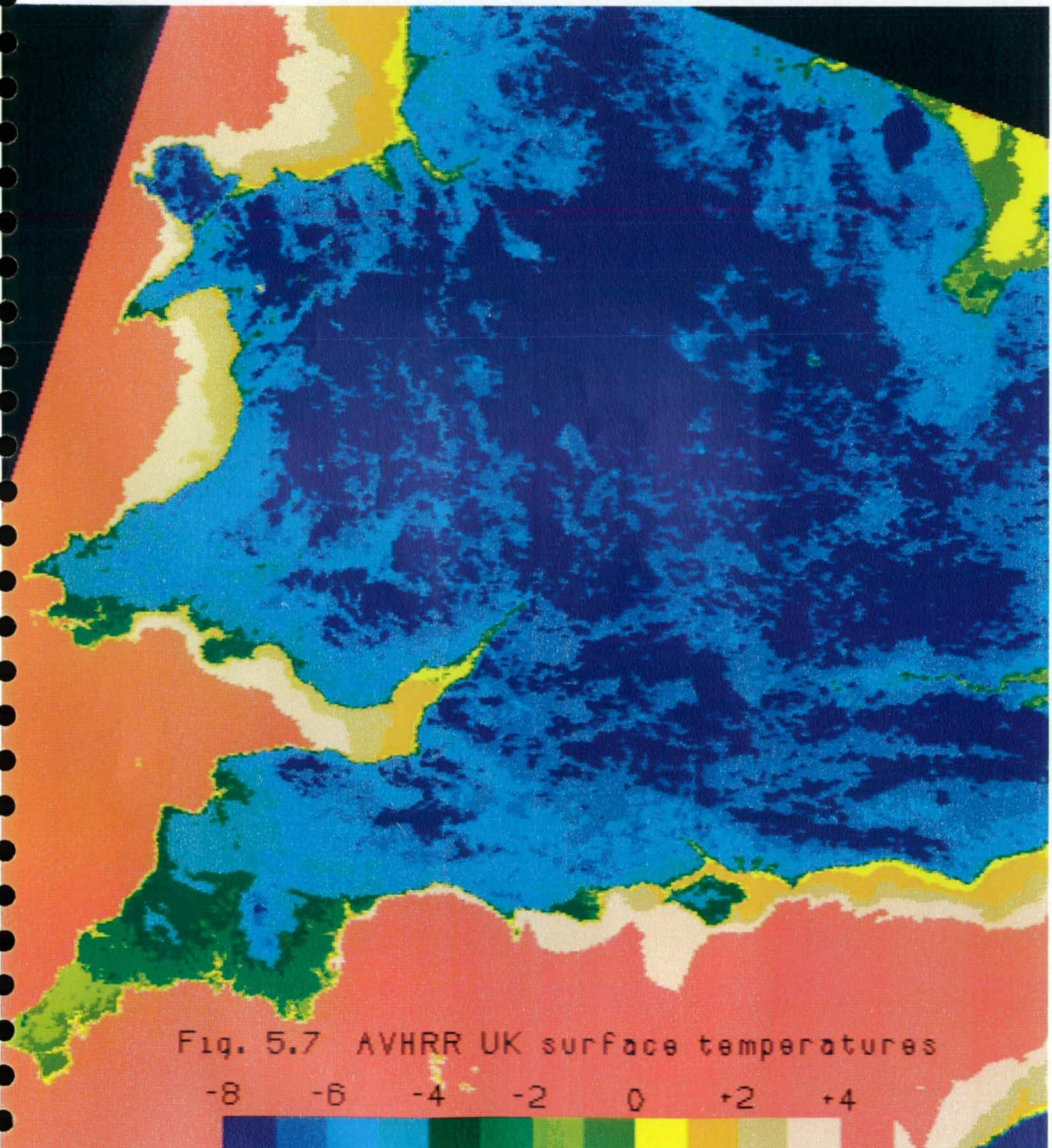


Fig. 5.7 AVHRR UK surface temperatures

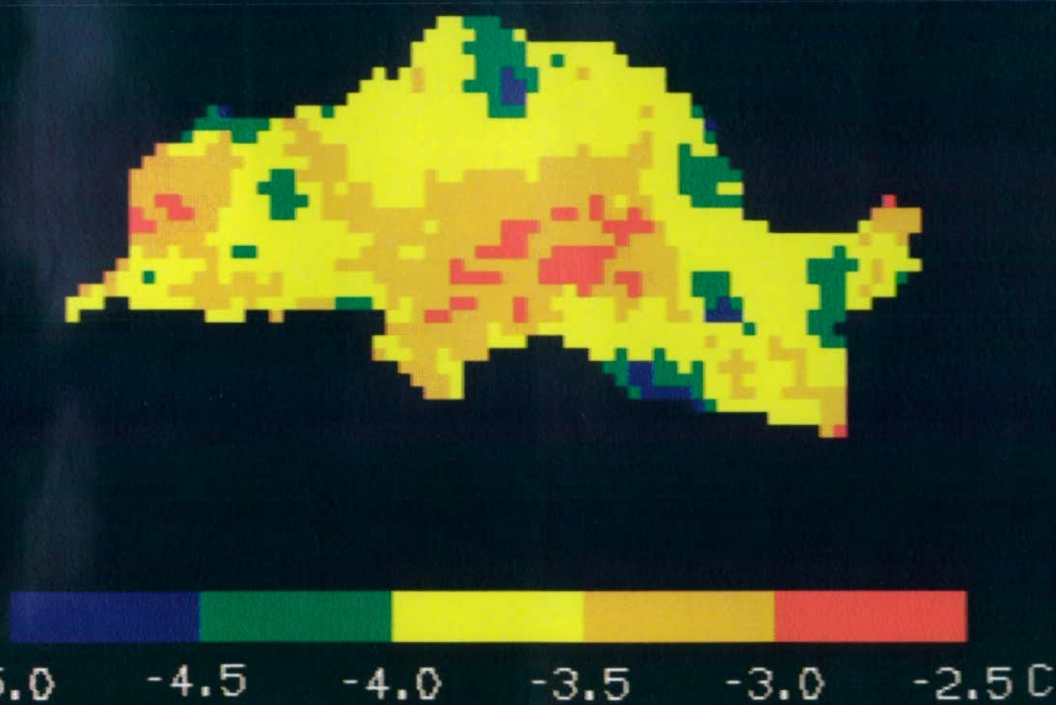


Fig. 5.8 Temperature distribution in the Kennet

AVHRR image Jan. 1987

this was applied to the Kennet catchment; the resulting temperature distribution is shown in Fig. 5.9. The temperature range was -11.0 to -8.5°C. The 'colder' temperatures are mainly confined to the south of the catchment, and the 'warmer' temperatures to the north. Again, the agreement between both measured and AVHRR derived air temperatures and altitude was poor.

(iv) January 1992 AVHRR image

The image was recorded at 0310 GMT on the 23rd January 1992. Fortunately, most of southern England was cloud free during the time of overpass, and it was possible to use both bands 4 and 5 for distributing the recorded point air temperatures.

As for the previous images, the AVHRR combined bands 4 and 5 radiances were calibrated using the sea surface and average Kennet catchment minimum air temperatures. In this case, there was no need to adjust the latter for time differences, as the minimum temperatures were recorded at almost exactly the time of satellite overpass.

The two calibration values used were:-

	AVHRR (Radiances)	Ground values
Average for Kennet catchment	75	-6.9
Sea Surface	1	+5.0

and the derived regression was:

Temp (°C) = -0.16 x Radiance +4.84

In this case, for convenience, the radiance values were scaled in the opposite sense to the previous AVHRR images. This is the reason for the difference in the regression for this image.

The regression was applied to the Kennet catchment; the resulting temperature distribution is shown in Fig. 5.10. The temperature range was -8.4 to -6.0°C with, seemingly, little correspondence between the distribution and topography or with the temperature distributions found using the previous images.

5.5 ESTIMATING THE AREAL EXTENT AND DEPTH OF FREEZING SOIL

As indicated in Section 5.3, a decision was taken to use air minimum temperatures for converting AVHRR derived surface temperatures to soil temperatures. Figures 1-4 in Appendix III show regressions of soil temperatures at the various recorded depths against air temperatures for the three intensively instrumented sites. The data used for these regressions have been confined to air temperatures close to and below 0°C. There is a great deal of scatter in the various data sets, particularly at 'higher' temperatures and, in most cases, it would probably be more appropriate to use exponential curves rather than the straight line regressions shown.

However, the purpose of developing these relationships is to obtain estimates of the air temperatures at which the various soil temperatures drop to freezing. For this, the straight line regressions shown are as good as the more realistic exponential curves. Table 5.5 shows these air temperatures at which freezing soil conditions are reached.

These values have been used to convert the AVHRR derived surface air temperature distribution into the extent of frozen soil at various depths in the Kennet catchment. Two scenarios have been considered:

a) Assuming that the whole of the Kennet catchment is covered by grass (or green vegetation), and using only the 'grass' values in Table 5.5. The different factors from the three sites have been applied according to the distribution shown in Fig. 4.2.

b) As above with the further assumption that the arable areas identified from the Landsat August 1984 image (Fig. 3.6) are in fact, bare earth. For these areas, the Wallingford 'soil' factors have been applied.

Table 5.5 Air Temperatures at which frozen soil conditions occur

LOCATION			
Wallingford	Grass	1 cm	-9.2°C
		5 cm	-10.7°C
		10 cm	-12.2°C
	Soil	1 cm	+0.1°C
		5 cm	-6.4°C
		10 cm	-9.4°C
Lambourn	Grass	1 cm	-5.5°C
		2.5 cm	-5.9°C
		5 cm	-7.2°C
		7.5 cm	-8.5°C
		10 cm	-8.2°C
Lackam	Grass	1 cm	-7.6°C
		5 cm	-8.3°C
		10 cm	-9.3°C

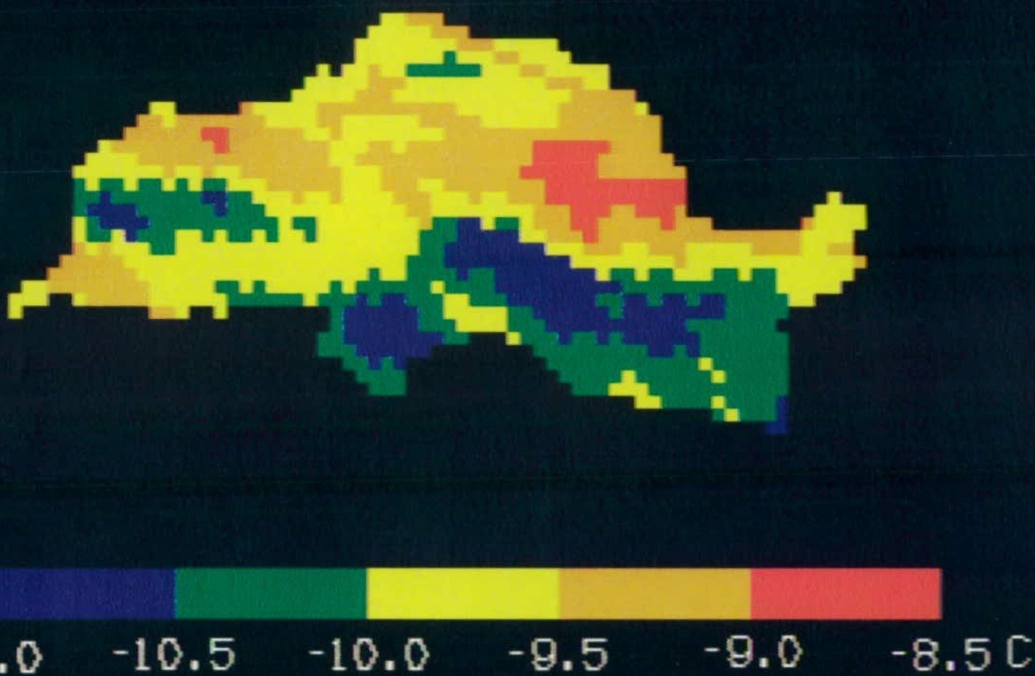


Fig. 5.9 Temperature distribution in the Kennet

AVHRR image Dec. 1991

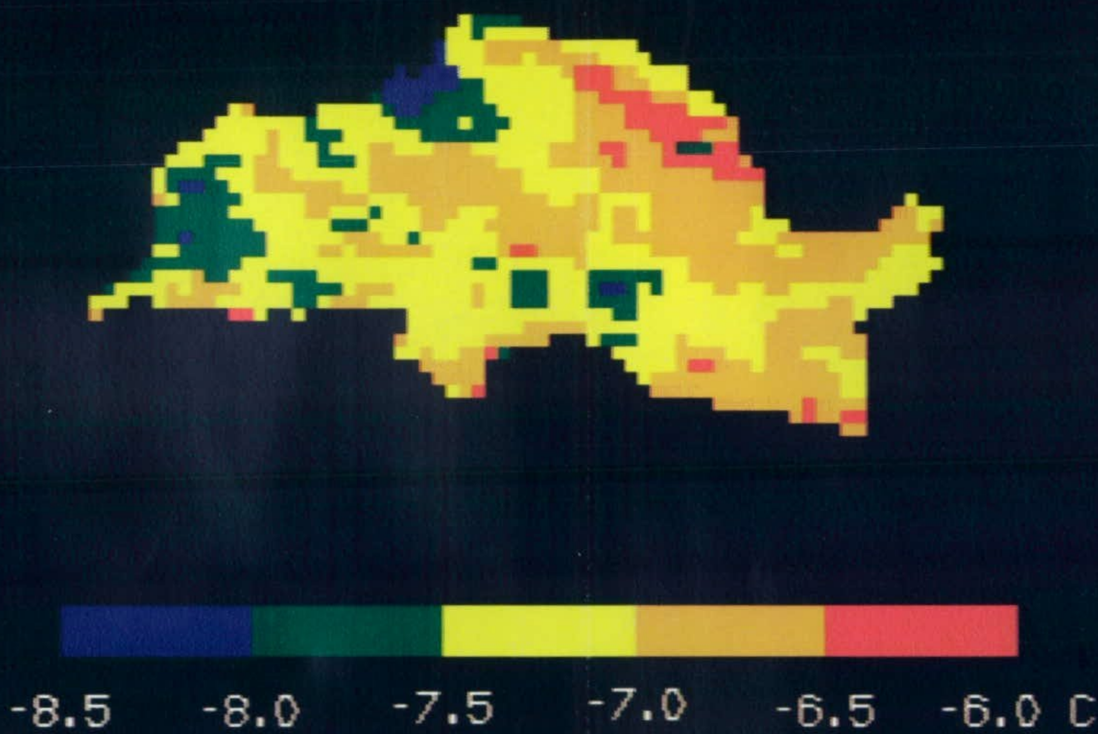


Fig 5.10 Temperature distribution in the Kennet

AVHRR image Jan. 1992

(i) January 1987 image

Figure 5.8 indicates that the air temperatures distribution over the Kennet at time of satellite overpass was -2.5 to -5.0°C. At these temperatures, the only soil likely to be frozen is at a depth of 1 cm under bare earth. As such conditions are unlikely to be significant for impervious freezing surfaces, this image was not analysed further.

(ii) December 1991 image

The air temperature range over the Kennet catchment derived from the AVHRR image and ground measurements was -11.0 to -8.5°C. At these air temperatures, the factors in Table 5.5 suggest that:

(a) For those areas of the catchment represented by the Lambourn site (Fig. 4.2), the soil would have been frozen to beyond 10 cm. In reality, the Lambourn site was only frozen to 1 cm depth. The reason for this discrepancy lies in the fact that the recorded minimum air temperature was actually -7.5°C, and not -9.6°C as suggested by the AVHRR image. Even so, Table 5.5 suggests that the soil would have been frozen to a depth of 5 cm. The length of duration of freezing at 1 cm depth was 38 hours.

(b) All areas of the catchment represented by the Lackam site would have been frozen to 5 cm depth. The situation at 10 cm depth would depend on the estimated air temperature. At Lackam, the soil was frozen to a depth of 1 cm for 45 hours, and to a depth of 5 cm for 6 hours. Table 5.5 suggests that, with a minimum air temperature of -10.5°C, the soil should have been frozen to a depth of 10 cm.

(c) None of the areas represented by the Wallingford site would be frozen to a depth of 10 cm; the situation at 1 cm and 5 cm depth would depend on the estimated air temperature. At Wallingford, the soil was frozen to a depth of 1 cm for approximately 100 hours, and to a depth of 5 cm for 5 hours. With a minimum air temperature of -10.5°C, it would have been expected that the soil would have been frozen to a depth of 1 cm only.

These discrepancies highlight the uncertainties in estimating the depths of freezing soil.

The top figure in Fig. 5.11 shows the distribution of frozen soil (blue colouration) at 10 cm depth over the Kennet catchment assuming complete grass coverage. As indicated above, only those areas represented by the Wallingford site and parts of those represented by the Lackam site, dependent on air temperature, remain non-frozen (red colouration). If bare earth factors are then applied to arable areas (Fig. 3.6), the non-frozen areas are reduced as shown in the lower figure.

The range of temperature values for the different soil depths over the Kennet catchment were estimated as:

	Grass	Soil
1 cm	+0.3 → -2.7°C	-5.2 → -6.7°C
5 cm	+1.0 → -2.0°C	-1.1 → -2.4°C
10 cm	+1.8 → -1.7°C	+0.5 → -0.7°C

(iii) January 1992 image

Figure 5.10 indicates that the air temperature distribution over the Kennet catchment at the time of overpass was -8.4 to -6.0°C. At these air temperatures, the factors in Table 5.5 suggest:

(a) For those areas of the catchment represented by the Lambourn site (Fig. 4.2), the soil would have been frozen to beyond 2.5 cm. Freezing at lower depths would be dependent on the local air temperatures. In reality, the Lambourn site was only frozen to 1 cm depth. The reason for this discrepancy lies in the fact that the recorded minimum temperature was actually -5.6°C, and not -7.0°C, as suggested by the AVHRR image. The length of duration of freezing at 1 cm depth was 18 hours.

(b) For those areas of the catchment represented by the Lackam site (Fig. 4.2), freezing at 1 cm and, possibly 5 cm depth, would depend on the local air temperatures. In fact, the Lackam site was frozen briefly (5 hours) at 1 cm depth; this is in accordance with the measured air temperature of -8.0°C.

(c) None of the soils of the grassland areas represented by the Wallingford site would have been frozen. For bare earth areas, freezing should have occurred to a depth of 1 cm and, dependent on local air temperature, to a depth of 5 cm. In reality, at Wallingford, bare soil was frozen to a depth of 1 cm for 19 hours.

The range of temperature values for the different soil depths over the Kennet catchment were estimated as:

	Grass	Soil
1 cm	+1.3 → -1.4°C	-3.7 → -5.1°C
5 cm	+2.2 → -0.6°C	-0.3 → -1.0°C
10 cm	+3.0 → -0.2°C	+1.6 → -0.5°C

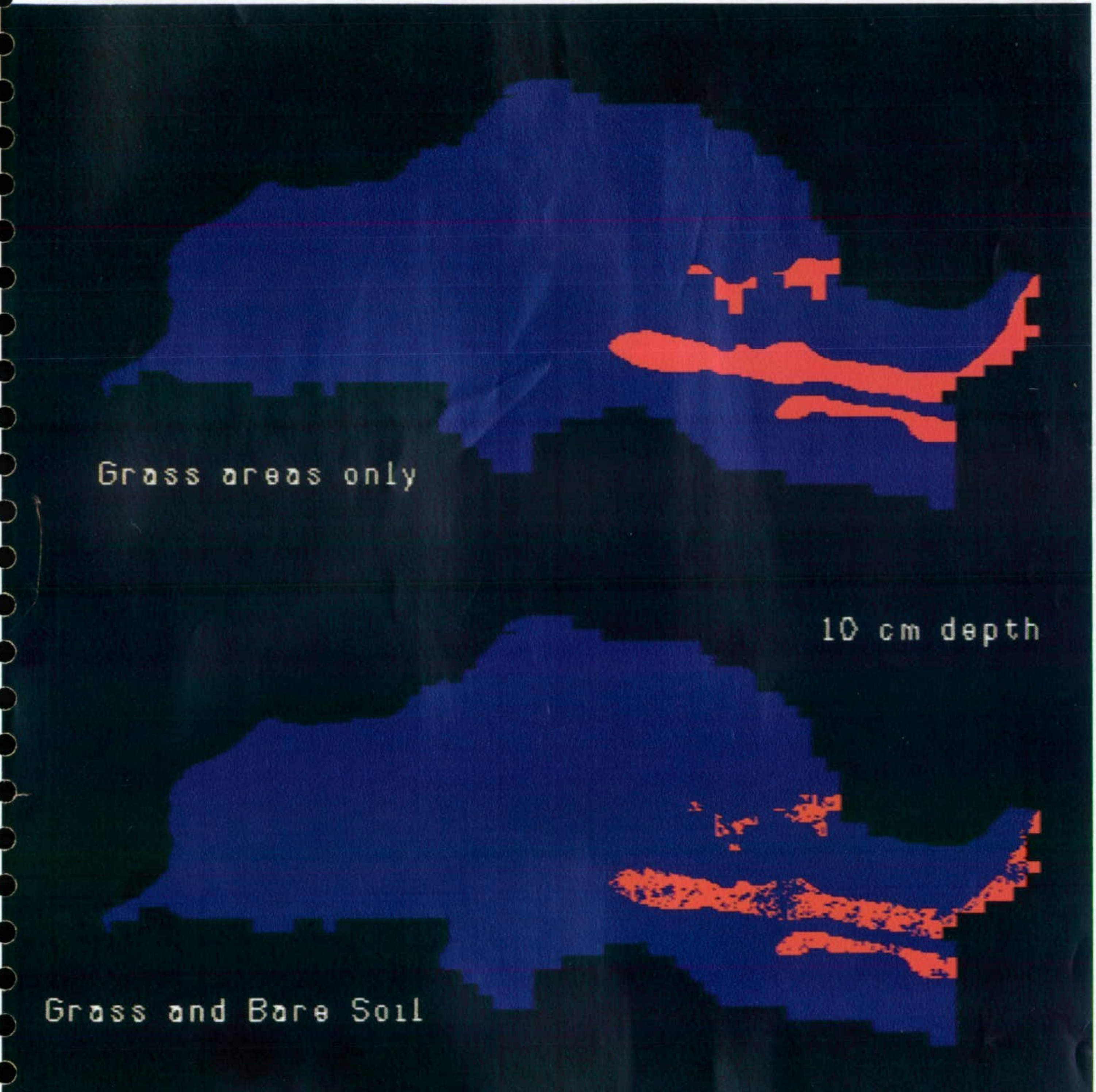


Fig. 5.11 Kennet catchment - frozen soil

6. Discussion

Inspection of the minimum daily air temperatures recorded at the Meteorological site at IH suggests that the number of cold nights during the winter of 1991/92 was about average. There were eight occurrences of minimum air temperature below -6°C; of these, two were below -10°C with a minimum of -10.5°C. The values of -6°C and -10°C have been chosen as the thresholds of the onset of freezing soil and widespread freezing soil in the Kennet, respectively, as suggested in Table 5.5 Although not as severe as the winter of 1981/82 (7 occurrences below -10°C, with a minimum value of -21.0°C), the values for 1991/92 are about average for the last twelve winters.

There were basically two prolonged cold periods - the 9th to the 13th December 1991, and the 22nd to the 25th January 1992. A total of six 'quick look' AVHRR photographs covering the two periods were studied; of these, two images, one for each period, were deemed sufficiently cloud free and suitable for analysis. Such a return of 'useable' AVHRR images is typical. It has been estimated that the overall availability of clear daytime AVHRR scenes over the UK for 1980-87 was 18.7%. If clear night time scenes are included, then the availability increases to 24.2% (Collin and Carlisle, 1989). It has been suggested that the chances of obtaining cloud-free images increases with decreasing temperature (Roach and Brownscombe, 1984). For this particular study, it was found that the 'best' image of the three analysed, the January 1987 image, was in fact obtained at the time of 'highest' temperature. It would seem then that cloud cover remains a problem even during frost conditions.

These cloud problems can be overcome using microwave imagery. However, processing such imagery poses as many, if not more, problems as the processing of thermal imagery. These problems have been outlined in WMO, 1985; these relate to calibration, atmospheric effects and surface emissivity. The biggest problem for the particular application reported on here relates to the coarse ground resolution, typical pixel size 50 km^2, associated with passive microwave imagery. Tables V-1 and V-2 of WMO, 1985 outline current and future satellite sensors for the detection of surface temperatures. Whilst the calibration of the sensors and the conversion of measured radiances to surface temperatures are likely to improve, the problem of cloud cover and the coarse resolution of satellite microwave sensors will persist.

The use of AVHRR images for determining sea surface temperatures is well established. Routines have been developed for geolocating the images and for correcting atmospheric attenuation using the 'split-window' technique. Root mean square errors of ± 0.7°C have been reported for sea surface temperatures derived from AVHRR images. These are slightly lower than those experienced using microwave imagery (WMO, 1985). Unfortunately, variations in emissivity over land surfaces limit their applicability for the determination of land surface temperatures. Although a number of theoretical formulations have been and are being developed for overcoming this problem, most operational applications use recorded ground temperatures for calibration purposes, when these are available. The problem here lies in relating a point recorded value to an area of 1 km^2, even assuming that the geocorrection of the AVHRR image is good enough to say with confidence that the point at which the ground surface/air temperature was recorded is within a 1 km^2 picture element. Using Landsat images, with their 30 m resolution in the visible bands, individual fields can be identified, and relating a point value to a particular picture element is relatively easy. This is not so with the coarser resolution AVHRR imagery, and reliance has to be made on a 'blind' geocorrection algorithm.

Another problem relates to which of the recorded temperature values, grass or air minimum, to use for calibration purposes. In this study, a case was made for using air temperatures, on the basis of the variation in grass temperatures over short distances due to location and to installation problems associated with grass thermometers. Unfortunately, problems also occur when using air temperatures. This is illustrated in Table 5.2, where the recorded air minimum temperatures at Wallingford and Benson, approximately 2 km apart, differed by over 1°C. The AVHRR radiance values suggested that the temperatures should have been almost identical. Also, the recorded air minimum temperature at Aborfield was over 3°C higher than the average for the sites used, whilst the AVHRR radiance value suggested that the temperature should have been average. Such discrepancies make the use of recorded temperatures from individual stations an optimistic procedure, and prompted the use of an average value over all the meteorological sites as one calibration point in this particular study. Fortunately, the sea surface temperature varies spatially to a much lesser extent, and the use of this as the second calibration point is more reasonable.

Whilst the use of AVHRR images to produce <u>absolute</u> values of land surface temperatures seems, at present, to be a difficult proposition, the production and use of <u>relative</u> values is much simpler. The main value of remotely sensed images is not in giving absolute values but, in combination with a number of recorded values or ground 'truths', in extending these recorded values over an area of interest. This is what has been done in this study. The recorded radiances in the thermal band(s) of the AVHRR images have been corrected using air temperature values at a number of points, thus producing maps of air temperatures over the area of interest, in this case the Kennet catchment. Using the derived regressions between AVHRR radiance values and air temperatures, mean absolute errors of 0.7°C and 1.2°C for air temperatures recorded at individual sites in the Kennet were obtained, respectively, for the January 1987 and December 1991 images. Further, the recorded air temperatures at three sites have been related to soil temperatures at different depths and, at one site, different land cover. In this way, four sets of regressions have been obtained, three for grass under different soil types and one for bare earth. The Kennet catchment has been sub-divided according to soil type, and regressions applied according to this sub-division. What, in effect, has been achieved is to establish relationships between AVHRR radiances over the Kennet and soil temperatures at different depths, these relationships varying according to soil type. Whether this distribution of soil temperature to air temperature relationships is sensible can only be judged by the installation of further soil temperature probes. The results for the three intensively instrumented sites do show discrepancies between the 'modelled' and observed depths of freezing (see Section 5.5.(ii)).

The three sites chosen for the recording of soil temperatures seem to encompass the range of soils present within the Kennet catchment. Whilst the air temperatures experienced at the three sites are similar, the soil temperatures under grass at identical depths are very different (Table 5.5). This could be as a result of a combination of factors:

(i) Differences in probe calibration
(ii) Incorrect installation depths
(iii) Condition of the grass sward
(iv) Different soil types

Each soil temperature probe used was individually calibrated in the laboratory to ± 0.1°C prior to installation. Although it is possible that some drift in the calibration may have occurred during the course of the study, it is unlikely that it could cause the observed temperature differences. In any case, such a drift would have been manifest in the recorded values; this was not observed. Whilst every effort was made to ensure that the depths of installation were correct, some errors may have been made. However, a comparison of the paired soil probes at Lackam College (Section 5.1(ii)) suggests that the resulting error would be small (± 0.5°C). Also, the data from the intermediate depths at upper Lambourn (Section 5.1(i)) suggest that, even if installation errors of ± 2.5 cm had been made, the resulting temperature differences would have been much smaller than those between sites. The condition of the grass sward would be expected to have some influence on soil temperatures. Thus, a lush sward would 'buffer' the effects of low air temperatures better than a sparse sward. Whilst this may be important during the growing season, it likely to be less significant during the winter months when growth is restricted. Also, care was taken to cut the grass at regular intervals so maintaining a constant height.

It is likely then that the main reason for the soil temperature differences between the sites is a reflection of the different soils. Certainly the temperature differences seem to be intuitively in the right sense. The lowest soil temperatures, for comparative air temperatures, occur at upper Lambourn. The soil here is sandy and contains a number of flints. Such a soil would be expected to conduct heat more readily than the heavier, clayey soil at Wallingford. This is reflected in the relatively higher soil temperatures observed at Wallingford. The soil temperatures at Lackam College seem to be intermediate between these two extremes.

Perhaps of more significance is the differences in soil temperatures under grass and bare earth experienced at Wallingford. The lower soil temperatures under bare earth illustrate the 'buffering' effect of the grass sward. Quite what this means in terms of the arable areas of the Kennet, mainly sown with autumn cereal, is uncertain. In retrospect, it would have been instructive to install a set of soil temperature probes in a field of autumn sown cereal. As it is, the distributions of frozen soil over the Kennet shown in Section 5.5 are the two extreme conditions likely to occur.

Perhaps one of the more surprising aspects of the study is the non-existence of similar air temperature distributions over the Kennet catchment for the three AVHRR images analysed. Collier *et al.*, 1989, in their study of an area of approximately 80 km^2 in the Scottish Highlands using AVHRR images found good correlations between low surface temperature and topography, with discrete areas of extremely low minima in the Spey Valley. On the other hand Kalma *et al.*, 1983, in their study of a 225 km^2 area in the state of Victoria in Australia, concluded that imagery from the Heat Capacity Mapping Mission satellite (HCMM) had insufficient spatial resolution (pixel area 0.36 km^2) for local frost mapping. The results obtained in the study reported on here using the AVHRR images (pixel area 1 km^2) supports the conclusion of Kalma *et al.*, 1983.

Assuming that a 'sensible' distribution of frozen ground temperatures has been established, it is necessary to determine how this information can be used to model its effects on the stream hydrograph. In the first place, the temperature at which frozen soil becomes impervious to water movement has to be established. It has been shown that the rate of water movement in soils decreases rapidly with decreasing temperature below 0°C (Hoekstra, 1966). This is a function of changes in the thickness of unfrozen water films surrounding soil particles with temperature. This has been shown to decrease rapidly between 0°C and -5°C, and more gradually at lower temperatures (Anderson, 1968). This suggests a temperature of -5°C at which soil water movement becomes so restricted that soil saturation and hence possible flooding problems occur. If this is really the case, the results for the December 1991 image suggests that it was only at 1 cm depth under bare soil that the soil became impermeable (Section 5.5(ii)). Further, it has been shown that low temperatures affects water movement more in light soils than heavy soils (Harlan, 1973).

The above information, together with the distribution of frozen ground surfaces, can be used for flood forecasting purposes. The simplest method is to use a lumped modelling approach and assume that, at a certain temperature, the soil becomes completely impervious. A value of -5°C would seem appropriate, at least for initial purposes, though this value may be optimized. Models such as the Wallingford storm-sewage package (WASSP; DOE, 1981) may be employed. This model expresses percentage runoff as a function of percentage impervious surface within the catchment, a soil index, and a catchment wetness index. Although originally developed for urban runoff estimation, such a procedure could equally well be used for modelling runoff from partially-frozen catchments.

Alternatively, given the horizontal and vertical distribution of soil temperatures, more sophisticated models such as the IHDM (Beven *et al.*, 1987) or the SHE (Abbot *et al.*, 1986) could be used. Both distributed models require as inputs hydraulic conductivities, horizontally and vertically distributed. Such information may be obtained from the empirical conductivity equations for frozen and unfrozen soil given by Kersten (1949).

Precipitation inputs during frozen ground conditions are more likely to be in the form of snow than rain. Although significant snow accumulations in Britain are relatively infrequent, spatially varied and short-lived, a significant proportion of the worst floods on record in Britain have a snowmelt contribution (see Table 7.4 of NERC, 1975). There has been a great deal written in the scientific literature concerning the snowmelt process and its modelling. Inevitable, most of the papers deal with North American, Scandinavian and Alpine regions. Papers relevant to the UK include Archer, 1983; Ferguson, 1984; Mawdsley *et al.*, 1991 and Morris 1982. Papers describing models of snowmelt processes over impermeable surfaces include Colbeck, 1974 and Dunne *et al.*, 1976. The feasibility of using satellite imagery for operational snow monitoring in the UK, also using AVHRR images, has recently been demonstrated (Lucas and Harrison, 1989).

Finally, the Kennet flood records from the gauging station at Theale held on the Surface Water Archive at IH have been inspected to determine how often peak flows are associated with frozen ground conditions. Of the 58 maximum winter (November - March, inc.) monthly flows for the years 1980 to 1991, two were associated with an air temperature, at Wallingford, of less than -10°C, a further four with an air temperature less than -5°C, and a further fourteen with an air temperature less than 0°C. Also, seven of these events were associated with lying snow immediately prior to the event. However, a detailed examination of the rainfall and flow records, and the meteorological records at the various sites listed in Table 4.1 would be required to determine the role of the state of ground surface in the generation of these peak flows.

Conclusions

During the course of this study the following conclusions were reached:

1. Of the three currently operational satellites that provide remotely sensed images in the appropriate bands for estimating surface temperatures, only the AVHRR sensor onboard the NOAA series of satellites gives the spatial and temporal resolution required for identifying frozen ground conditions within water catchment areas of the UK.

2. Even with the availability of four images a day from the NOAA satellites, cloud cover restricts their use even under conditions which favour clear skies.

3. Whilst the estimation of sea surface temperatures using AVHRR images has become a routine application, ground surface temperatures, because of the variability in emissivity, requires the use of theoretical formulations or ground calibration values.

4. Overall, it was found that air temperatures, and not grass temperatures, are more appropriate for calibration purposes over a 1 km^2 pixel of the AVHRR sensor.

5. Poor correlation was found between the air temperature distribution over the area of interest and the topography. This was presumably due to the coarse spatial resolution, 1 km, of the AVHRR sensor. A comparison of temperature distributions using AVHRR and Landsat (30 m ground resolution) images showed the averaging effect of the coarser AVHRR images.

6. Good relationships were obtained between air and soil temperatures at the three instrumented sites. These were found to differ for different soil types and, in particular, the presence or lack of vegetative cover. It was found that soil temperatures under bare earth were substantially lower than those under grass.

7. Given the above relationships, it was found that maps of the distribution of frozen ground over the area of interest could be produced; models exist to use these distributions to estimate their effect on the streamflow hydrograph.

Acknowledgements

The study was part financed by the Ministry of Agriculture, Fisheries and Food under programme no. FD4 - River Flood Protection. The AVHRR images used in the study were supplied by the Satellite Receiving Station at the University of Dundee. Thanks are given to Dr Peter Baylis and his staff for prompt delivery of the various satellite products. The Landsat image was obtained from the NERC archives. Advice and assistance for analysing the AVHRR images was given by Stephen Groom and Martin France of NERC Computer Services.

The cooperation of Mr Ted Culling and his staff at Lackam College and Mr Peter Hermann and his staff at Warren Farm, Upper Lambourn is much appreciated. Other meteorological data were supplied from the Climatological Observers link.

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APPENDIX I Details of Flow Gauging Stations within the Kennet Catchment

1. Kennet at Theale
2. Lambourn at Shaw
3. Enborne at Brimpton
4. Dun at Hungerford
5. Kennet at Marlborough
6. Kennet at Knighton
7. Aldbourne at Ramsbury
8. Winterbourne at Bagnor
9. Lambourn at Welford
10. Lambourn at East Shefford

Gauging Station Summary

KENNET AT THEALE

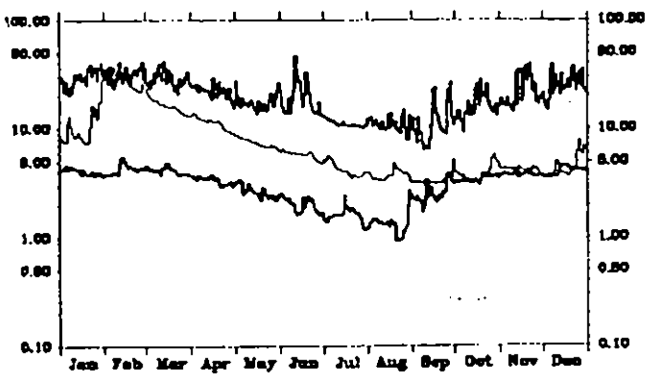
Station Number
039016

Gauged Flows
1961-1991

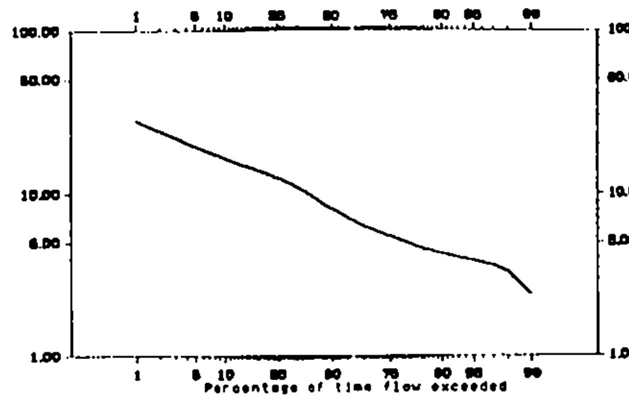
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 649 708

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1961 to 1991 excluding those for the featured year (1990)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	9.50	
Mean flow (ls^{-1}/km^2)	9.19	
Mean flow ($10^6m^3/yr$)	299.7	
Peak flow & date	59.8	11 Jun 1971
Highest daily mean & date	46.7	11 Jun 1971
Lowest daily mean & date	0.925	21 Aug 1976
10 day minimum & end date	1.102	28 Aug 1976
60 day minimum & end date	1.460	28 Aug 1976
10% exceedance	16.520	
50% exceedance	8.182	
95% exceedance	3.866	
Mean annual flood	37.3	
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	1033.0
Level stn. (mOD)	43.40
Max alt. (mOD)	297
IH Baseflow index	0.87
FSR slope (m/km)	1.46
1941-70 rainfall (mm)	770
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Factors Affecting Flow Regime

- Flow influenced by groundwater abstraction and/or recharge.
- Flow reduced by industrial and/or agricultural abstraction.
- Augmentation from surface water and/or ground water.

Rainfall and Runoff

	Rainfall (mm) (1961-1990)					Runoff (mm) (1961-1991)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	75	140	1984	15	1987	54	59	1969	11	1976
Feb	53	139	1990	8	1965	35	64	1990	11	1976
Mar	68	162	1981	15	1973	38	57	1967	11	1976
Apr	50	109	1966	2	1984	31	50	1979	9	1976
May	60	131	1979	8	1990	26	40	1979	7	1976
Jun	60	177	1971	5	1962	21	47	1971	5	1976
Jul	48	100	1988	18	1984	17	29	1971	4	1976
Aug	65	152	1977	20	1983	15	25	1971	4	1976
Sep	65	169	1974	13	1971	13	25	1968	7	1976
Oct	68	156	1967	4	1978	16	36	1966	9	1989
Nov	73	170	1970	31	1990	19	44	1974	10	1978
Dec	82	150	1989	15	1988	26	47	1968	12	1990
Annual	767	940	1966	579	1964	299	393	1966	124	1976

Station and Catchment Description

Crump weir (15.9m broad) equipped with auxiliary crest and downstream level recorders. All but highest flows contained. Net impact of abstractions and discharges is very limited (but augmentation from Lambourn Scheme during droughts). High baseflow component but responsive contribution from the River Enbourne.

A mainly pervious catchment (80% Chalk) with a significant clay sub-catchment. Rural headwaters; urban development (and growth) concentrated along the valley.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rainfall	Some or no rainfall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	-

	01234	56789
1960s	-eAAA	AAAAA
1970s	AAAAA	AAAAA
1980s	AAAAA	AAAAA
1990s	Ae	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

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12 Nov 1991

Gauging Station Summary

LAMBOURN AT SHAW

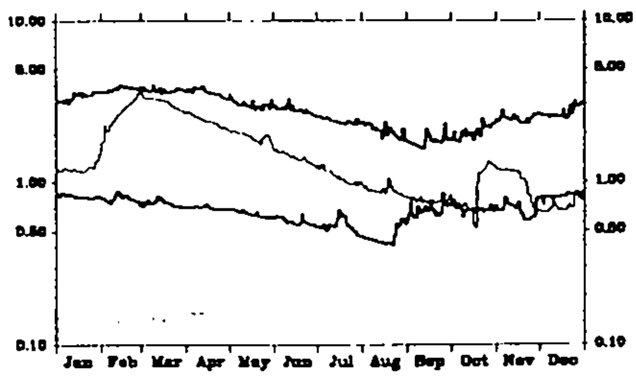
Station Number
039019

Gauged Flows
1962-1991

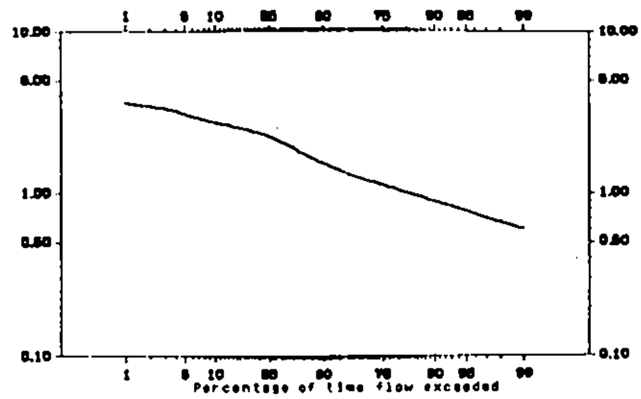
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 470 682

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1962 to 1991 excluding those for the featured year (1990)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	1.69	
Mean flow (ls^{-1}/km^2)	7.23	
Mean flow ($10^6m^3/yr$)	53.4	
Peak flow & date	5.0	13 Nov 1974
Highest daily mean & date	4.0	14 Feb 1988
Lowest daily mean & date	0.411	22 Aug 1976
10 day minimum & end date	0.420	22 Aug 1976
60 day minimum & end date	0.498	27 Aug 1976
10% exceedance	2.762	
50% exceedance	1.536	
95% exceedance	0.784	
Mean annual flood	3.5	
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	234.1
Level stn. (mOD)	75.60
Max alt. (mOD)	261
IH Baseflow index	0.96
FSR slope (m/km)	2.00
1941-70 rainfall (mm)	737
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Factors Affecting Flow Regime

- Flow influenced by groundwater abstraction and/or recharge.
- Augmentation from surface water and/or ground water.

Rainfall and Runoff

	Rainfall (mm) (1962-1990)					Runoff (mm) (1962-1991)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	68	136	1984	13	1987	20	39	1969	9	1976
Feb	50	126	1990	9	1965	23	40	1988	9	1976
Mar	64	161	1981	12	1973	28	41	1967	9	1976
Apr	48	102	1966	5	1984	26	39	1979	8	1976
May	59	121	1979	8	1990	24	34	1979	7	1976
Jun	58	154	1971	6	1962	20	31	1981	6	1976
Jul	49	100	1988	18	1984	17	27	1971	6	1976
Aug	61	149	1977	14	1985	15	23	1971	6	1976
Sep	61	157	1974	12	1971	13	19	1968	8	1965
Oct	63	152	1967	5	1978	13	22	1968	8	1965
Nov	71	171	1970	27	1990	13	26	1966	8	1965
Dec	77	151	1989	14	1988	16	29	1974	8	1990
Annual	729	920	1966	555	1964	220	289	1967	99	1976

Station and Catchment Description

Crump weir (10.67m broad) with auxiliary downstream recorder. Possibility of a small overspill in high floods when storage may be provided by Donnington Lake. D/s sluices occasionally influence flows, otherwise artificial disturbance is limited; but significant groundwater abstraction (particularly when the West Berks Groundwater Scheme has operated - providing low flow support). Flow pattern is baseflow dominated.

Pervious (Chalk), rural catchment in the Berkshire Downs.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rainfall	Some or no rainfall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	-

	01234	56789
1960s	--EAA	AAAAA
1970s	AAAAA	AAAAA
1980s	AAAAA	AAAAA
1990s	Aa	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

Gauging Station Summary

ENBORNE AT BRIMPTON

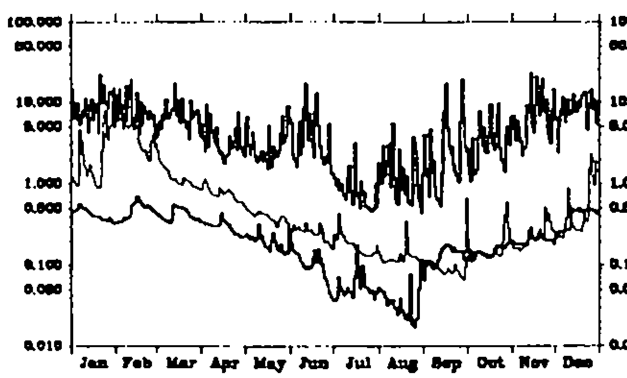
Station Number
039025

Gauged Flows
1967-1991

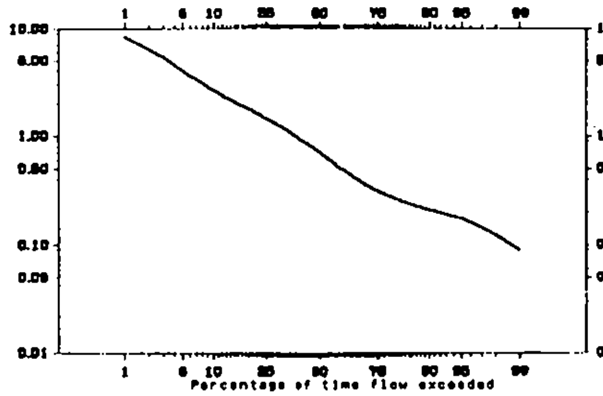
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 568 648

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1967 to 1991 excluding those for the featured year (1990)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	1.23	
Mean flow (ls^{-1}/km^2)	8.37	
Mean flow ($10^6m^3/yr$)	39.0	
Peak flow & date	30.6	20 Jan 1975
Highest daily mean & date	22.8	14 Nov 1974
Lowest daily mean & date	0.017	25 Aug 1976
10 day minimum & end date	0.026	27 Aug 1976
60 day minimum & end date	0.045	27 Aug 1976
10% exceedance	2.684	
50% exceedance	0.720	
95% exceedance	0.177	
Mean annual flood	17.5	
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	147.6
Level stn. (mOD)	59.40
Max alt. (mOD)	297
IH Baseflow index	0.54
FSR slope (m/km)	3.20
1941-70 rainfall (mm)	798
FSR stream freq. (junctions/km^2)	0.78
FSR percentage urban	0

Factors Affecting Flow Regime

- Flow influenced by groundwater abstraction and/or recharge.
- Flow reduced by industrial and/or agricultural abstraction.

Rainfall and Runoff

	Rainfall (mm) (1967-1990)					Runoff (mm) (1967-1991)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	86	143	1988	15	1987	47	80	1975	8	1976
Feb	59	155	1990	11	1986	37	95	1990	10	1976
Mar	71	157	1981	12	1990	36	72	1979	8	1976
Apr	46	102	1983	1	1984	22	40	1987	5	1976
May	62	134	1979	9	1990	17	40	1979	4	1976
Jun	62	197	1971	18	1975	12	60	1971	2	1976
Jul	44	103	1980	13	1982	6	11	1971	1	1976
Aug	61	140	1977	19	1985	6	13	1986	1	1976
Sep	64	165	1974	11	1971	8	45	1968	2	1990
Oct	71	167	1987	2	1978	13	54	1967	3	1978
Nov	77	202	1970	30	1988	23	89	1974	4	1978
Dec	89	188	1978	14	1988	36	62	1968	11	1990
Annual	792	1016	1974	629	1975	264	373	1974	140	1973

Station and Catchment Description

Asymmetrical compound Crump weir (crest widths: 3.0m and 4.6m). Modular range up to 18 cumecs. Due to overtopping of the banks, highest flows are under-estimated. Net impact of abstractions (mostly groundwater) and discharges is very limited, but overall there is a net export of water. Impact of West Berks Groundwater Scheme occasionally evident on lows flows (from 1989).

Chalk outcrops in the headwaters but catchment is mainly impervious (Tertiary clays). Land use is principally agricultural.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rain-fall	Some or no rain-fall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	-

	01234	56789
1960s	-----	--eAA
1970s	AAAAA	AAAAA
1980s	AAAAA	AAAAA
1990s	Ae	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

Gauging Station Summary

DUN AT HUNGERFORD

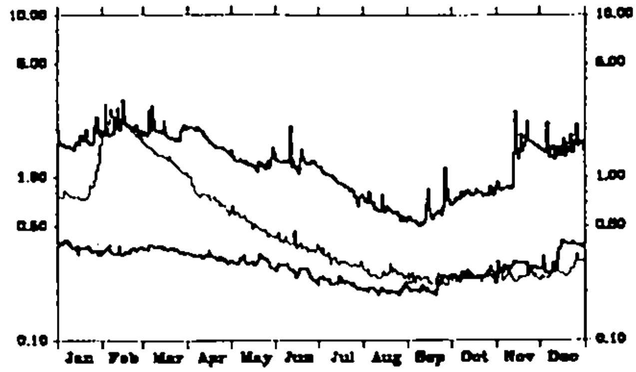
Station Number 039028

Gauged Flows 1968-1991

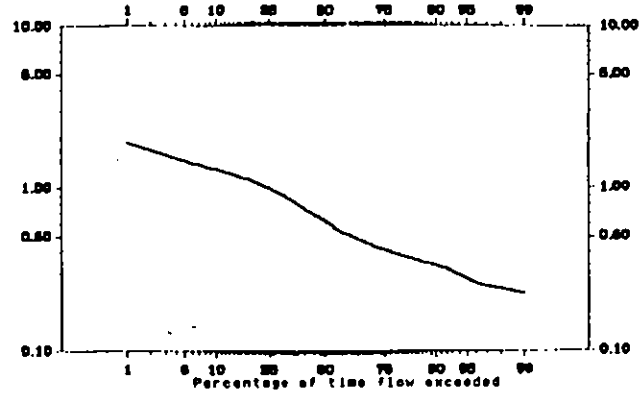
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 321 685

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1968 to 1991 excluding those for the featured year (1990)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	0.73	
Mean flow (ls^{-1}/km^2)	7.25	
Mean flow ($10^6m^3/yr$)	23.2	
Peak flow & date	3.5	14 Nov 1974
Highest daily mean & date	3.0	15 Feb 1974
Lowest daily mean & date	0.188	20 Sep 1976
10 day minimum & end date	0.195	26 Aug 1976
60 day minimum & end date	0.203	21 Sep 1976
10% exceedance	1.308	
50% exceedance	0.630	
95% exceedance	0.277	
Mean annual flood	2.5	
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	101.3
Level stn. (mOD)	99.00
Max alt. (mOD)	289
IH Baseflow index	0.95
FSR slope (m/km)	2.80
1941-70 rainfall (mm)	789
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Factors Affecting Flow Regime

- Natural to within 10% at the 95 percentile flow.
- Flow influenced by groundwater abstraction and/or recharge.

Rainfall and Runoff

	Rainfall (mm) (1960-1990)					Runoff (mm) (1968-1991)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	82	153	1984	15	1987	26	42	1982	10	1976
Feb	56	150	1990	12	1986	29	50	1990	9	1976
Mar	71	165	1981	15	1973	31	45	1972	10	1976
Apr	46	88	1983	2	1984	25	44	1979	8	1976
May	57	123	1979	7	1990	21	35	1979	8	1976
Jun	60	166	1971	8	1975	17	29	1979	7	1976
Jul	46	101	1988	18	1984	14	24	1971	6	1976
Aug	60	126	1977	17	1983	11	17	1971	5	1976
Sep	64	169	1974	11	1971	10	15	1968	5	1976
Oct	66	135	1976	4	1978	11	20	1968	7	1990
Nov	76	185	1970	33	1990	13	33	1974	6	1990
Dec	85	157	1989	16	1988	19	34	1982	7	1990
Annual	769	967	1974	605	1973	228	284	1982	186	1976

Station and Catchment Description

Crump weir, 10.7m broad. Full range and modular. Abstractions and discharges are of minor significance. Small net loss but essentially a natural baseflow-dominated flow regime from the catchment.

A mainly pervious (Chalk) catchment of rural character (chiefly agricultural but the Dun drains part of Savernake Forest).

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rainfall	Some or no rainfall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	-

	01234	56789
1960s	-----	---EA
1970s	AAAAA	AAAAA
1980s	AAAAA	AAAAA
1990s	Ae	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

Institute of Hydrology (Surface Water Archive Service) Wallingford, Oxon OX10 8BB, UK. Tel. 0491 38800.

12 Nov 1991

Gauging Station Summary

KENNET AT MARLBOROUGH

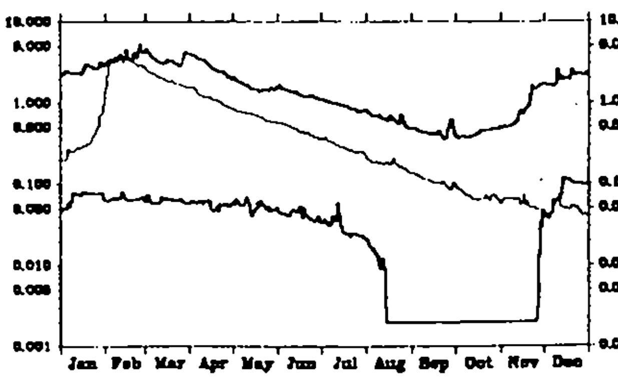
Station Number
039037

Gauged Flows
1972-1991

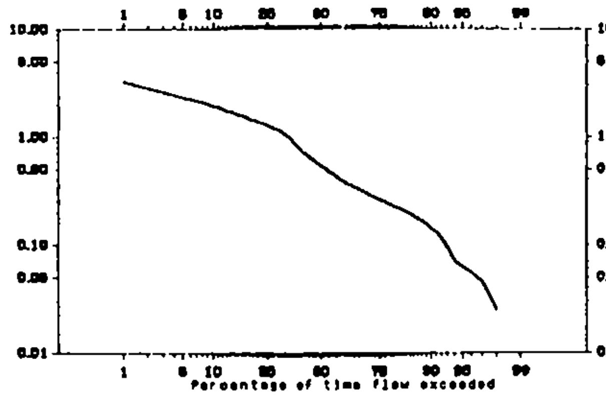
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 187 686

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1972 to 1991 excluding those for the featured year (1990)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	0.83	
Mean flow (ls^{-1}/km^2)	5.83	
Mean flow ($10^6m^3/yr$)	26.1	
Peak flow & date	6.1	25 Feb 1977
Highest daily mean & date	5.2	25 Feb 1977
Lowest daily mean & date	0.002	25 Nov 1976
10 day minimum & end date	0.002	25 Nov 1976
60 day minimum & end date	0.002	25 Nov 1976
10% exceedance	1.958	
50% exceedance	0.545	
95% exceedance	0.064	
Mean annual flood		
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	142.0
Level stn. (mOD)	126.50
Max alt. (mOD)	297
IH Baseflow index	0.95
FSR slope (m/km)	2.27
1941-70 rainfall (mm)	817
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Factors Affecting Flow Regime

- Flow influenced by groundwater abstraction and/or recharge.

Rainfall and Runoff

	Rainfall (mm) (1972-1990)					Runoff (mm) (1972-1991)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	78	148	1984	12	1987	22	46	1982	1	1976
Feb	60	137	1977	8	1986	31	58	1977	1	1976
Mar	76	188	1981	15	1973	31	61	1977	1	1976
Apr	45	93	1983	1	1984	25	52	1979	1	1976
May	58	128	1983	7	1990	19	29	1979	1	1976
Jun	59	121	1985	5	1975	14	23	1983	1	1976
Jul	53	103	1978	20	1984	10	17	1979	1	1976
Aug	62	144	1977	22	1972	7	11	1979	0	1976
Sep	70	175	1974	19	1979	5	7	1981	0	1976
Oct	73	138	1976	7	1978	4	8	1974	0	1976
Nov	68	137	1984	30	1990	5	17	1974	0	1976
Dec	90	152	1989	16	1988	11	36	1982	1	1990
Annual	792	955	1977	619	1973	183	298	1977	12	1976

Station and Catchment Description

Crump weir, 6.1m broad, with crest tapping plus Crump crested side weir for high flows. Full range and not subject to drowning. Runoff is low and baseflow dominated. The hydrological catchment is smaller than the topographical catchment; some diminution in flow also results from groundwater abstraction.

Chalk catchment; predominantly rural.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rainfall	Some or no rainfall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	-

	01234	56789
1970s	-=EAA	AAAAA
1980s	AAAAA	AAAAA
1990s	Ae	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

Institute of Hydrology (Surface Water Archive Service) Wallingford, Oxon OX10 8BB, UK. Tel. 0491 38800.

12 Nov 1991

Gauging Station Summary

KENNET AT KNIGHTON

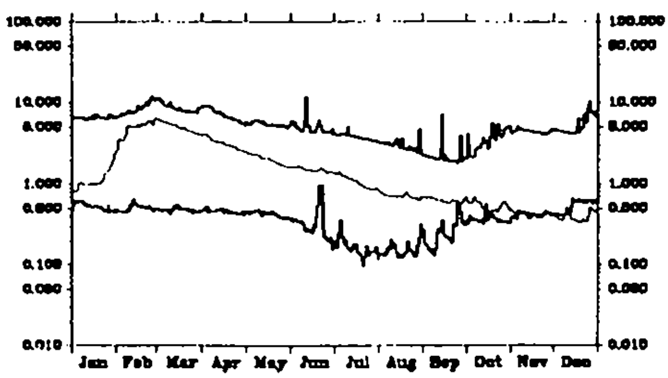
Station Number
039043

Gauged Flows
1962-1991

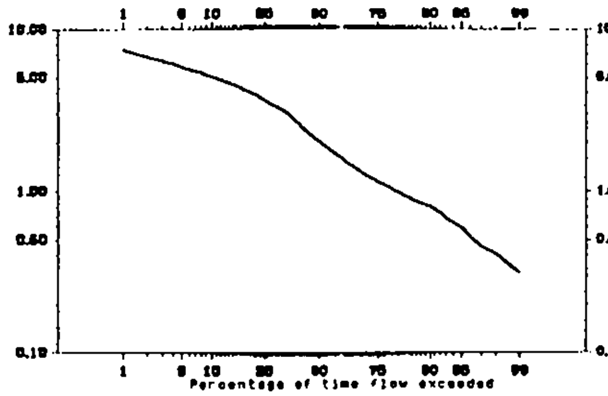
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 295 710

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1962 to 1991 excluding those for the featured year (1990)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	2.49	
Mean flow (ls^{-1}/km^2)	8.45	
Mean flow ($10^6m^3/yr$)	78.7	
Peak flow & date	13.7	3 Jun 1975
Highest daily mean & date	11.9	11 Jun 1971
Lowest daily mean & date	0.096	21 Jul 1976
10 day minimum & end date	0.134	26 Jul 1976
60 day minimum & end date	0.155	9 Sep 1976
10% exceedance	5.082	
50% exceedance	2.012	
95% exceedance	0.598	
Mean annual flood		
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	295.0
Level stn. (mOD)	104.90
Max alt. (mOD)	297
IH Baseflow index	0.95
FSR slope (m/km)	3.28
1941-70 rainfall (mm)	800
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Factors Affecting Flow Regime

- Flow influenced by groundwater abstraction and/or recharge.

Rainfall and Runoff

	Rainfall (mm) (1962-1990)					Runoff (mm) (1962-1991)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	75	147	1984	11	1987	27	59	1969	5	1976
Feb	55	135	1990	7	1965	35	64	1977	4	1976
Mar	71	171	1981	15	1973	39	74	1977	4	1976
Apr	50	107	1966	2	1984	34	63	1979	4	1976
May	61	125	1967	8	1990	28	49	1966	4	1976
Jun	62	161	1971	6	1975	22	39	1971	3	1976
Jul	51	99	1988	13	1971	17	34	1971	2	1976
Aug	64	147	1977	20	1964	14	25	1971	1	1976
Sep	66	181	1974	15	1971	11	17	1971	3	1976
Oct	69	161	1967	6	1978	10	29	1966	3	1976
Nov	73	172	1970	30	1990	12	38	1966	4	1990
Dec	82	152	1989	16	1988	17	46	1968	4	1990
Annual	779	949	1974	545	1964	266	440	1966	51	1976

Station and Catchment Description

Two Crump weirs: 13.7m crest on the main channel plus a 1.7m crest on the Littlecote Stream. Very flat gradient - main river is subject to frequent drowning; very high submergence ratios - nearby station records are sometimes used to assess the daily flow. Some bypassing during floods. Flows slightly diminished by groundwater abstraction. Baseflow dominates the flow regime.

Chalk catchment. Mainly rural (includes part of Savernake Forest) but some urban growth in the valley.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rain-fall	Some or no rain-fall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	-

	01234	56789
1960s	--aEA	AAAAA
1970s	AAAAA	AAAAA
1980s	AAAAA	AAAAA
1990s	Aa	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

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12 Nov 1991

Gauging Station Summary

ALDBOURNE AT RAMSBURY

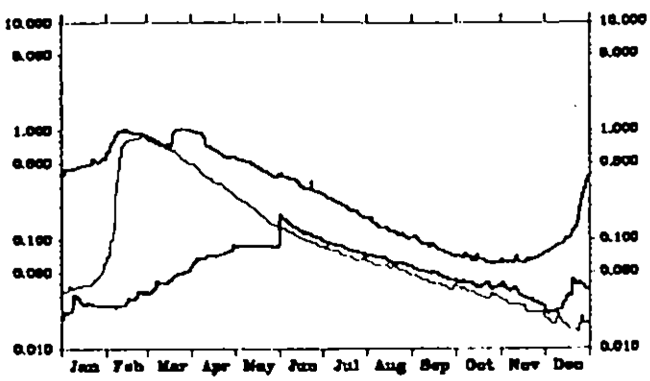
Station Number
039101

Gauged Flows
1982-1991

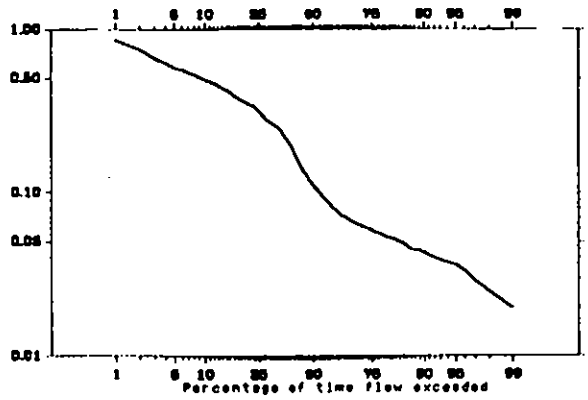
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 288 717

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1982 to 1991 excluding those for the featured year (1990)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	0.20	
Mean flow (ls^{-1}/km^2)	3.76	
Mean flow ($10^6m^3/yr$)	6.3	
Peak flow & date	1.2	26 Mar 1982
Highest daily mean & date	1.0	27 Mar 1982
Lowest daily mean & date	0.014	24 Dec 1990
10 day minimum & end date	0.015	25 Dec 1990
60 day minimum & end date	0.020	8 Jan 1991
10% exceedance	0.494	
50% exceedance	0.111	
95% exceedance	0.036	
Mean annual flood		
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	53.1
Level stn. (mOD)	
Max alt. (mOD)	
IH Baseflow index	
FSR slope (m/km)	
1941-70 rainfall (mm)	
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Factors Affecting Flow Regime

• Natural to within 10% at the 95 percentile flow.

Rainfall and Runoff

	Rainfall (mm) (1986-1990)					Runoff (mm) (1982-1991)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	83	137	1988	11	1987	11	24	1983	1	1991
Feb	70	144	1990	10	1986	22	43	1988	1	1991
Mar	60	75	1989	18	1990	22	40	1982	2	1991
Apr	52	69	1989	26	1988	17	36	1982	4	1991
May	39	86	1986	9	1990	14	24	1987	4	1991
Jun	53	110	1987	22	1986	10	16	1983	5	1990
Jul	53	108	1988	25	1990	7	10	1983	4	1990
Aug	62	110	1986	29	1987	4	6	1983	5	1990
Sep	41	58	1988	22	1989	3	4	1983	2	1990
Oct	84	140	1987	54	1990	3	3	1985	2	1990
Nov	59	118	1986	28	1990	2	3	1987	1	1990
Dec	81	151	1989	15	1988	3	7	1986	1	1990
Annual	737	861	1986	630	1990	118	155	1988	57	1989

Station and Catchment Description

Two Flat V weirs - 1:10 cross-slopes (one is located on a bypass stream). Theoretical calibration. All flows contained. Sensibly natural flow regime.

The Aldbourne drains a Chalk downland catchment. Land use is predominately agricultural - Aldbourne is the only significant settlement.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rain-fall	Some or no rain-fall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	-

	01234 56789
1980s	--eaa aAAAA
1990s	Ae

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

Institute of Hydrology (Surface Water Archive Service) Wallingford, Oxon OX10 8BB, UK. Tel. 0491 38800.

12 Nov 1991

Gauging Station Summary

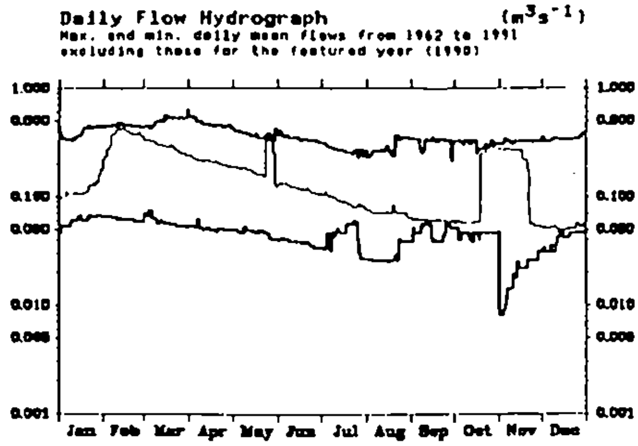
WINTERBOURNE ST AT BAGNOR

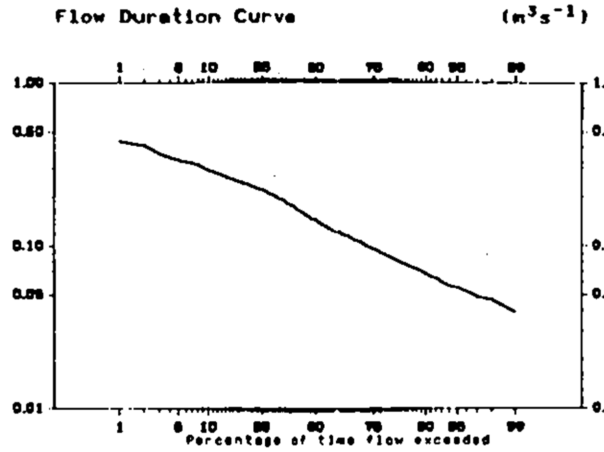
Station Number
039033

Gauged Flows
1962-1991

Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 453 694





Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	0.16	
Mean flow (ls^{-1}/km^2)	3.33	
Mean flow ($10^6m^3/yr$)	5.2	
Peak flow & date	0.7	31 Mar 1978
Highest daily mean & date	0.6	31 Mar 1978
Lowest daily mean & date	0.008	3 Nov 1969
10 day minimum & end date	0.011	10 Nov 1969
60 day minimum & end date	0.030	30 Dec 1969
10% exceedance	0.294	
50% exceedance	0.145	
95% exceedance	0.055	
Mean annual flood	0.4	
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	49.2
Level stn. (mOD)	80.50
Max alt. (mOD)	230
IH Baseflow index	0.96
FSR slope (m/km)	4.04
1941-70 rainfall (mm)	715
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Factors Affecting Flow Regime

- Flow influenced by groundwater abstraction and/or recharge.
- Augmentation from surface water and/or ground water.

Rainfall and Runoff

	Rainfall (mm) (1962-1990)					Runoff (mm) (1962-1991)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	67	130	1988	13	1987	9	21	1982	4	1970
Feb	50	129	1990	9	1965	10	22	1982	3	1976
Mar	63	154	1981	12	1973	13	27	1982	3	1976
Apr	48	96	1966	2	1984	12	25	1982	3	1976
May	57	122	1979	7	1990	11	20	1982	3	1976
Jun	59	161	1971	10	1975	10	18	1979	2	1976
Jul	47	97	1988	16	1990	8	14	1971	5	1965
Aug	60	147	1977	17	1983	7	14	1969	5	1965
Sep	59	159	1974	10	1971	6	17	1968	3	1965
Oct	63	155	1966	5	1978	6	15	1968	5	1965
Nov	69	166	1970	26	1990	6	17	1966	1	1969
Dec	75	155	1989	13	1988	7	19	1966	2	1969
Annual	717	926	1966	543	1990	105	164	1982	37	1965

Station and Catchment Description

Crump weir, 3m broad - originally 5.5m but reduced to improve sensitivity (in 1968). Full range. Runoff reduced by groundwater abstractions; for limited periods flows also substantially influenced by pumping, and flow augmentation, associated with the West Berks Groundwater Scheme (e.g. winter 1969/70, 1976 and 1989).

A Chalk catchment; very rural character.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rain-fall	Some or no rain-fall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	-

	01234	56789
1960s	--eAA	AAAAA
1970s	AAAAA	AAAAA
1980s	AAAAA	AAAAA
1990s	Ae	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

Gauging Station Summary

LAMBOURN AT WELFORD

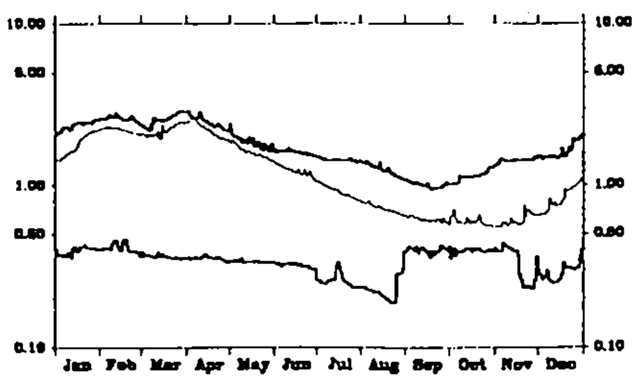
Station Number
039031

Gauged Flows
1962-1983

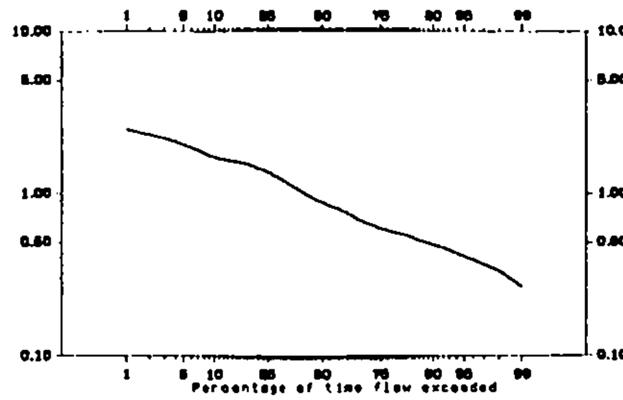
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 411 731

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1962 to 1983 excluding those for the featured year (1982)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	1.02	
Mean flow (ls^{-1}/km^2)	5.79	
Mean flow ($10^6m^3/yr$)	32.2	
Peak flow & date	3.1	5 Apr 1982
Highest daily mean & date	2.9	2 Apr 1967
Lowest daily mean & date	0.188	24 Aug 1976
10 day minimum & end date	0.196	25 Aug 1976
60 day minimum & end date	0.240	29 Aug 1976
10% exceedance	1.678	
50% exceedance	0.882	
95% exceedance	0.409	
Mean annual flood	2.0	
Bankfull flow		

Rainfall and Runoff

	Rainfall (mm) (1962-1983)					Runoff (mm) (1962-1983)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	66	113	1975	17	1976	15	36	1969	6	1976
Feb	51	129	1977	11	1965	17	36	1969	6	1976
Mar	72	162	1981	14	1973	22	59	1967	6	1976
Apr	52	100	1966	11	1976	23	36	1967	5	1976
May	64	129	1979	27	1974	20	28	1979	5	1976
Jun	62	163	1971	12	1975	17	25	1981	5	1976
Jul	50	96	1968	20	1982	14	22	1971	4	1976
Aug	65	150	1977	15	1983	12	19	1971	4	1976
Sep	67	177	1974	14	1971	10	14	1971	6	1965
Oct	62	157	1967	4	1978	10	17	1968	6	1965
Nov	73	165	1970	31	1973	10	21	1966	5	1976
Dec	78	142	1979	26	1963	12	24	1968	4	1976
Annual	762	939	1966	567	1964	182	248	1967	62	1976

Catchment Characteristics

Catchment area (km^2)	176.0
Level stn. (mOD)	95.70
Max alt. (mOD)	261
IH Baseflow index	0.98
FSR slope (m/km)	2.59
1941-70 rainfall (mm)	748
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Station and Catchment Description

Factors Affecting Flow Regime

- Flow influenced by groundwater abstraction and/or recharge.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rainfall	Some or no rainfall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	-	-

	01234	56789
1960s	--eAA	AAAAA
1970s	AAAAA	AAAAA
1980s	AAAE=	=====
1990s	=	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

No naturalised flow data available.

Gauging Station Summary

LAMBOURN AT EAST SHEFFORD

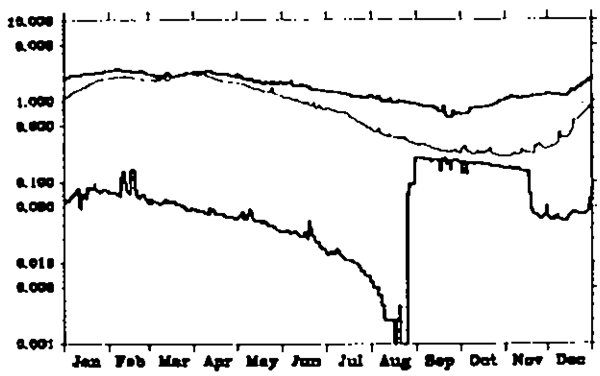
Station Number
039032

Gauged Flows
1966-1983

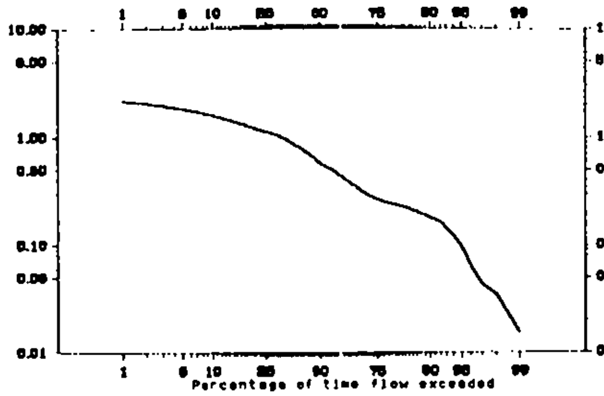
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 390 745

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1966 to 1983 excluding those for the featured year (1982)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	0.77	
Mean flow (ls^{-1}/km^2)	4.98	
Mean flow ($10^6m^3/yr$)	24.2	
Peak flow & date	2.5	7 Apr 1982
Highest daily mean & date	2.5	7 Feb 1969
Lowest daily mean & date	0.000	25 Aug 1976
10 day minimum & end date	0.001	25 Aug 1976
60 day minimum & end date	0.008	25 Aug 1976
10% exceedance	1.612	
50% exceedance	0.586	
95% exceedance	0.097	
Mean annual flood	1.8	
Bankfull flow		

Rainfall and Runoff

	Rainfall (mm) (1966-1983)					Runoff (mm) (1966-1983)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	70	114	1971	16	1976	12	37	1969	2	1976
Feb	53	131	1977	19	1973	17	36	1969	1	1976
Mar	71	162	1981	12	1973	23	34	1982	1	1976
Apr	46	98	1983	10	1976	23	36	1979	1	1976
May	65	125	1979	27	1974	19	31	1979	1	1976
Jun	57	149	1971	10	1975	15	25	1979	0	1976
Jul	50	99	1968	19	1977	12	21	1981	0	1976
Aug	64	149	1977	15	1983	9	17	1981	0	1976
Sep	68	168	1974	15	1971	7	13	1981	3	1973
Oct	67	158	1967	4	1978	4	15	1968	3	1973
Nov	69	161	1970	33	1973	6	19	1968	2	1973
Dec	78	140	1979	29	1975	8	24	1968	1	1976
Annual	758	891	1974	574	1973	157	224	1969	17	1976

Catchment Characteristics

Catchment area (km^2)	154.0
Level stn. (mOD)	101.90
Max alt. (mOD)	261
IH Baseflow index	0.97
FSR slope (m/km)	2.55
1941-70 rainfall (mm)	750
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Station and Catchment Description

Factors Affecting Flow Regime

- Flow influenced by groundwater abstraction and/or recharge.

Summary of Archived Data

Gauged Flows and Rainfall

Key:

	All rain-fall	Some or no rain-fall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	•	-

	01234	56789
1960s	-----	-eAAA
1970s	AAAAA	AAAAA
1980s	AAAE=	=====
1990s	=	

Naturalised Flows

Key:

All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	f
No naturalised flow data	-

No naturalised flow data available.

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12 Nov 1991

APPENDIX II Minimum and Maximum Daily Soil Temperatures at the Intensively Instrumented Sites

(a) Warren Farm, upper Lambourn

Figure 1 November 1991
2 December 1991
3 January 1992
4 February 1992
5 March 1992

(b) Lackam College

Figure 1 November 1991
2 December 1991
3 January 1992
4 February 1992
5 March 1992

(c) Wallingford

(i) Grass

Figure 1 November 1991
2 December 1991
3 January 1992
4 February 1992
5 March 1992

(ii) Soil

Figure 1 November 1991
2 December 1991
3 January 1992
4 February 1992
5 March 1992

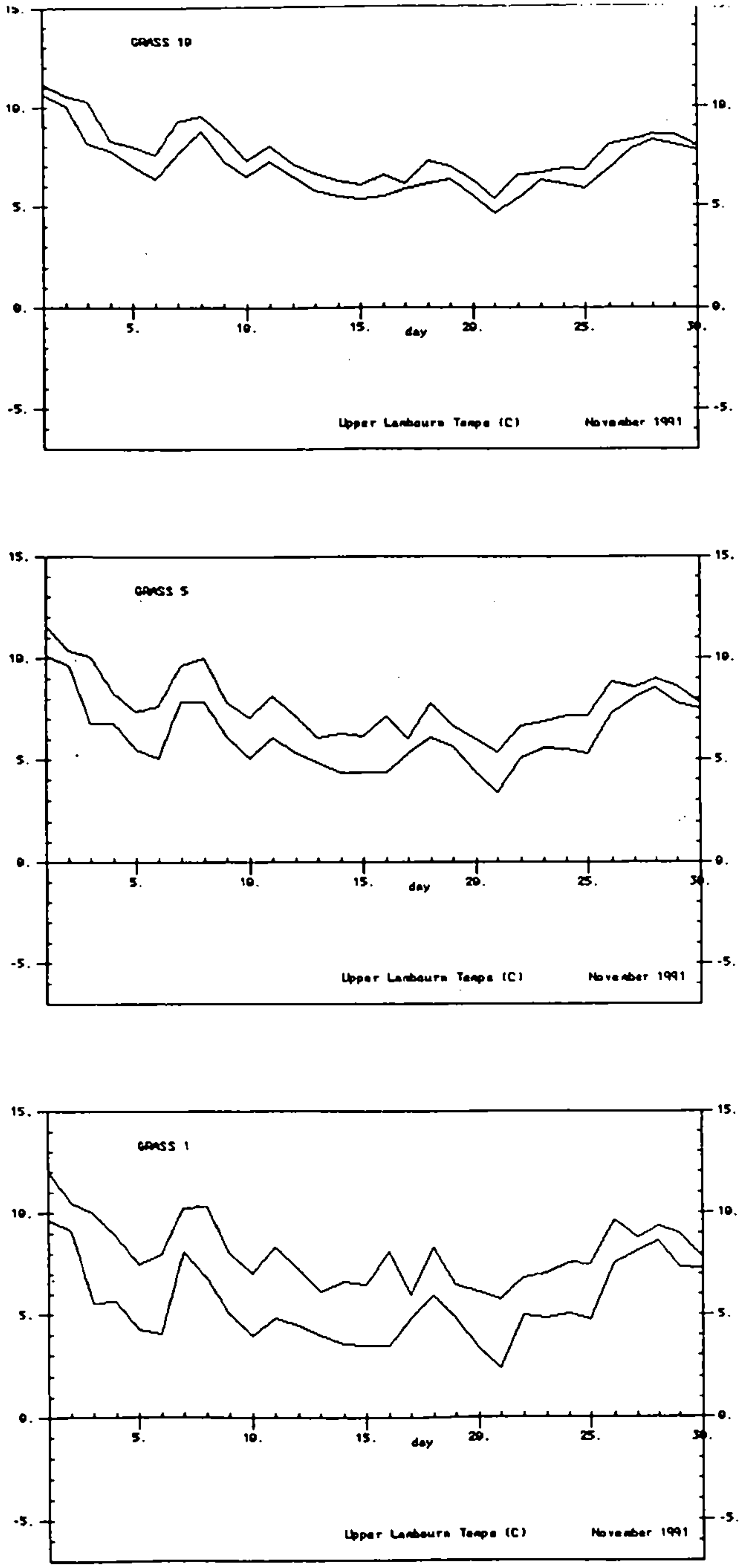


Fig. 1 Upper Lambourn, November 1991

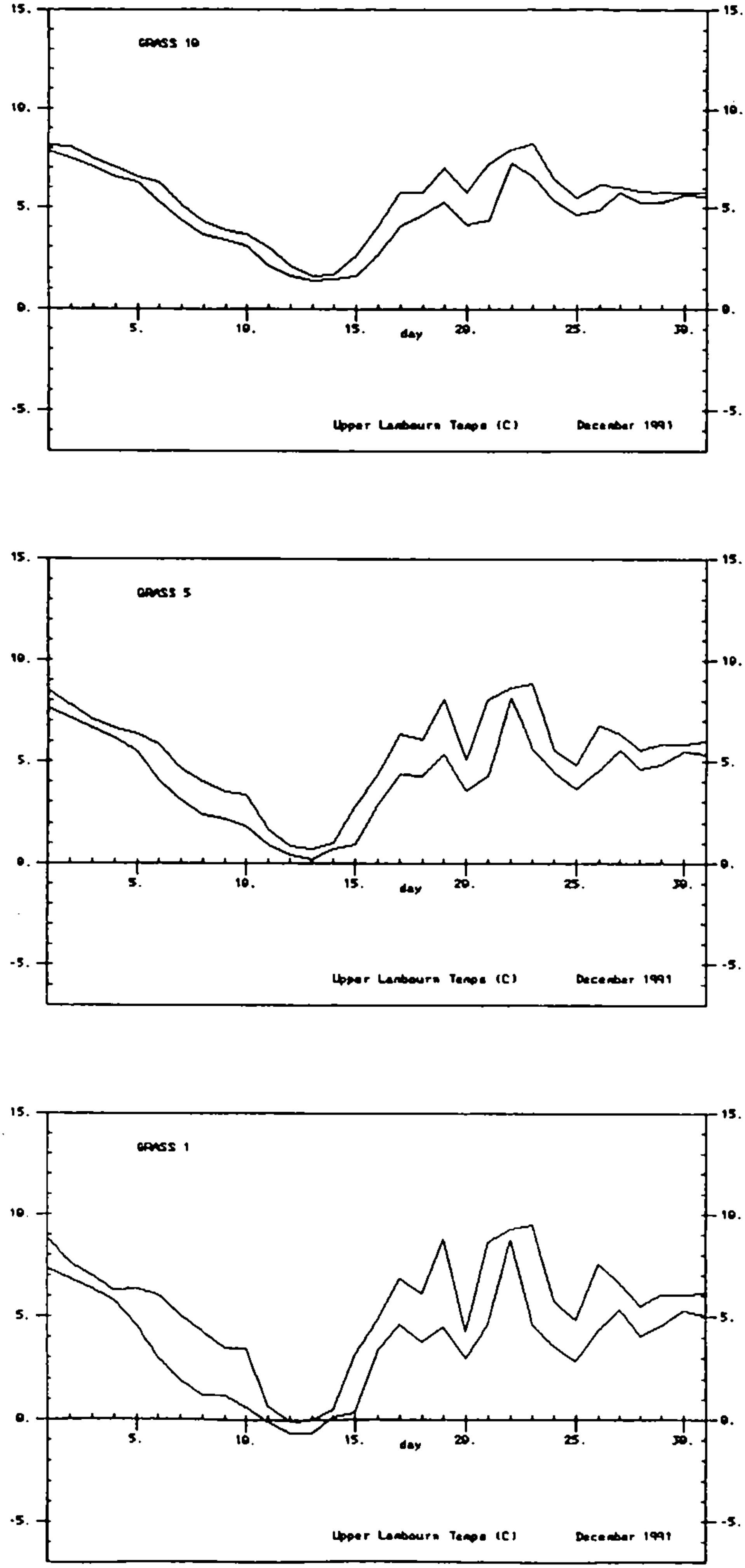
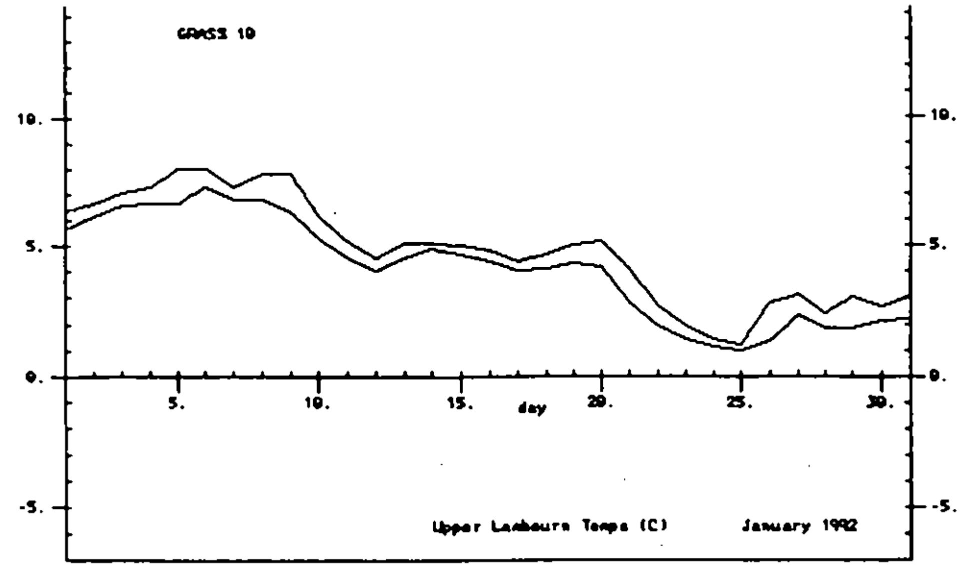
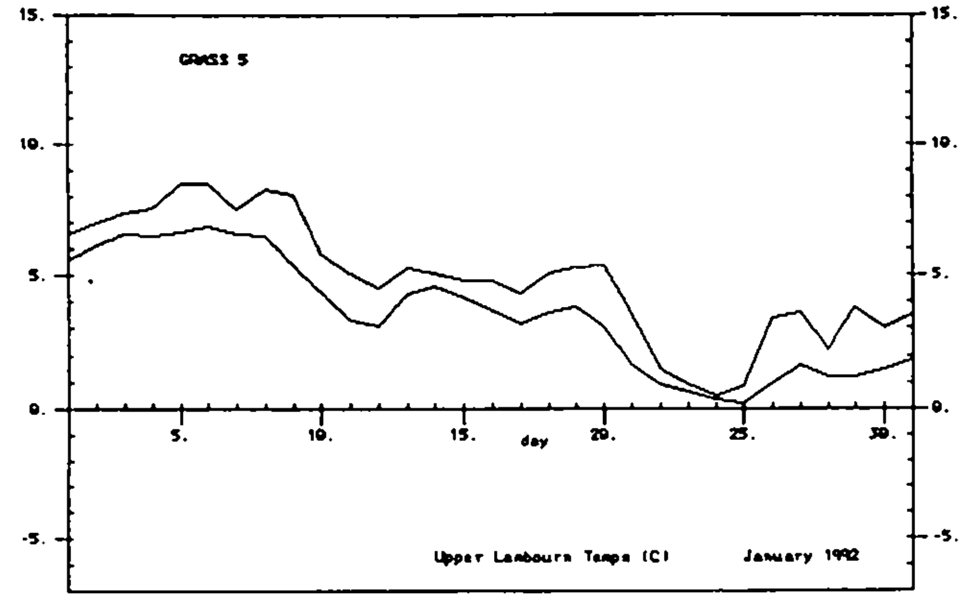


Fig. 2 Upper Lambourn December 1991





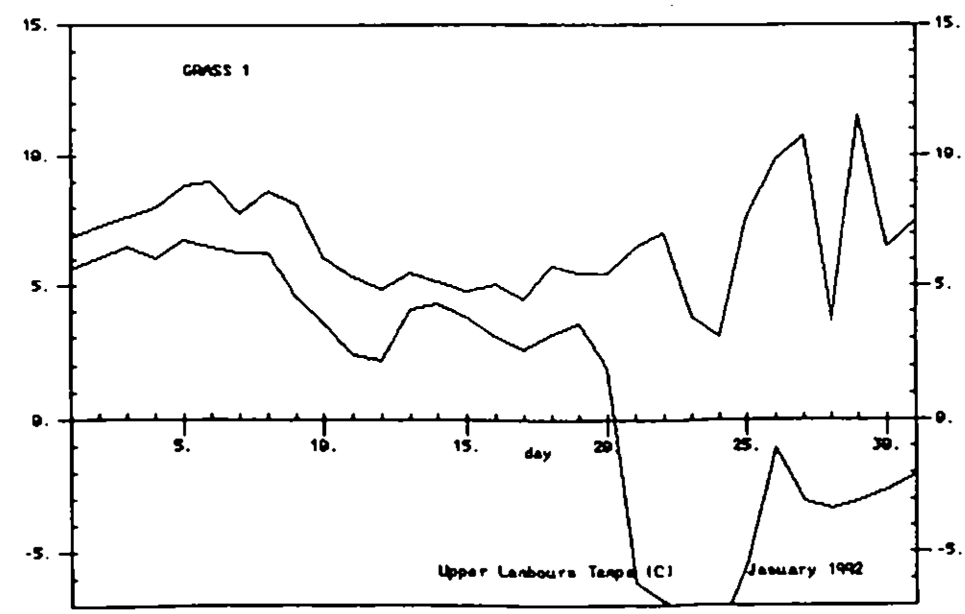


Fig. 3 Upper Lambourn January 1992

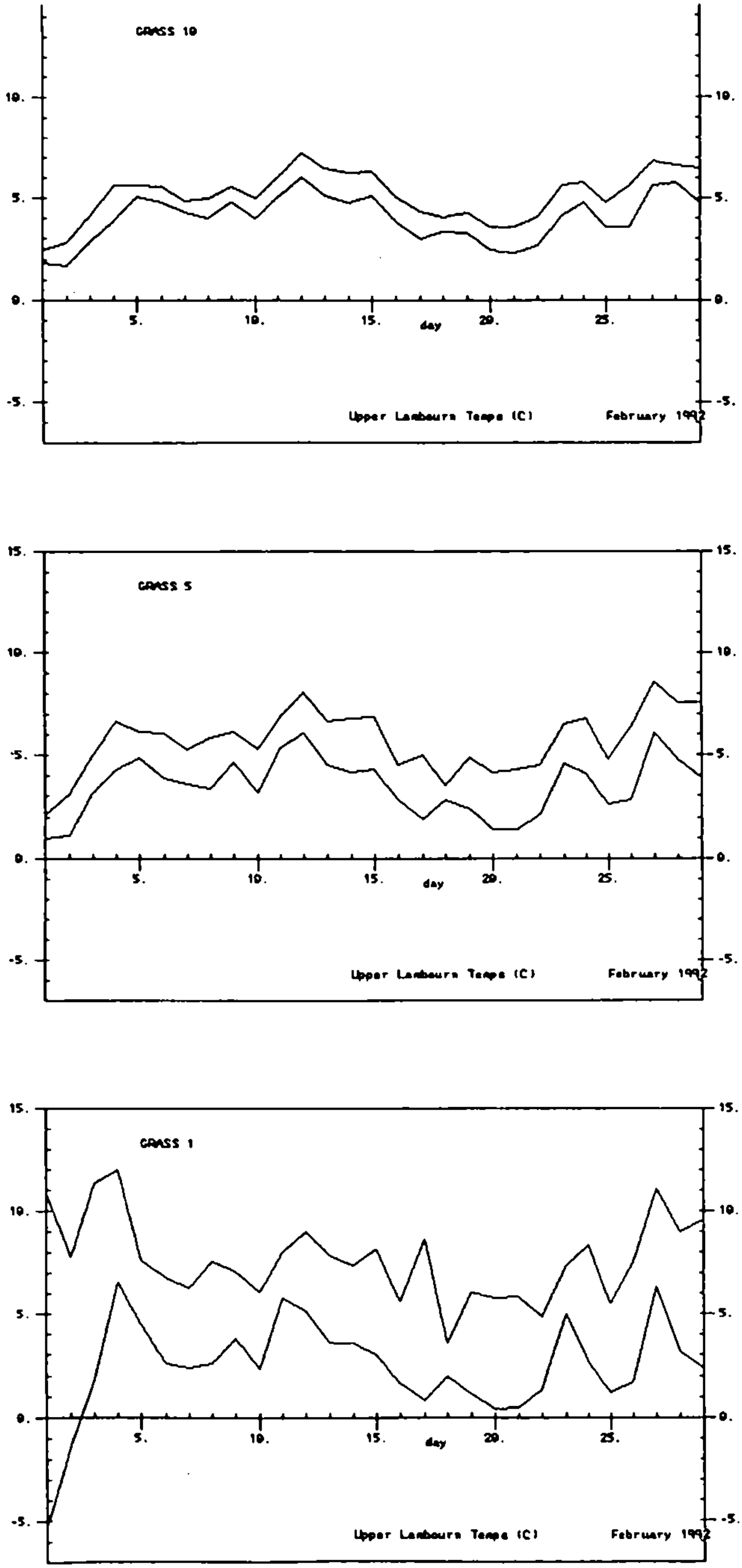
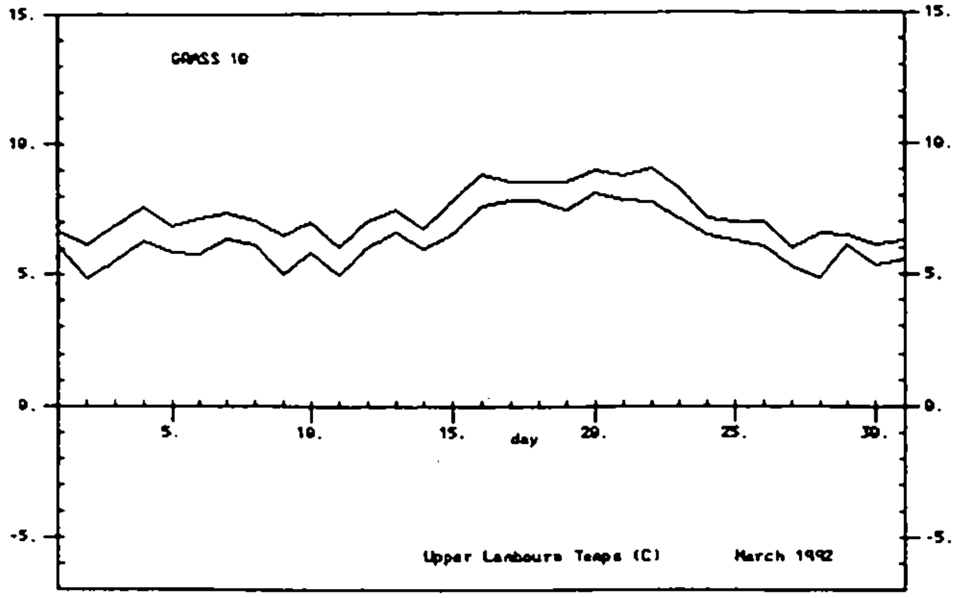
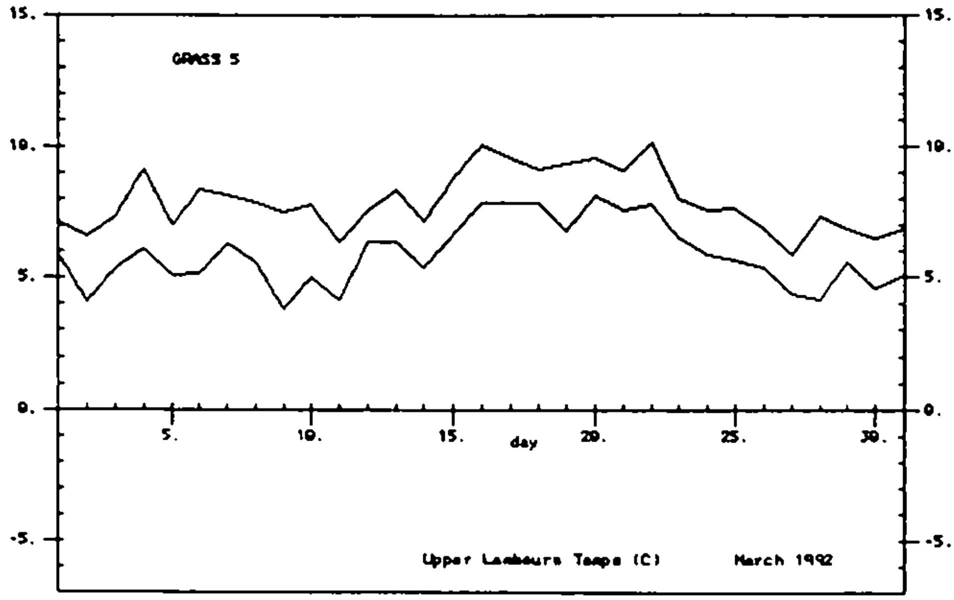


Fig 4 Upper Lambourn February 1992





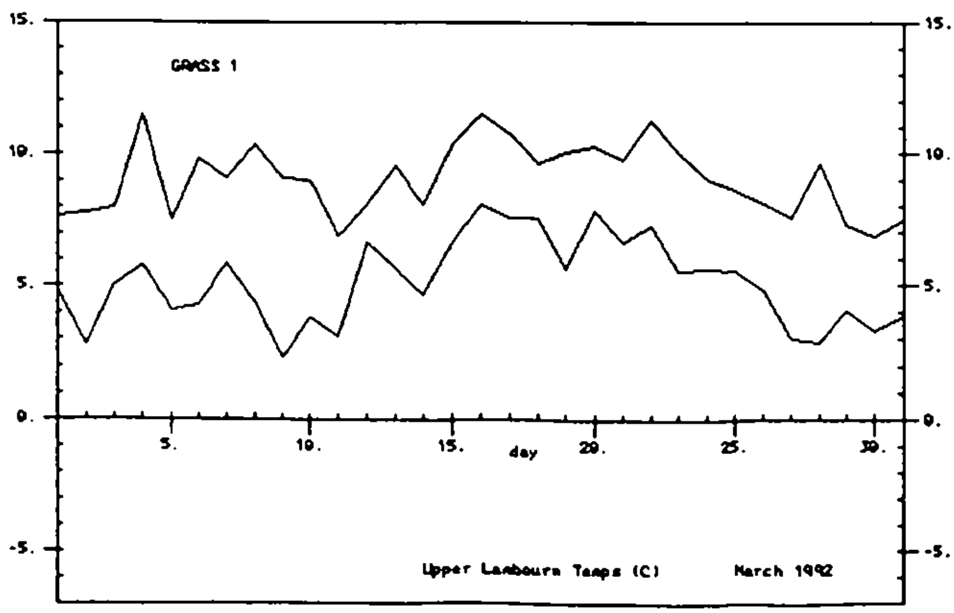
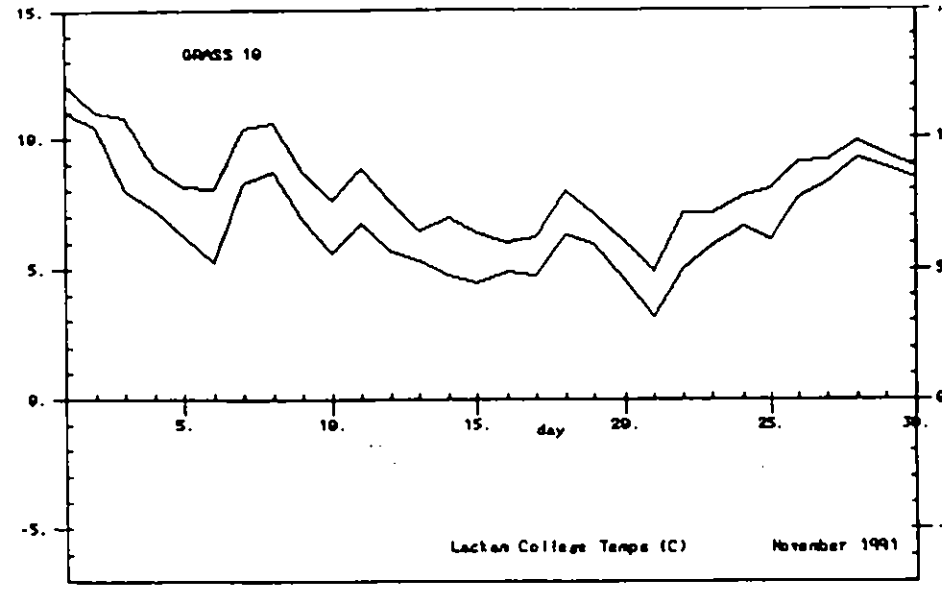
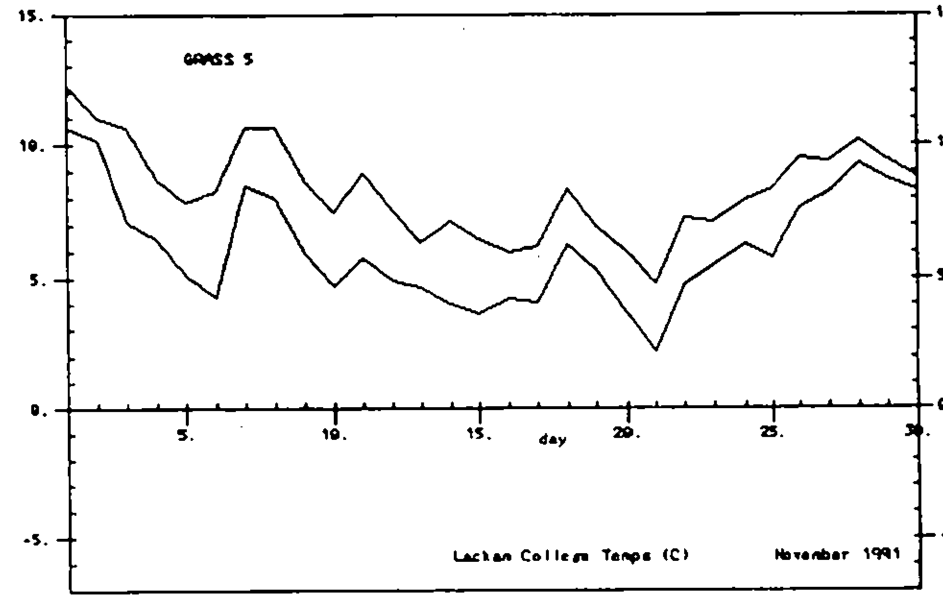


Fig. 5 Upper Lambourn March 1992





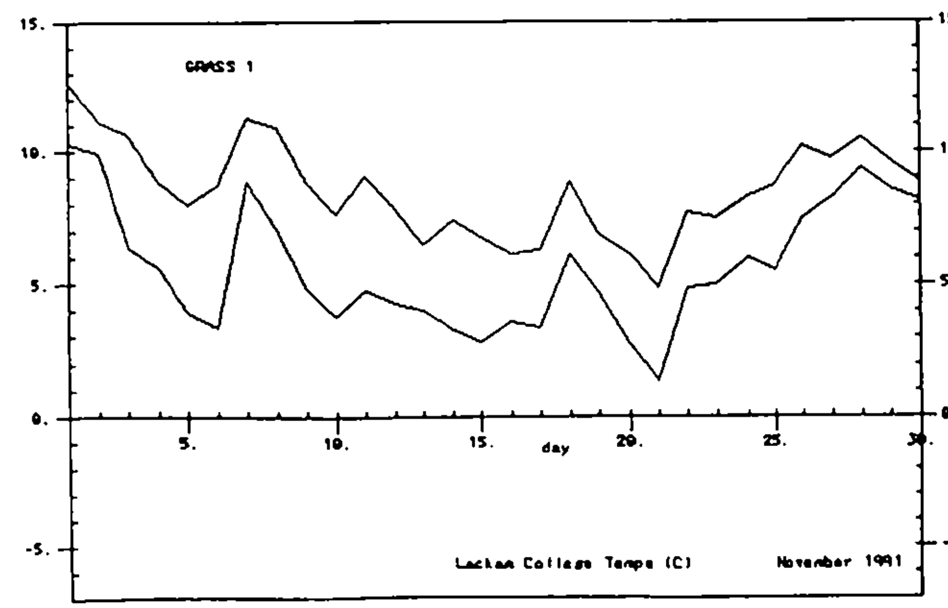


Fig. 1 Lackam College November 1991

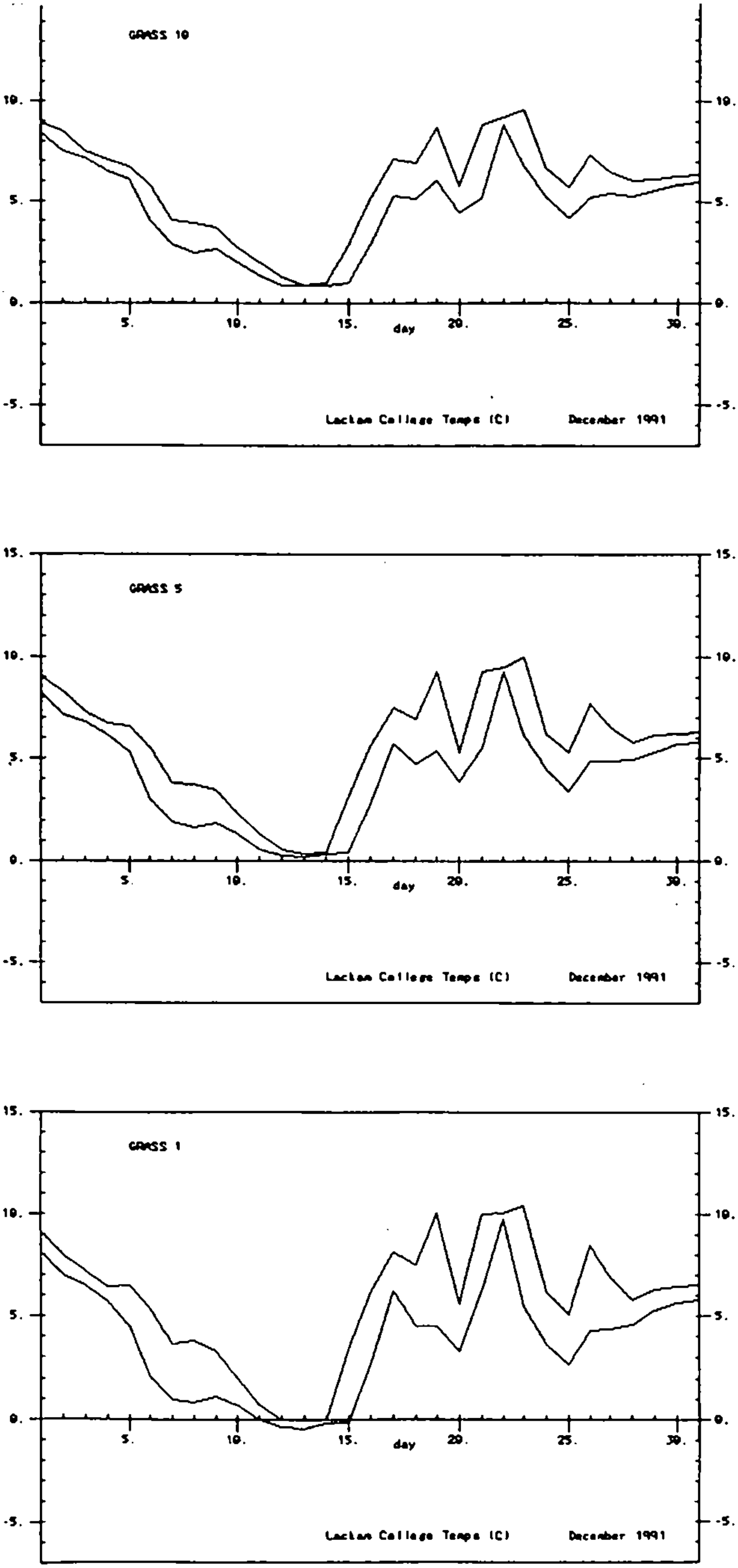


Fig. 2 Lackam College December 1991

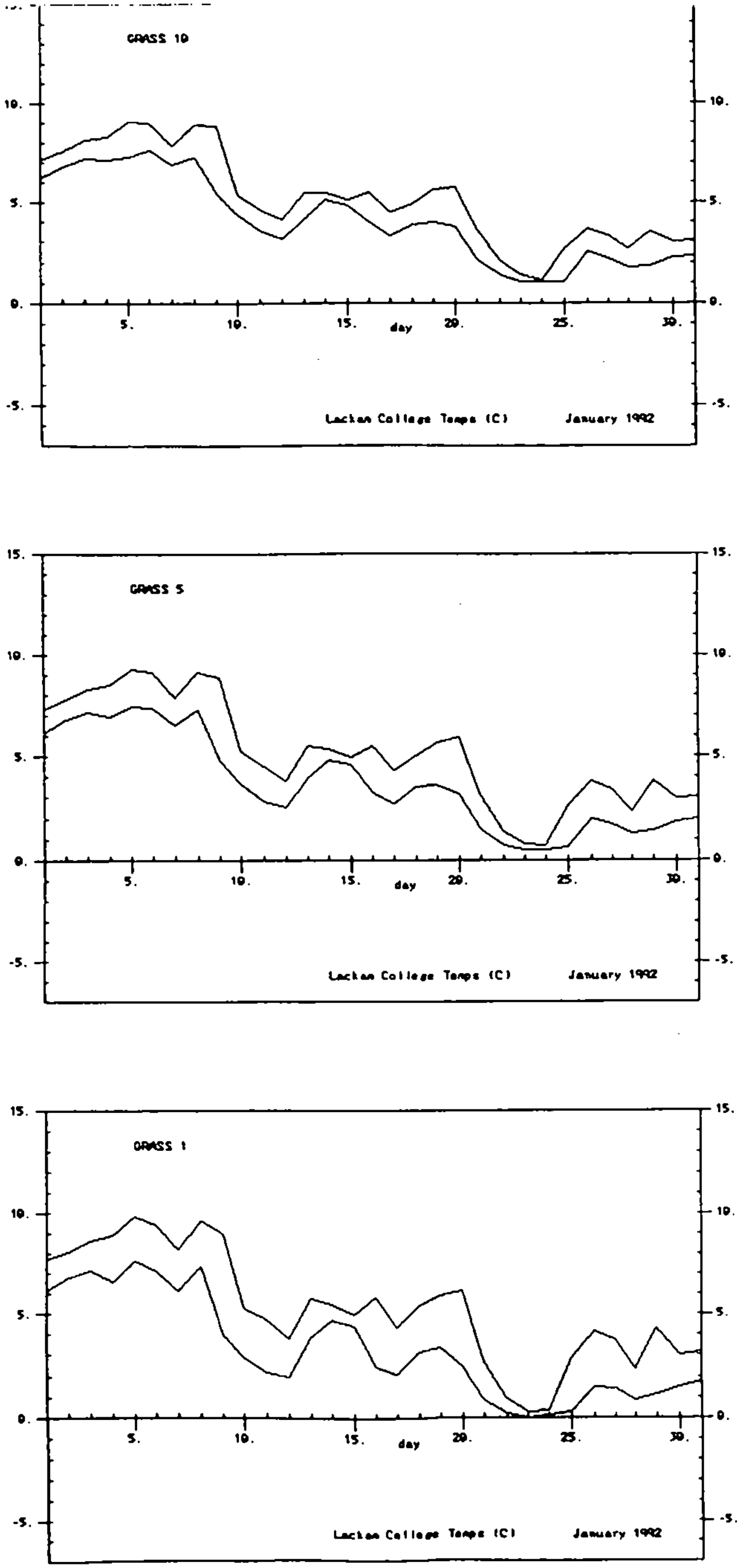
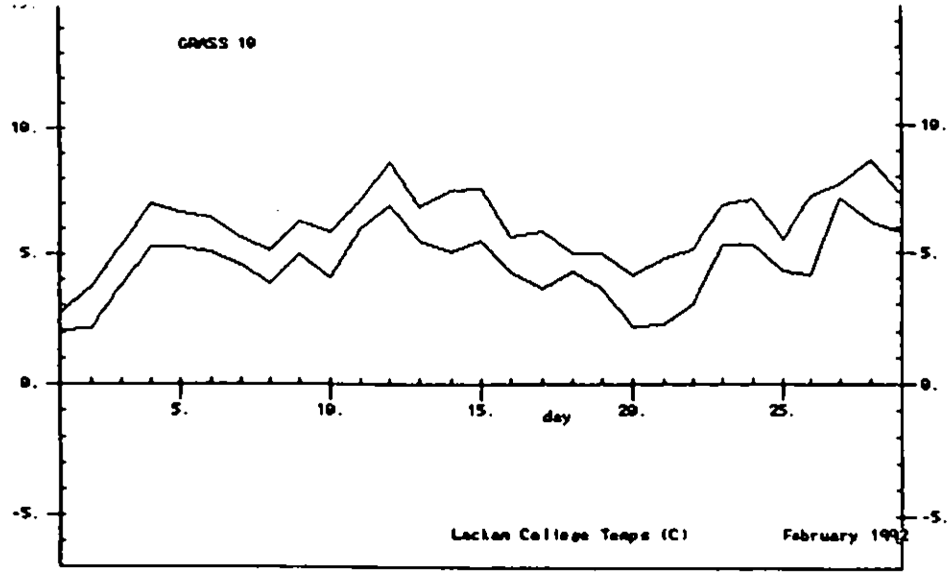
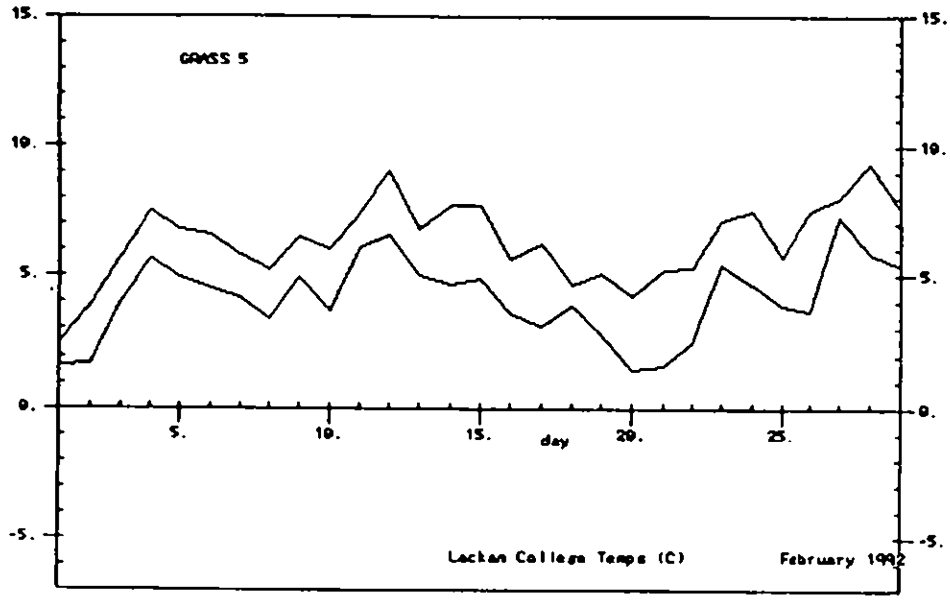


Fig. 3 Lackam College January 1992





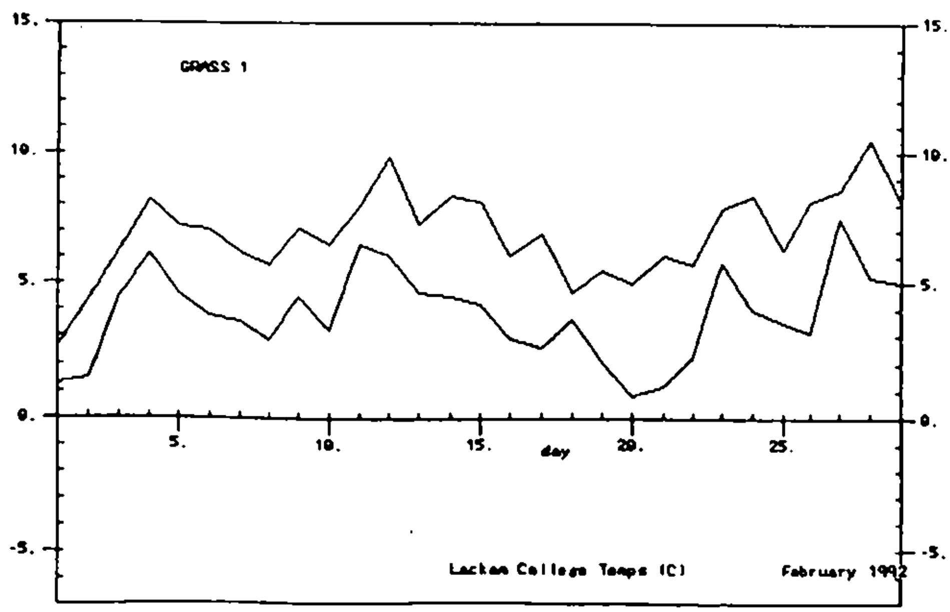


Fig. 4 Lackam College February 1992

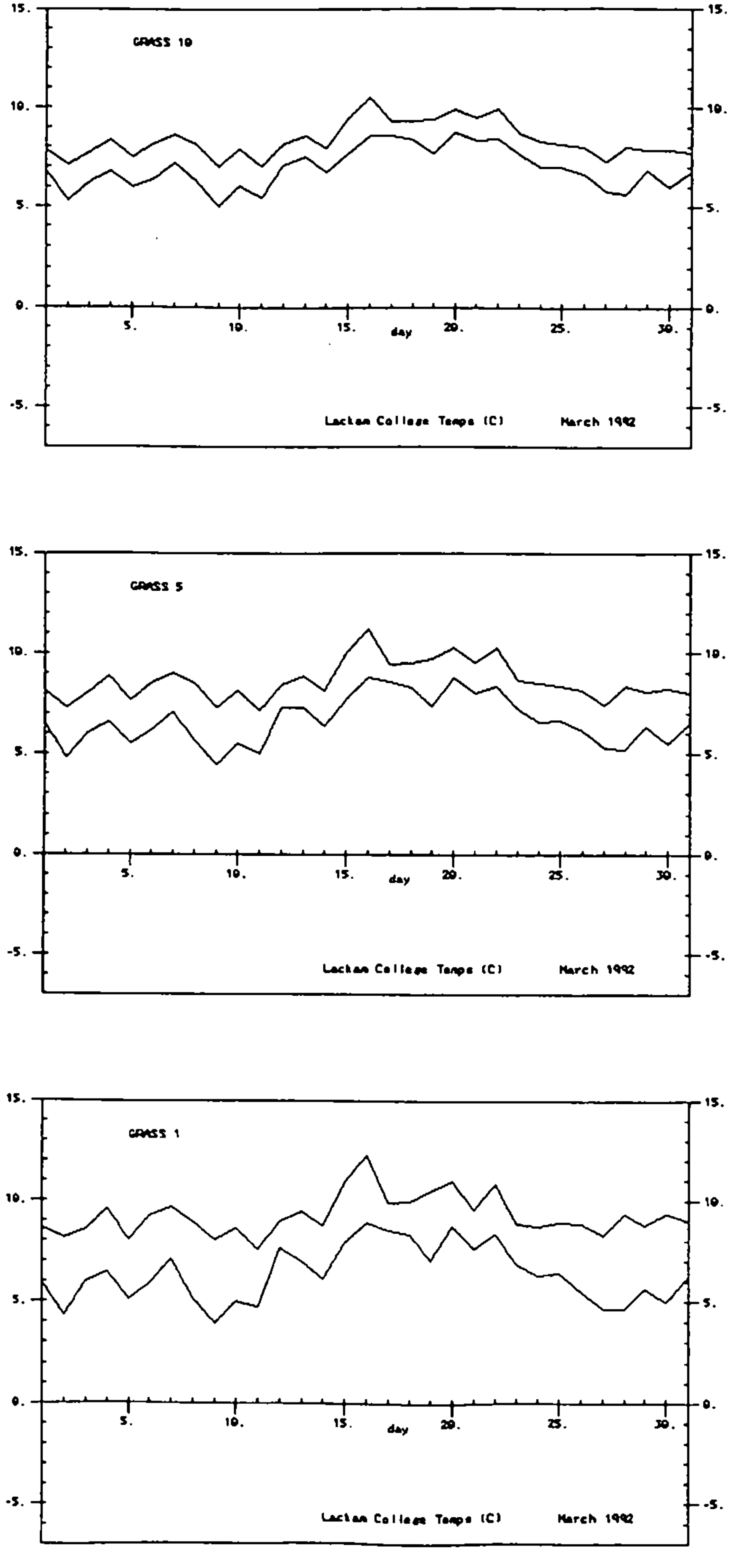
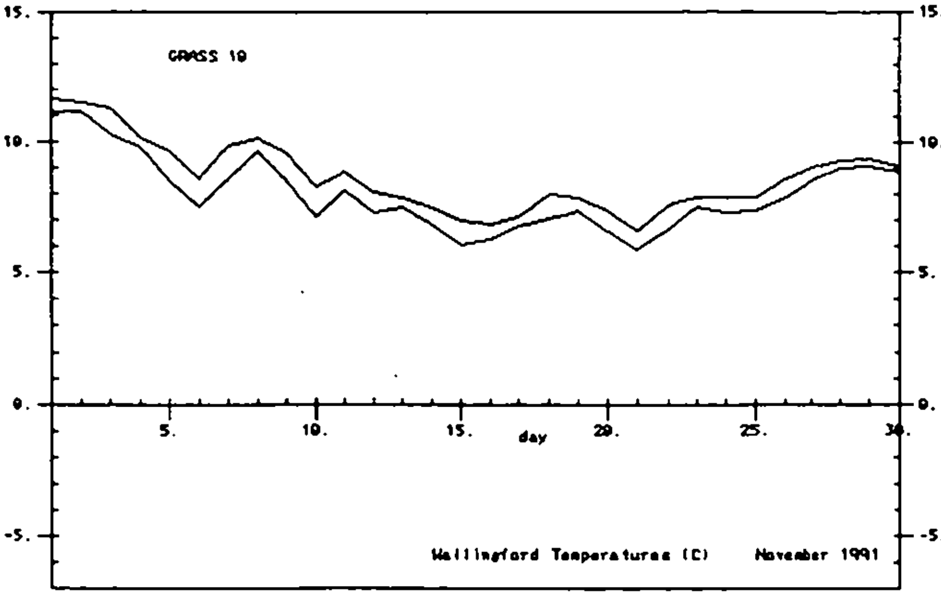
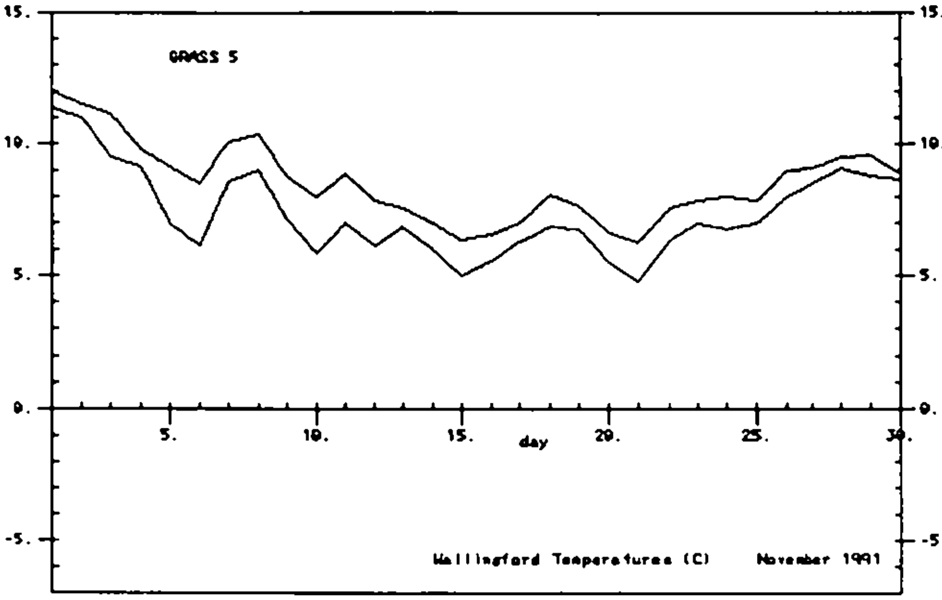


Fig. 5 Lackam College March 1992





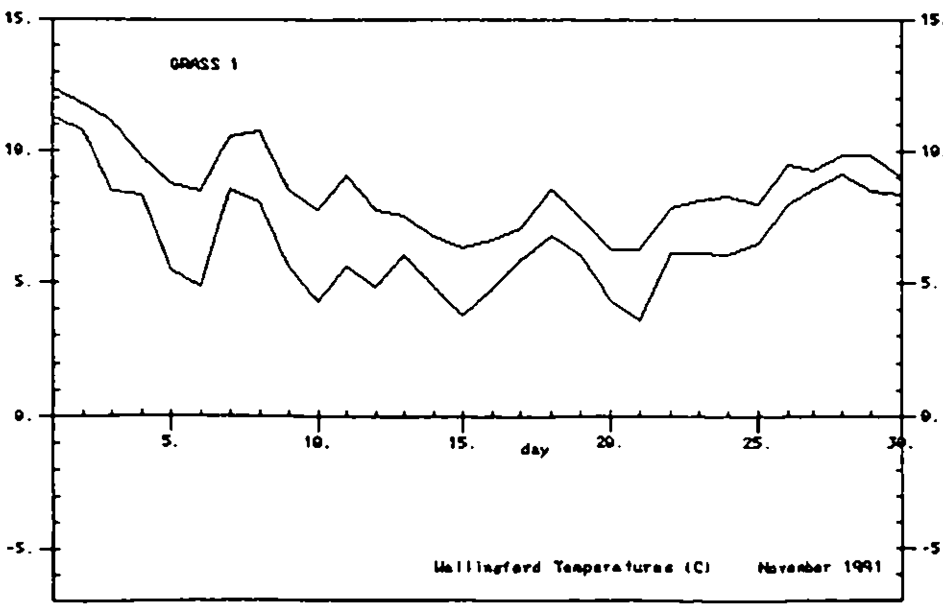


Fig. 1 Wallingford - Grass November 1991

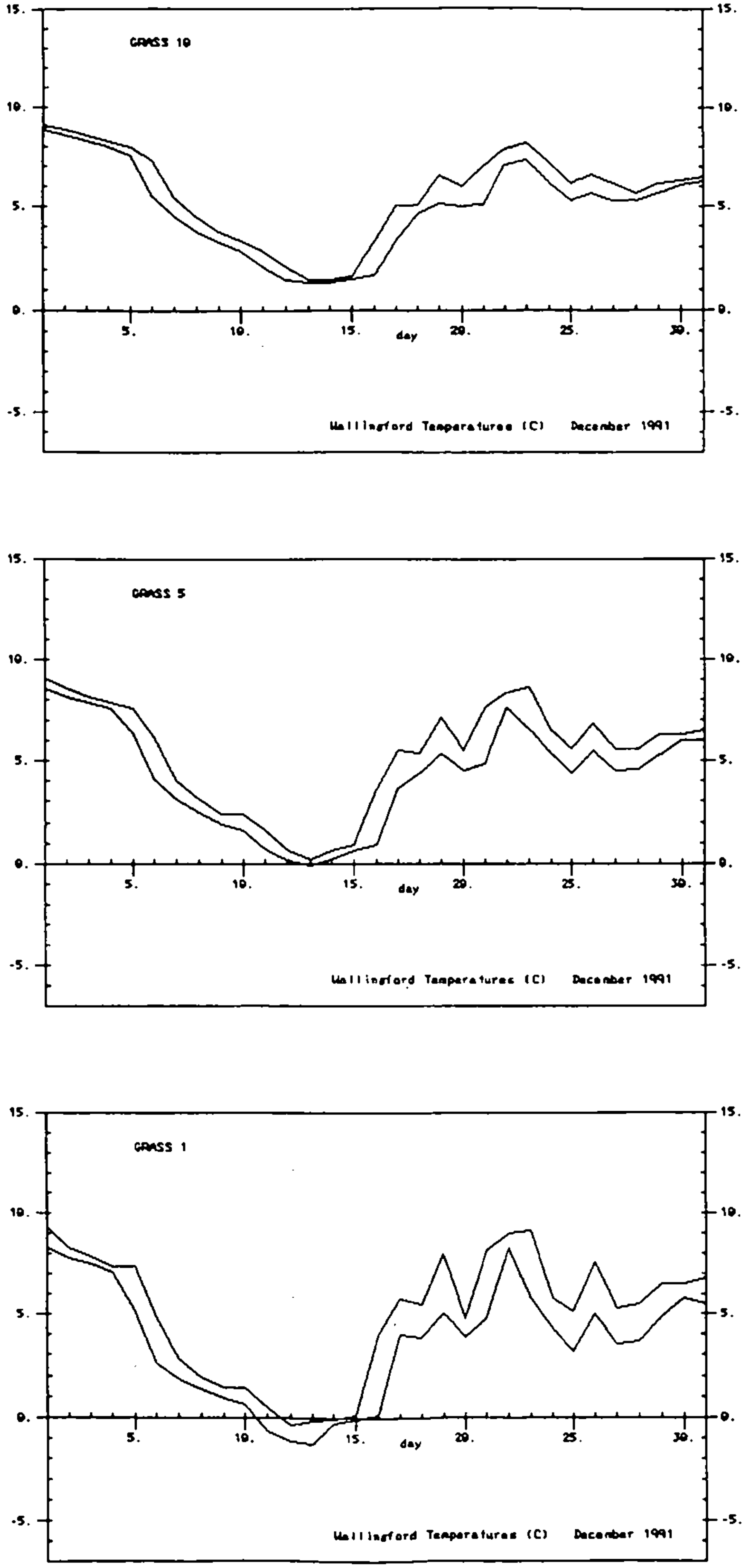
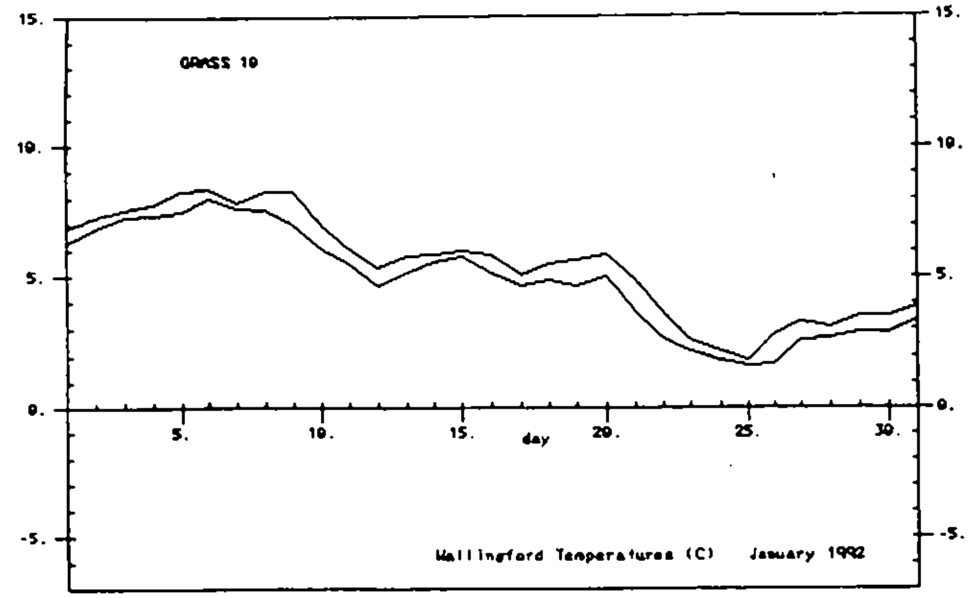
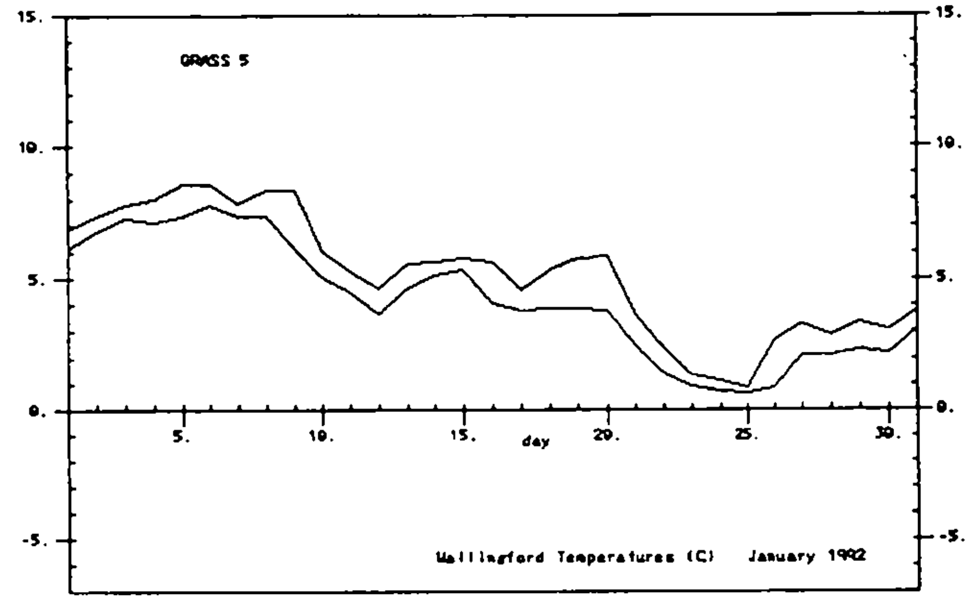


Fig. 2 Wallingford - Grass December 1991





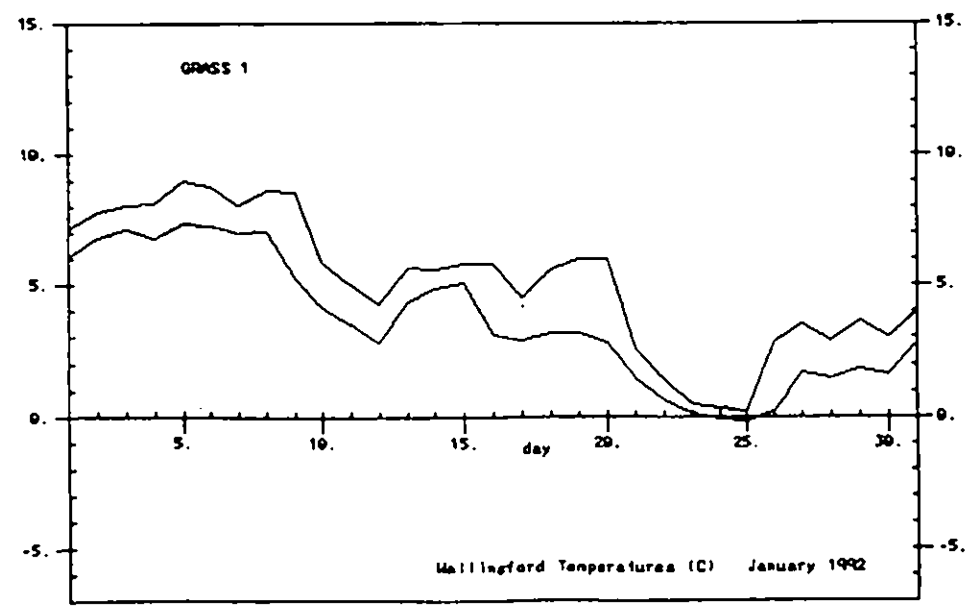
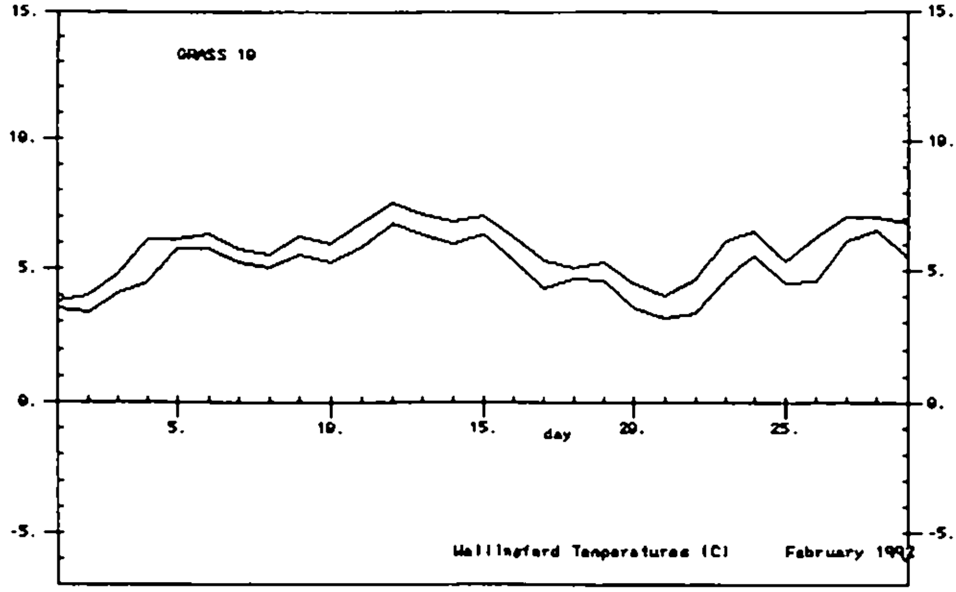
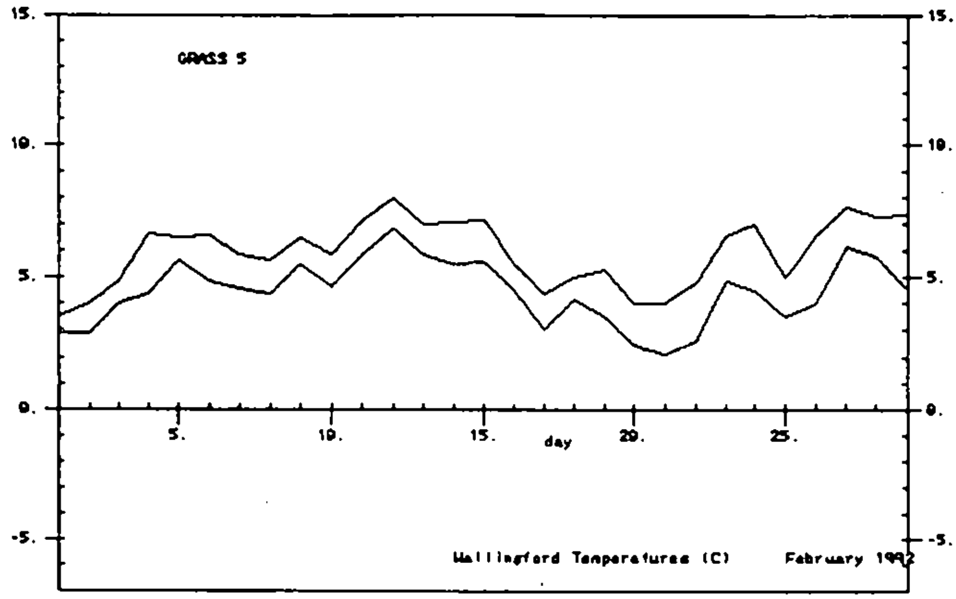


Fig. 3 Wallingford – Grass January 1992





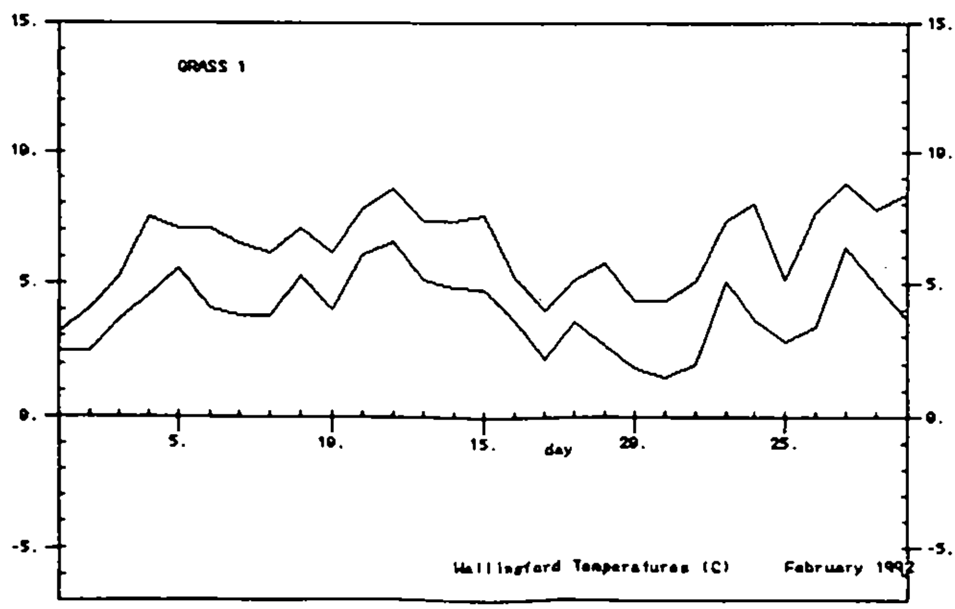


Fig. 4 Wallingford - Grass February 1992

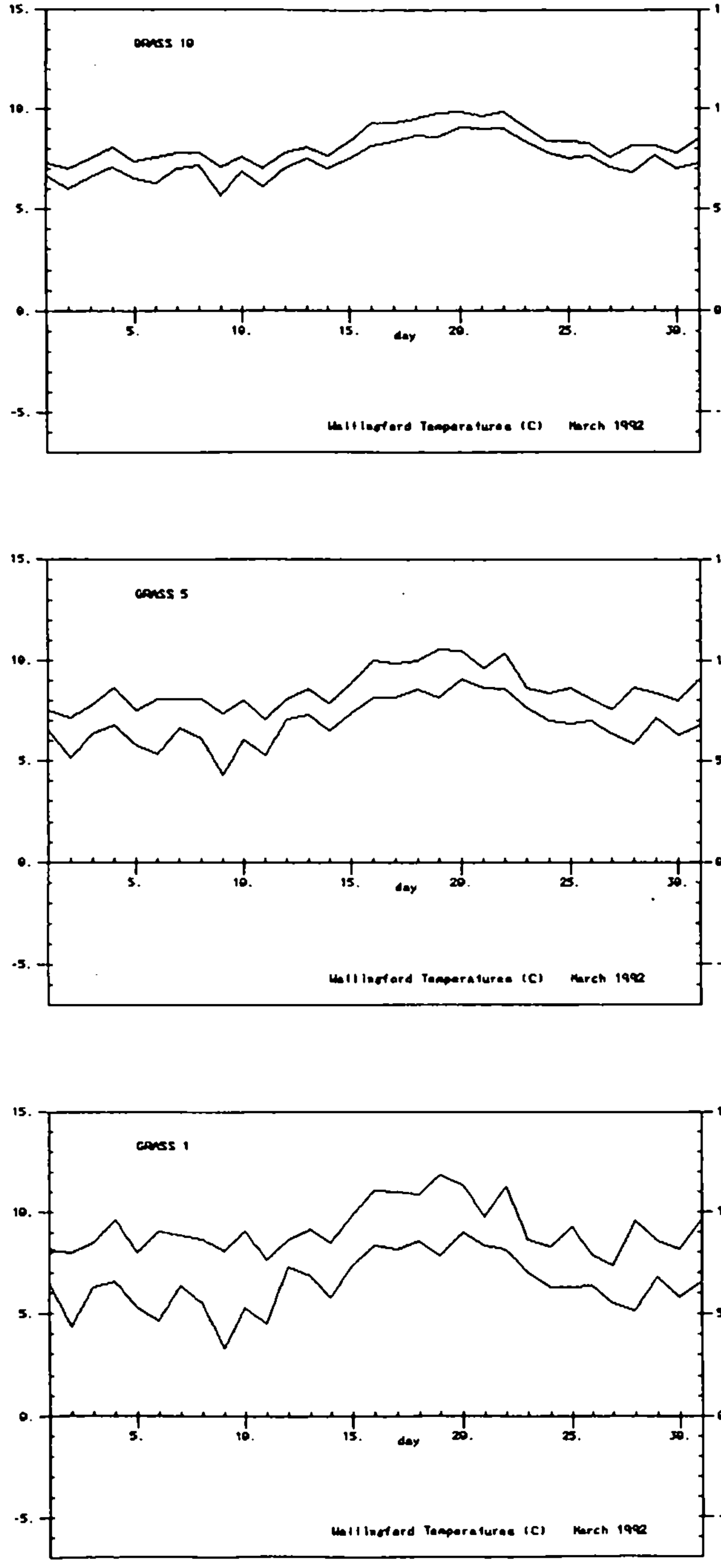


Fig. 5 Wallingford – Grass March 1992

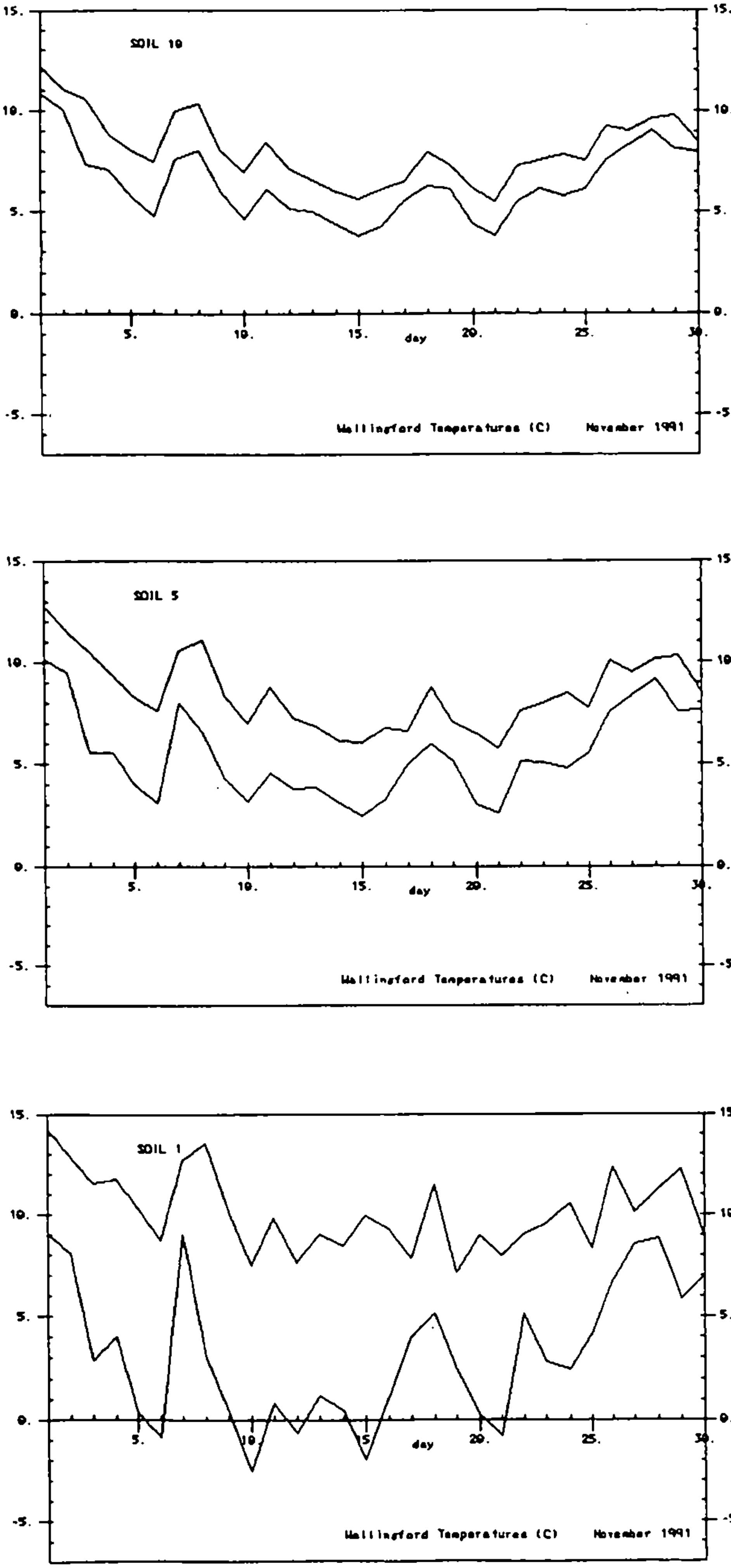


Fig. 1 Wallingford – Soil November 1991

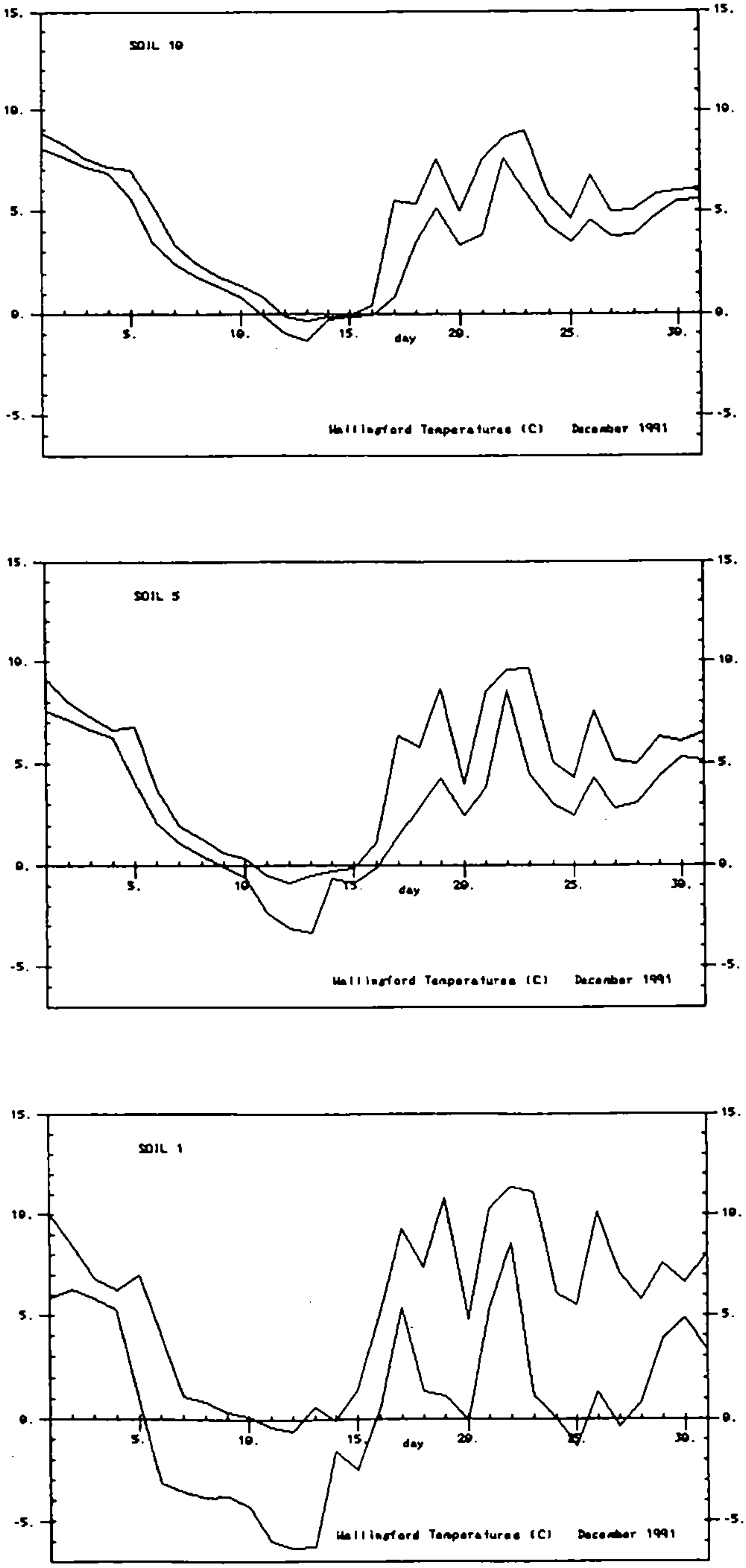


Fig. 2 Wallingford - Soil December 1991

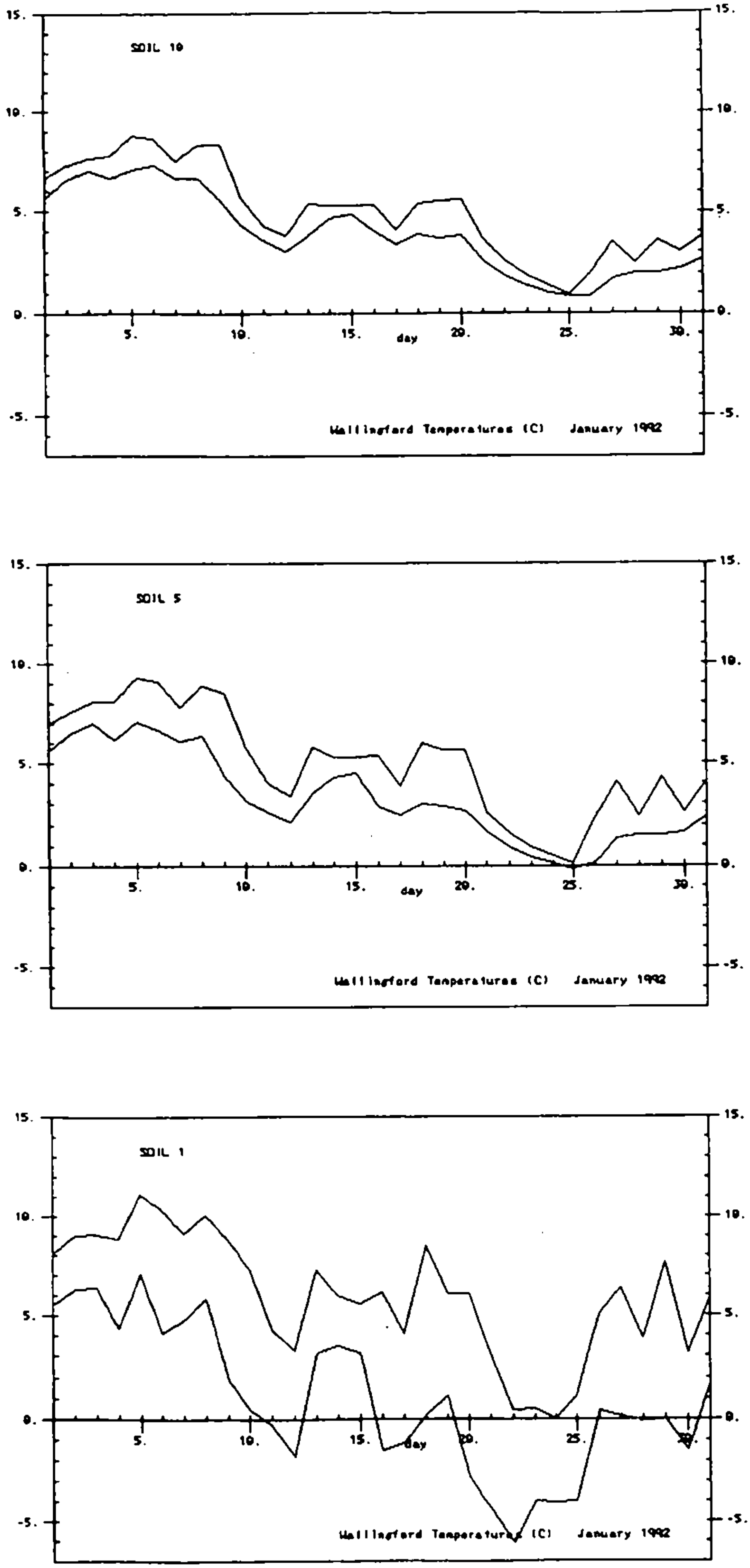
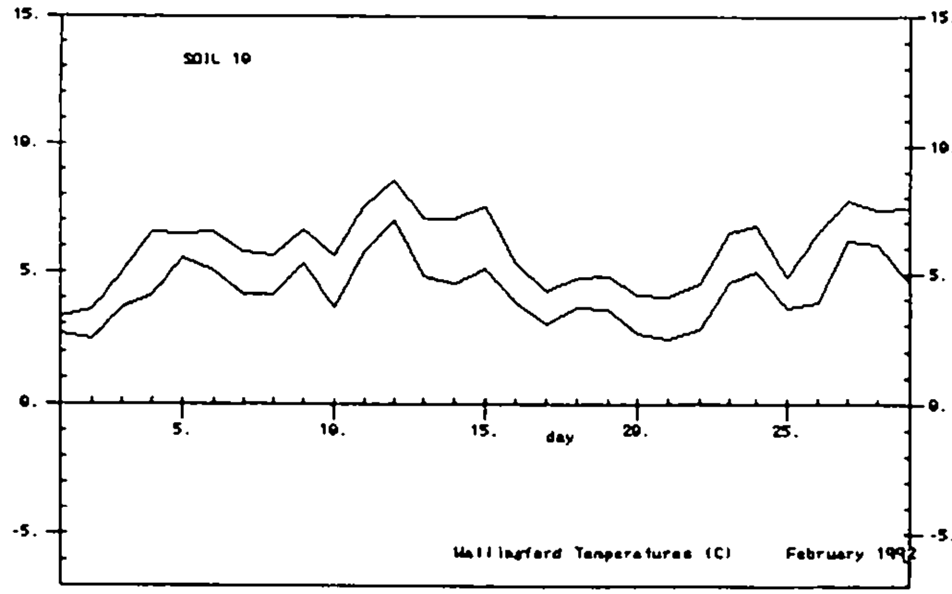
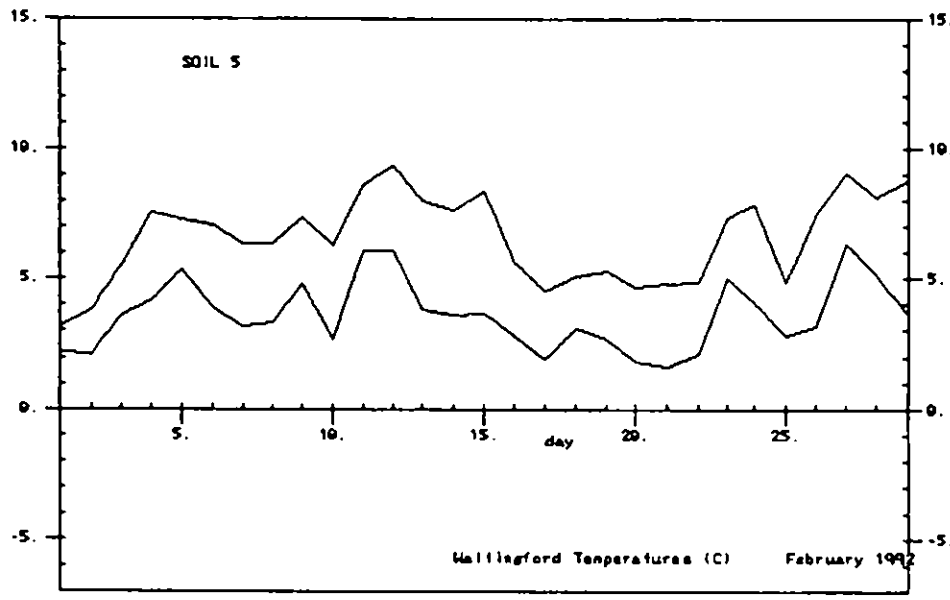


Fig. 3 Wallingford - Soil January 1992





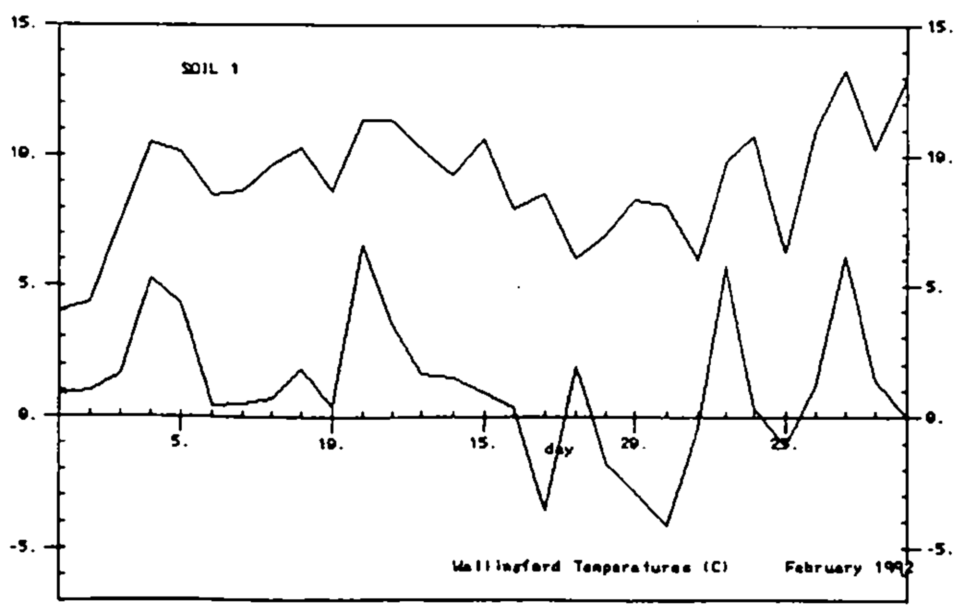
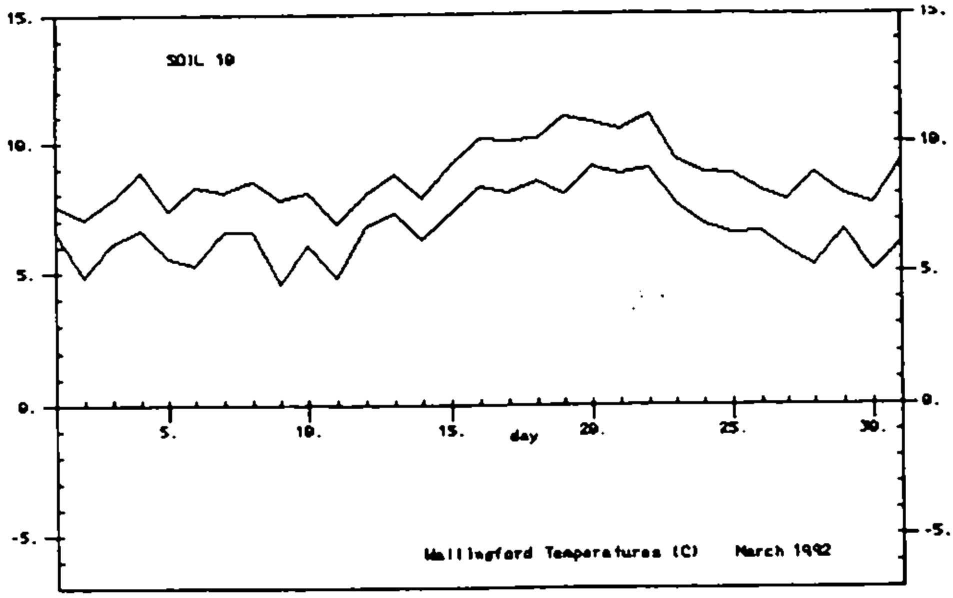
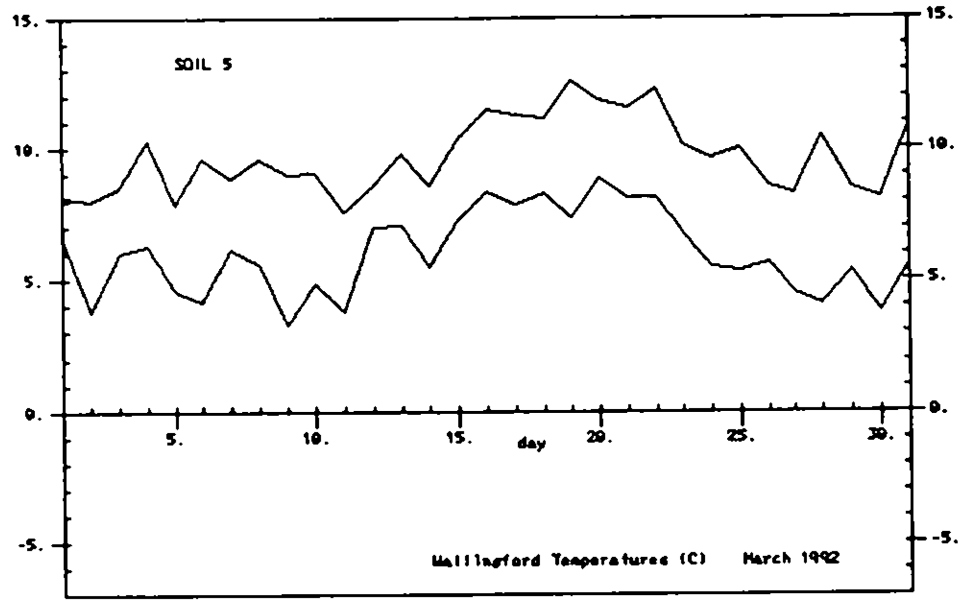


Fig. 4 Wallingford - Soil February 1992





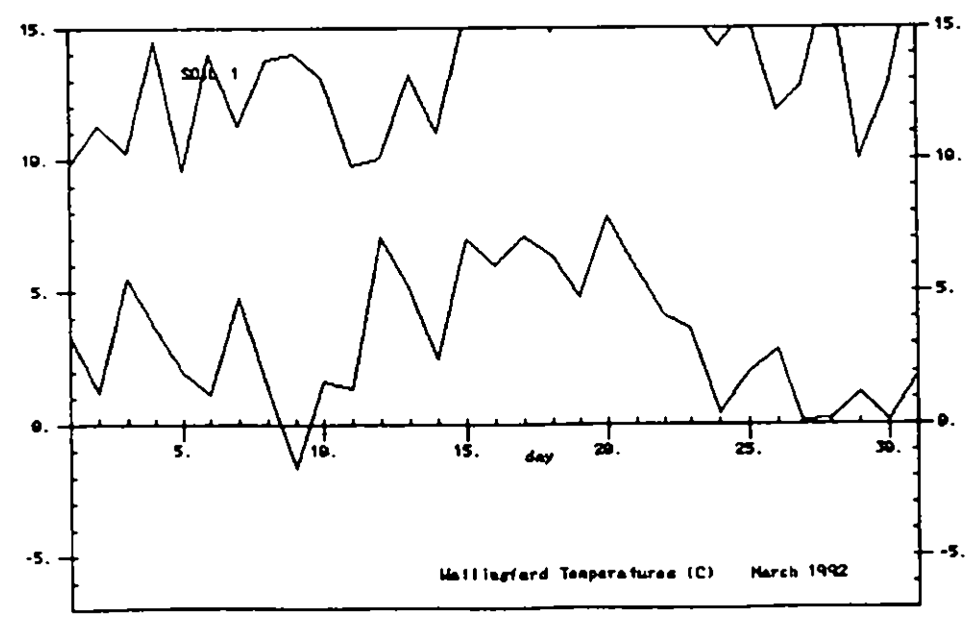
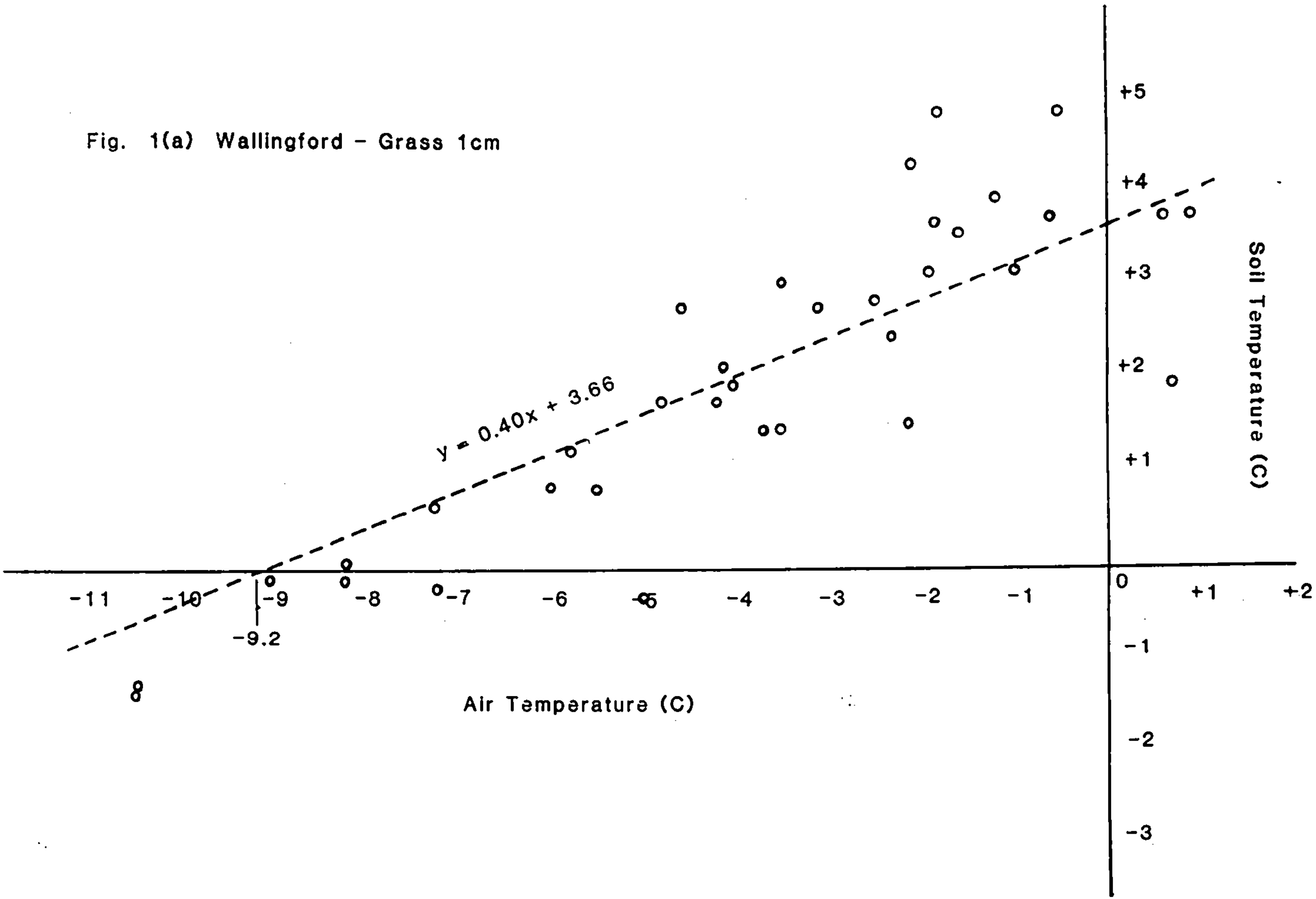


Fig. 5 Wallingford - Soil March 1992

APPENDIX III Regressions of Soil Temperature against Air Temperature

Figure	1(a)	Wallingford	Grass	1 cm
	1(b)			5 cm
	1(c)			10 cm
	2(a)		Soil	1 cm
	2(b)			5 cm
	2(c)			10 cm
	3(a)	Lambourn	Grass	1 cm
	3(b)			2.5 cm
	3(c)			5 cm
	3(d)			7.5 cm
	3(e)			10 cm
	4(a)	Lackam	Grass	1 cm
	4(b)			5 cm
	4(c)			10 cm

Fig. 1(a) Wallingford - Grass 1cm



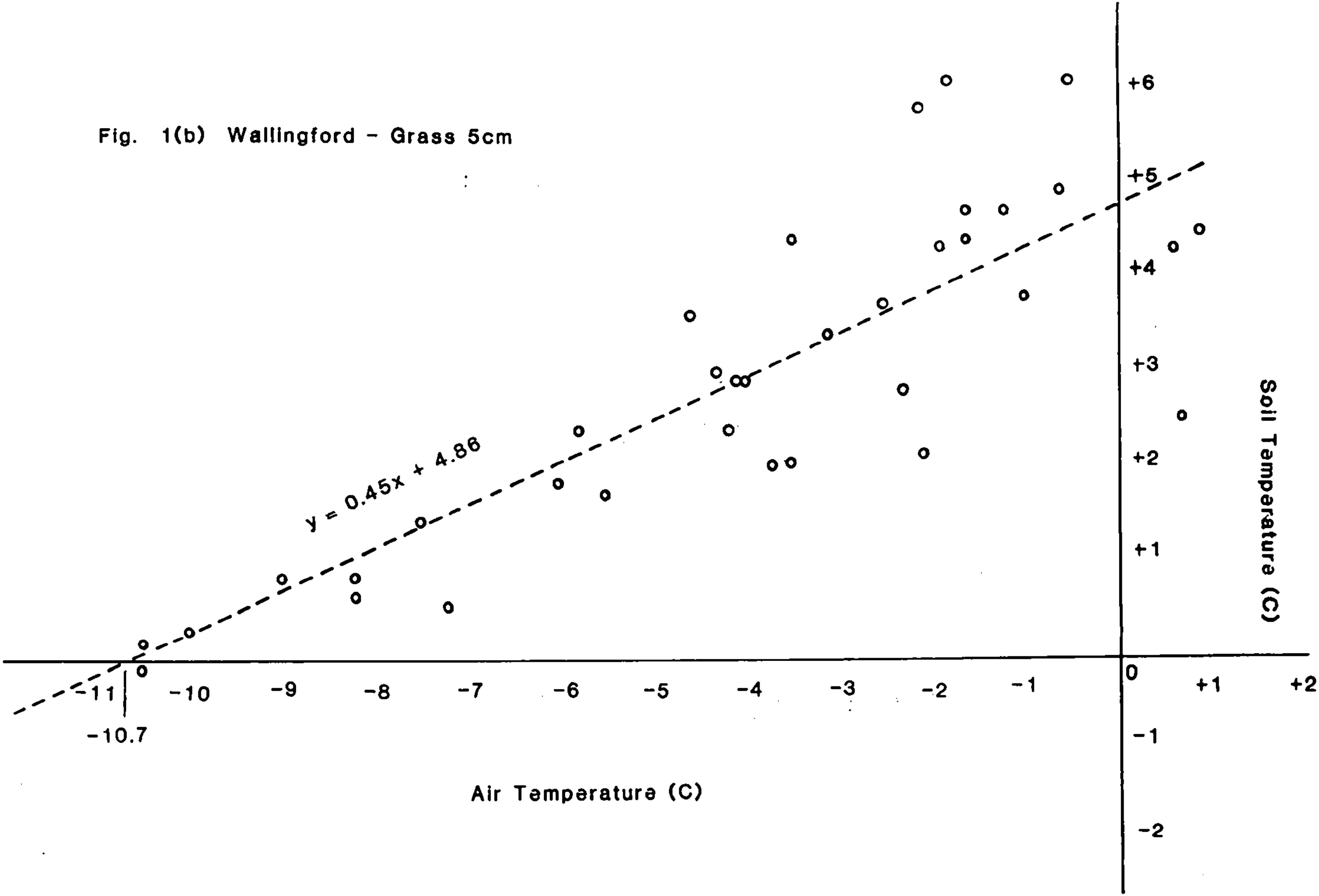
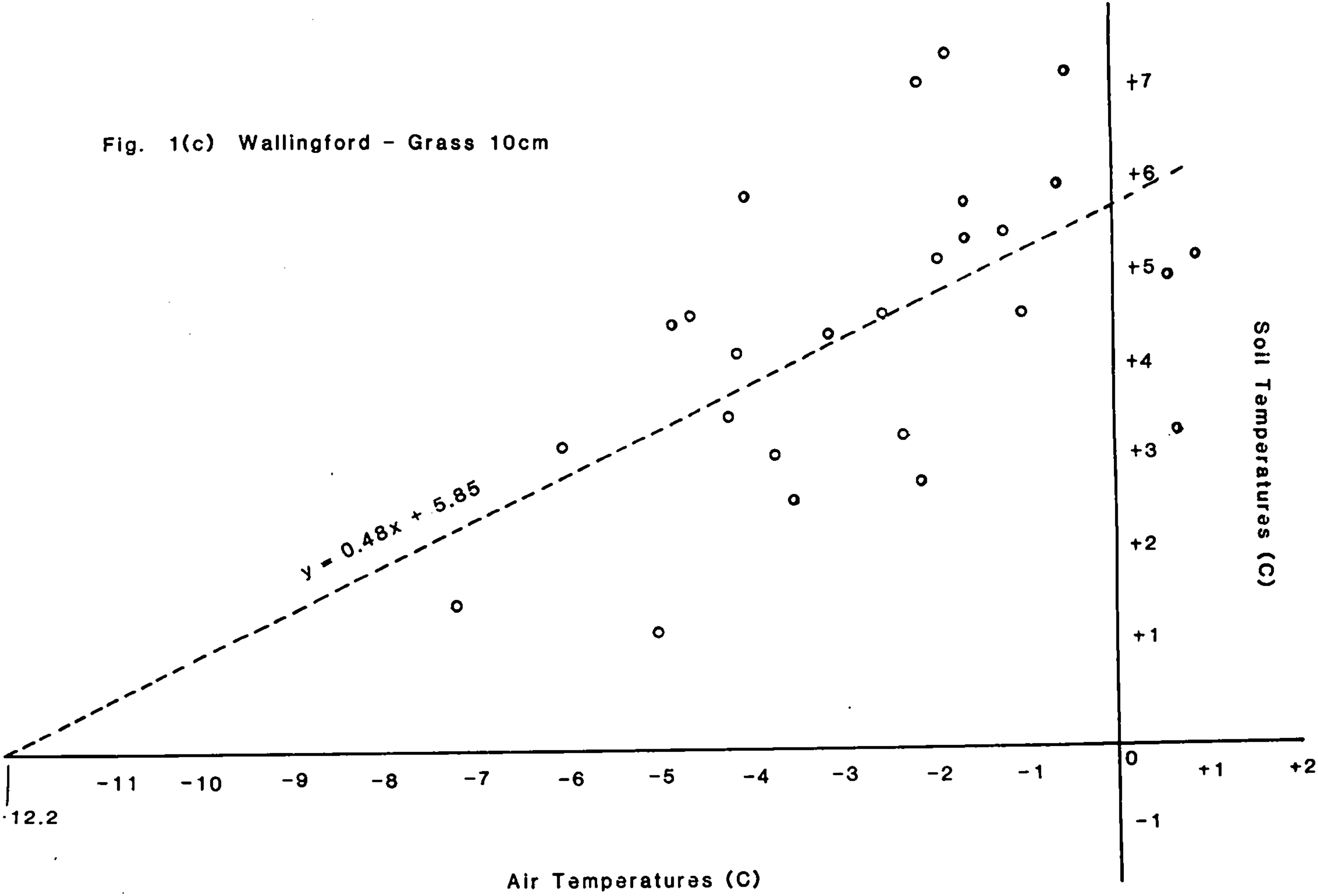


Fig. 1(b) Wallingford - Grass 5cm

Fig. 1(c) Wallingford - Grass 10cm



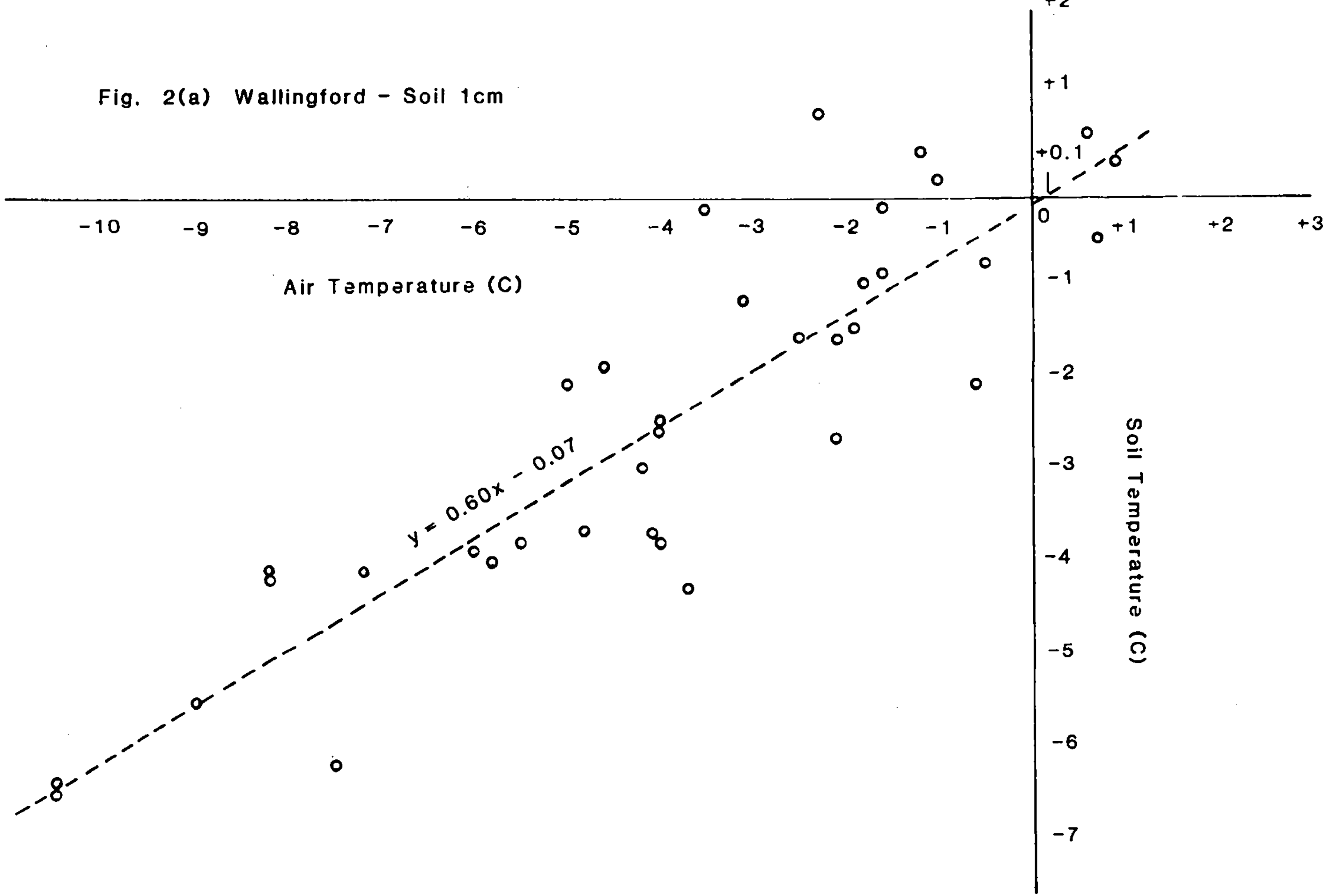


Fig. 2(a) Wallingford - Soil 1cm
Air Temperature (C)
Soil Temperature (C)
y = 0.60x - 0.07
+0.1
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
+1
+2
+3
-1
-2
-3
-4
-5
-6
-7

Fig. 2(b) Wallingford - Soil 5cm

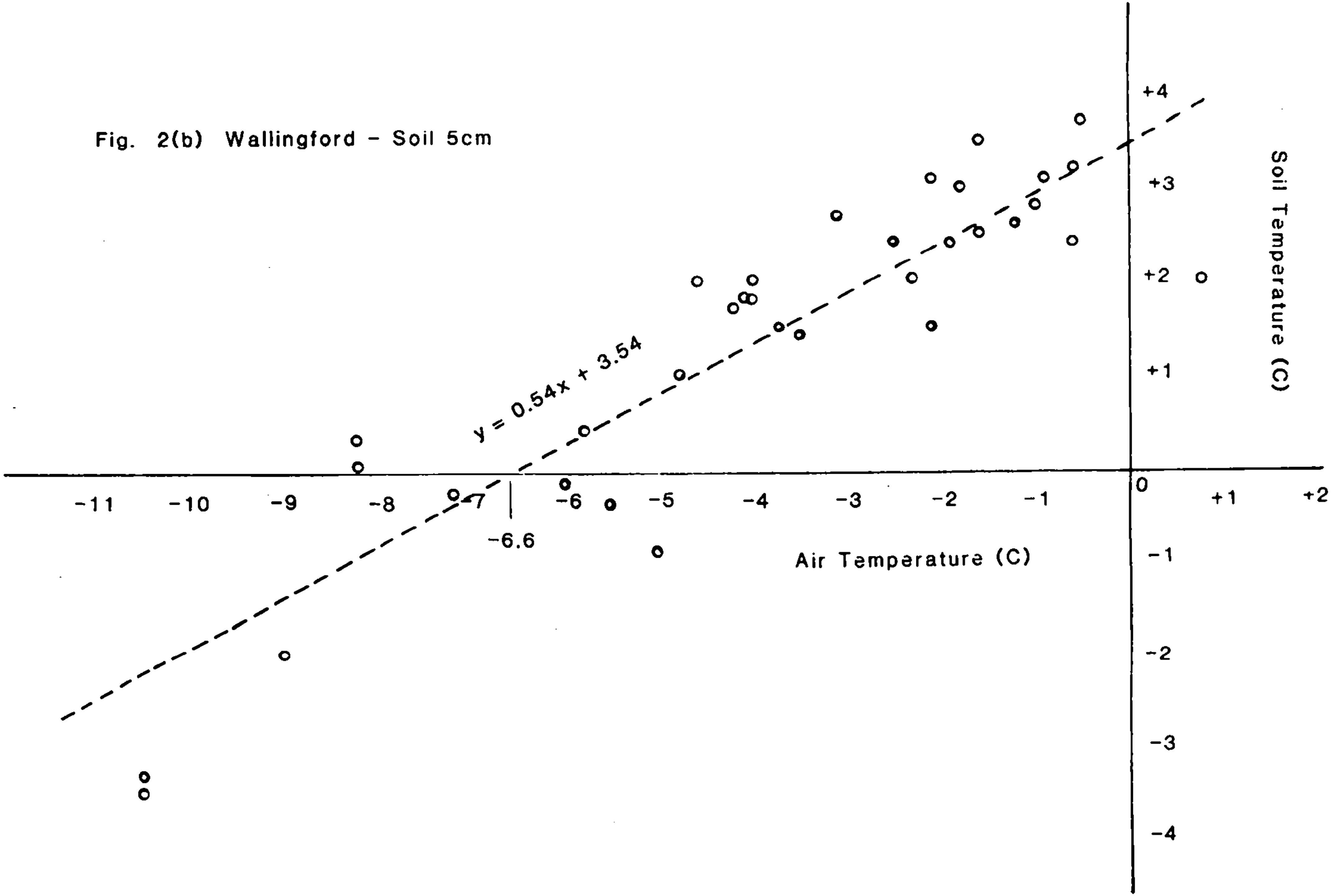


Fig. 2(c) Wallingford - Soil 10cm

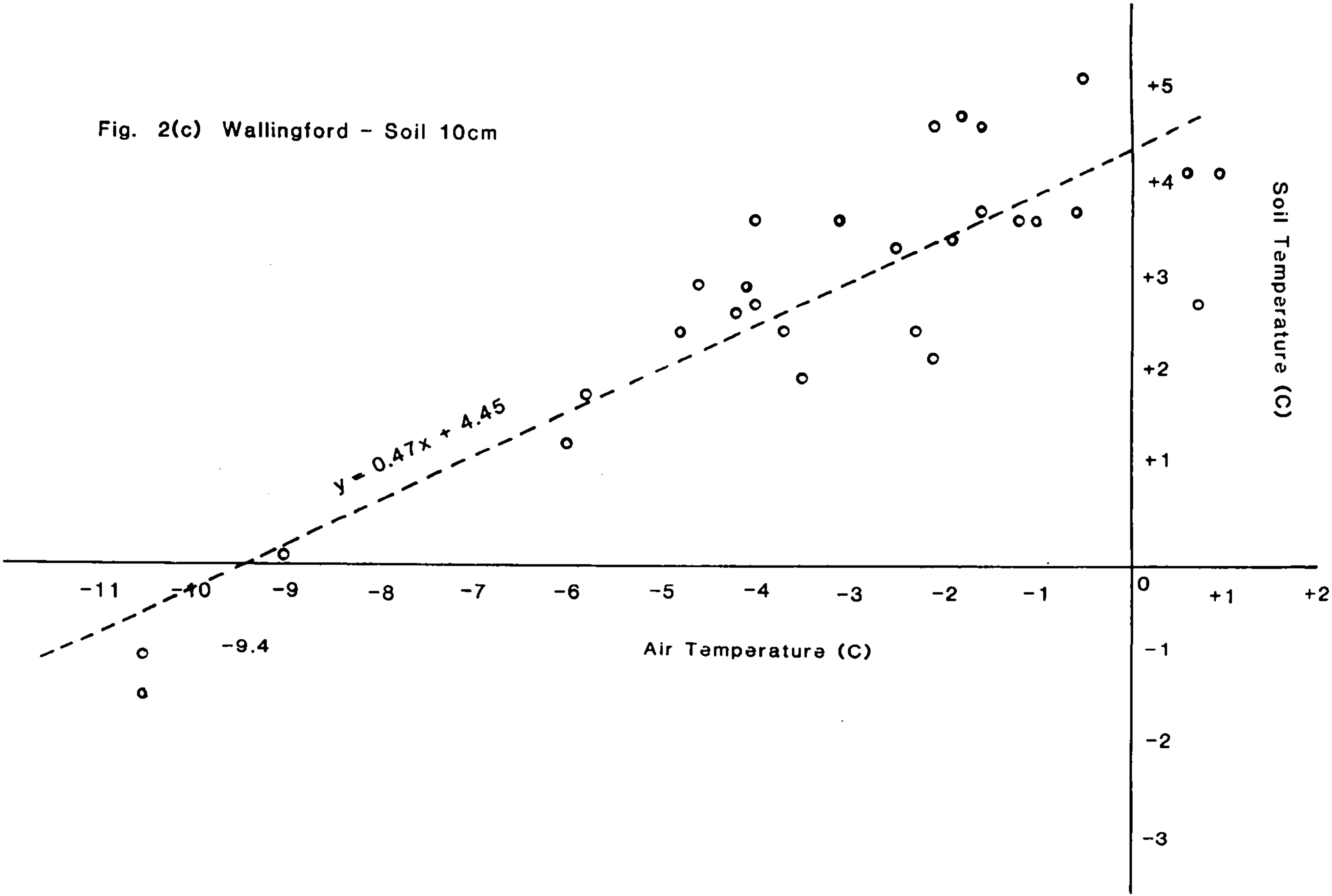


Fig. 3(a) Lambourn - Grass 1cm

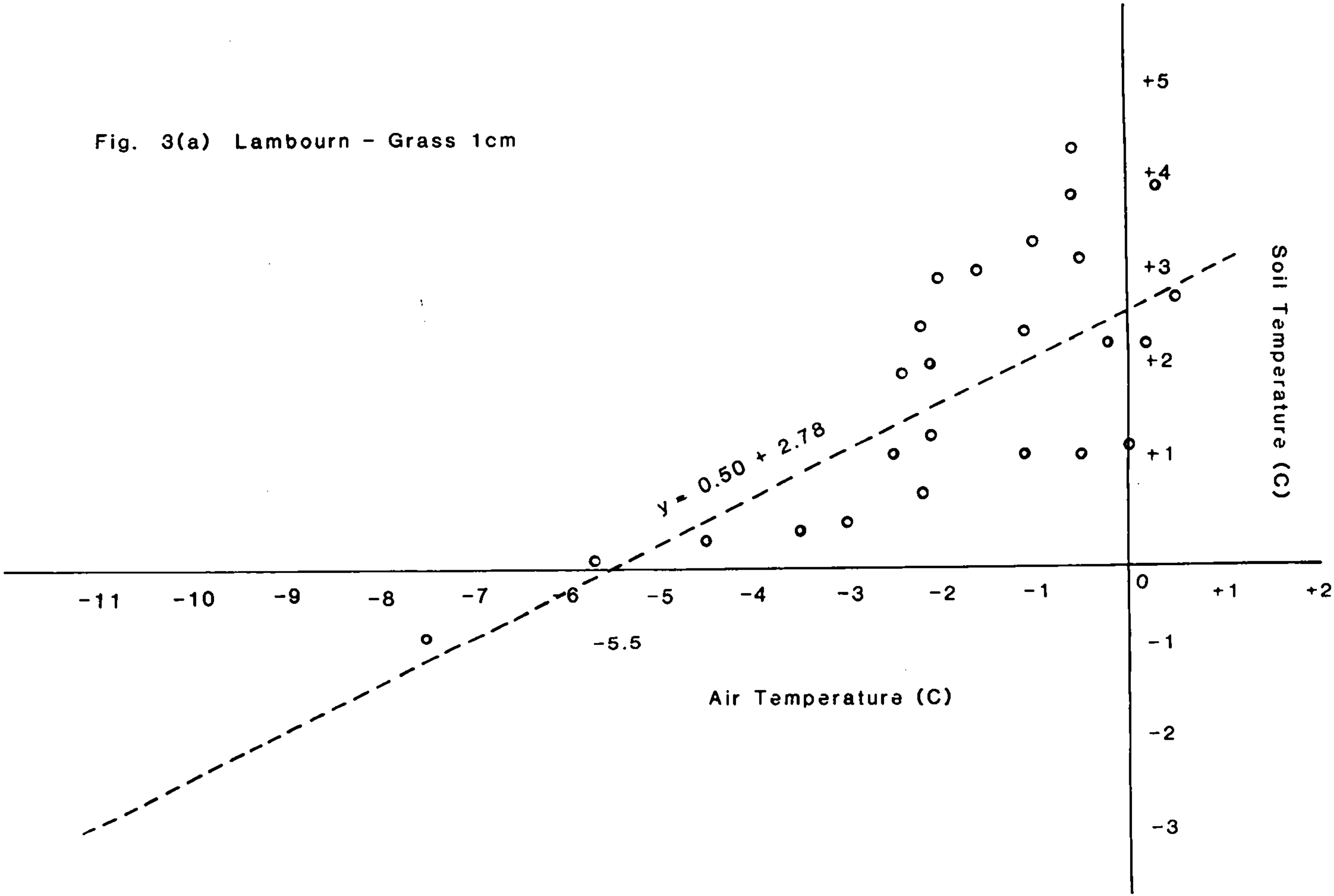


Fig. 3(b) Lambourn Grass 2.5cm

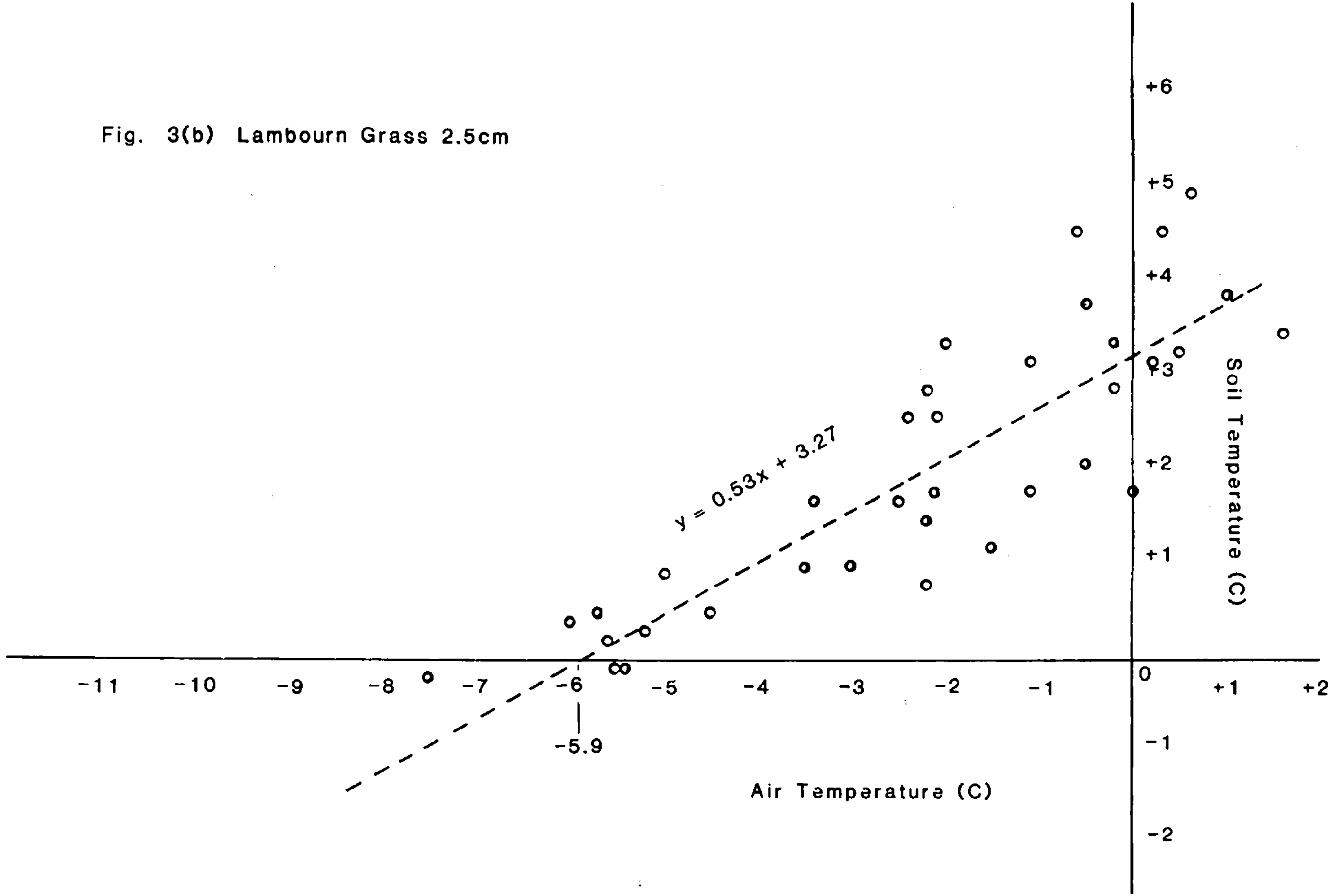


Fig. 3(c) Lambourn - Grass 5cm

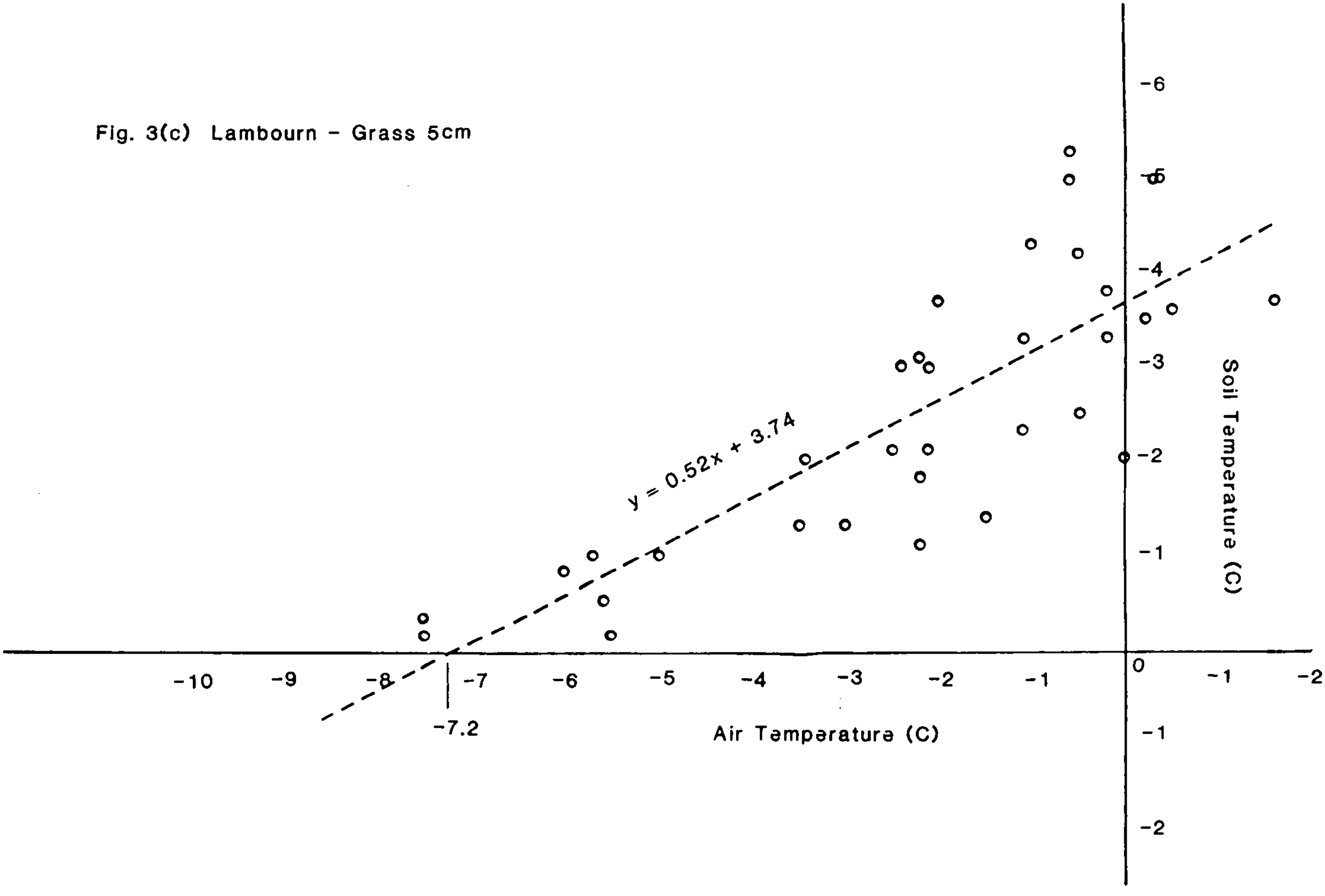


Fig. 3(d) Lambourn - Grass 7.5cm

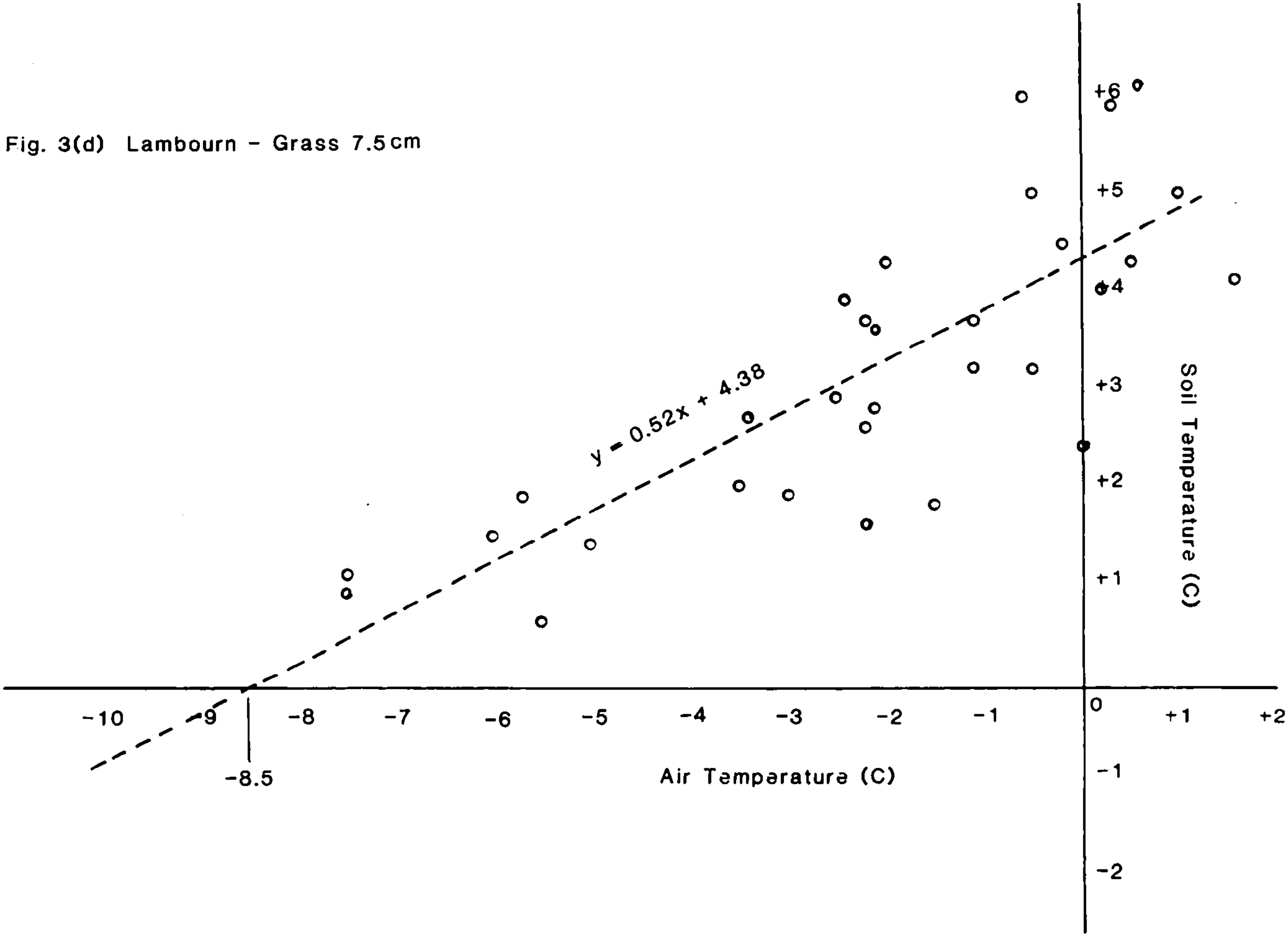


Fig. 3(a) Lambourn - Grass 10 cm

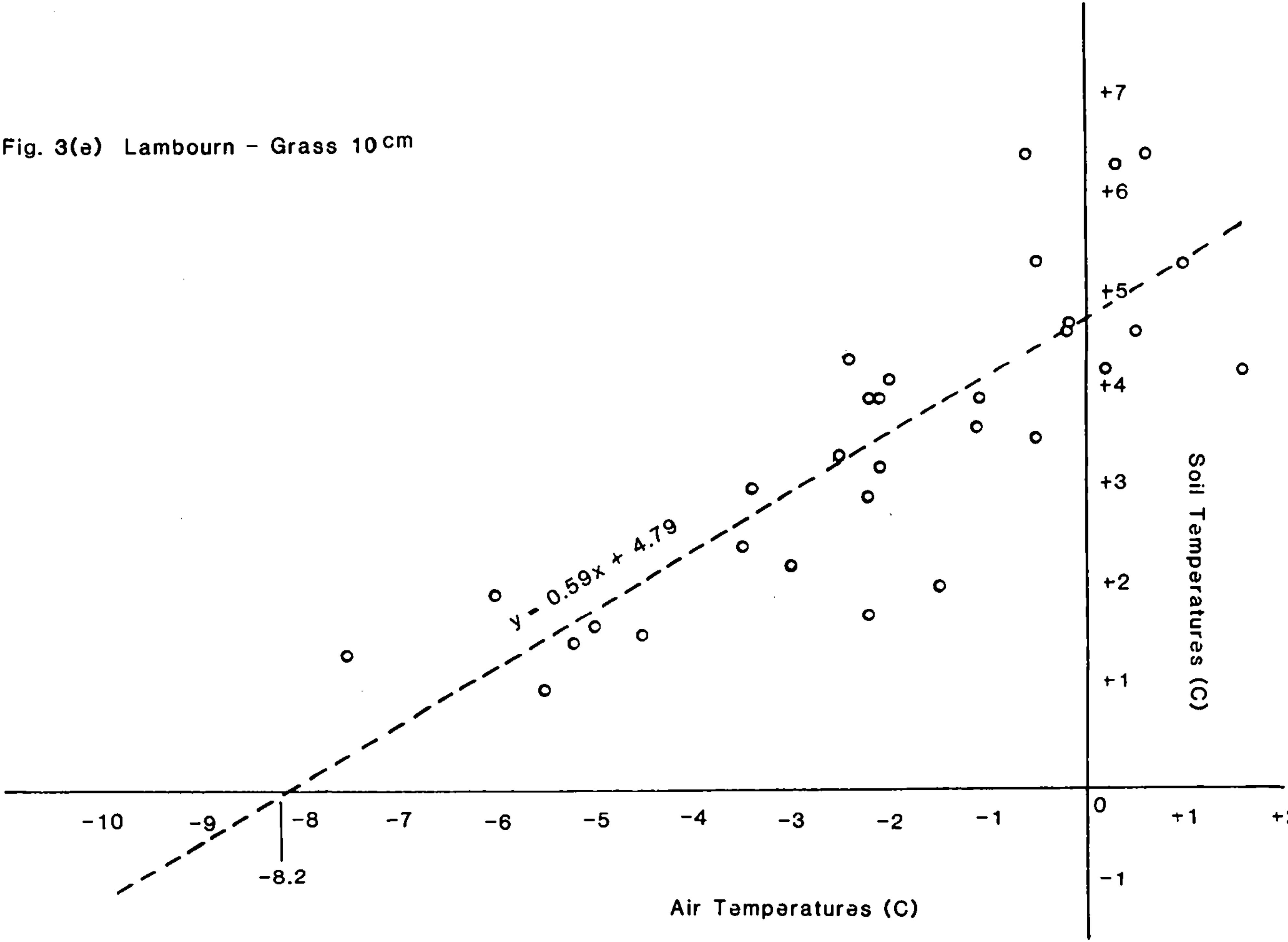


Fig. 4(a) Lackam - Grass 1cm

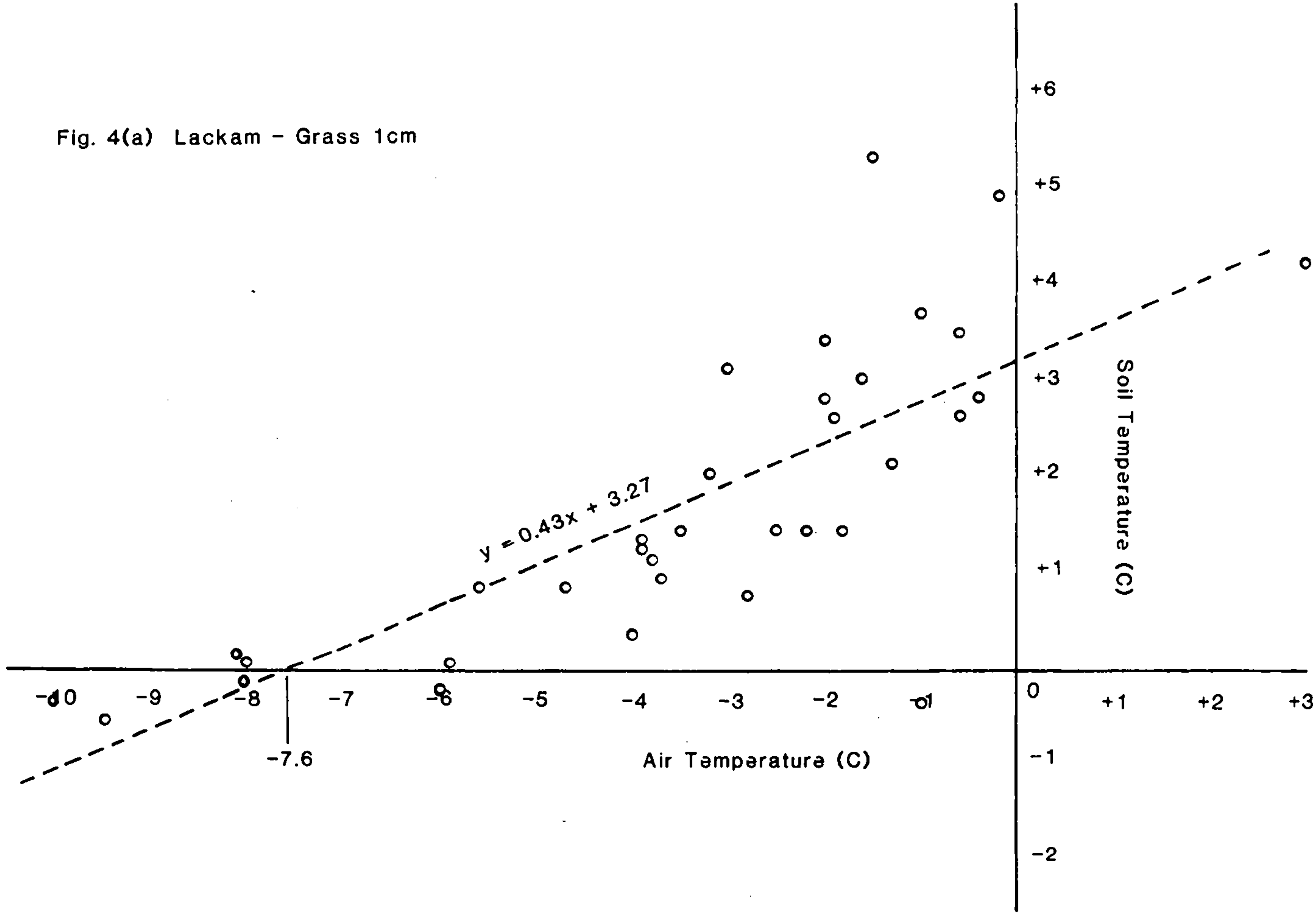


Fig. 4(b) Lackam - Grass 5cm

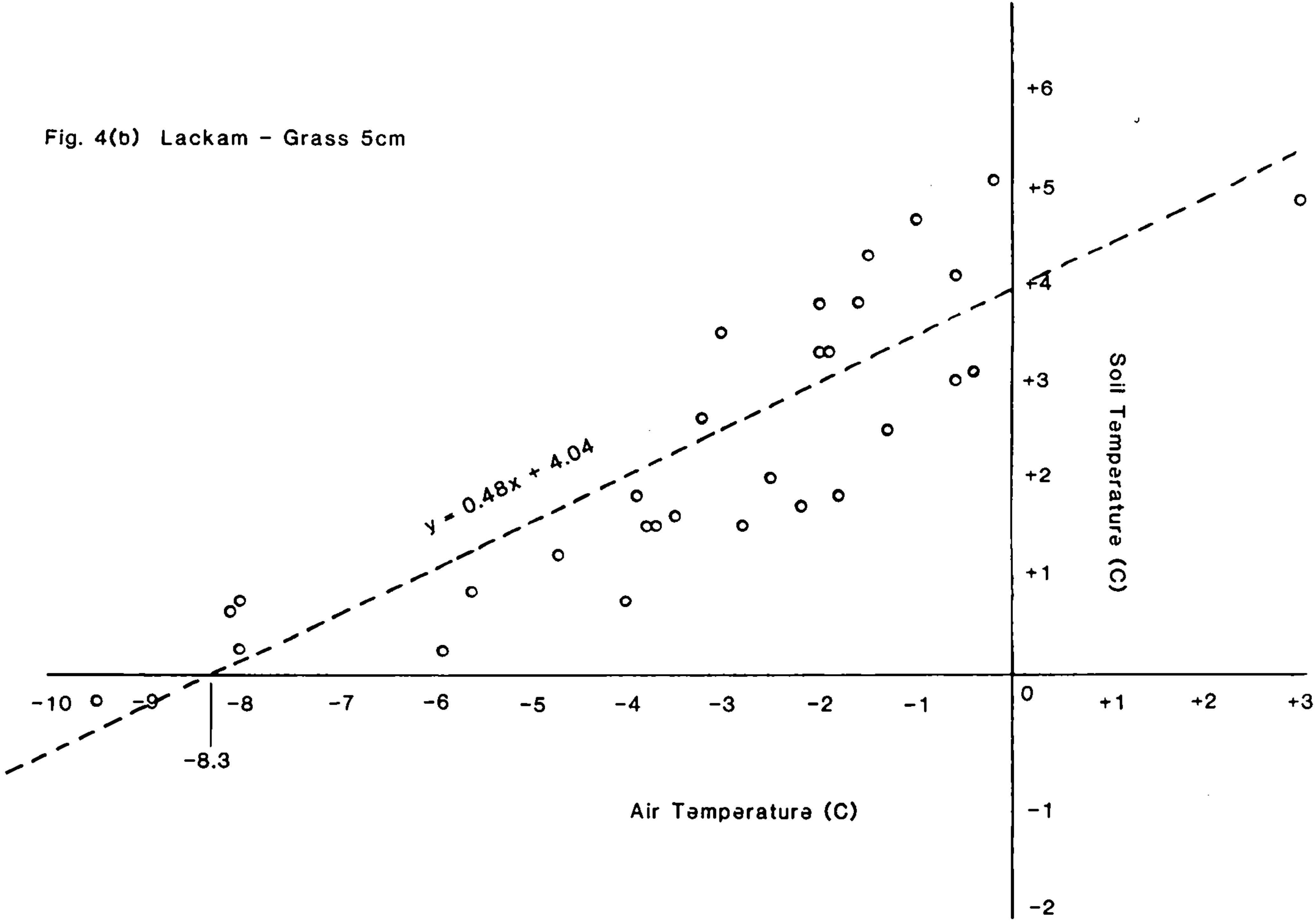
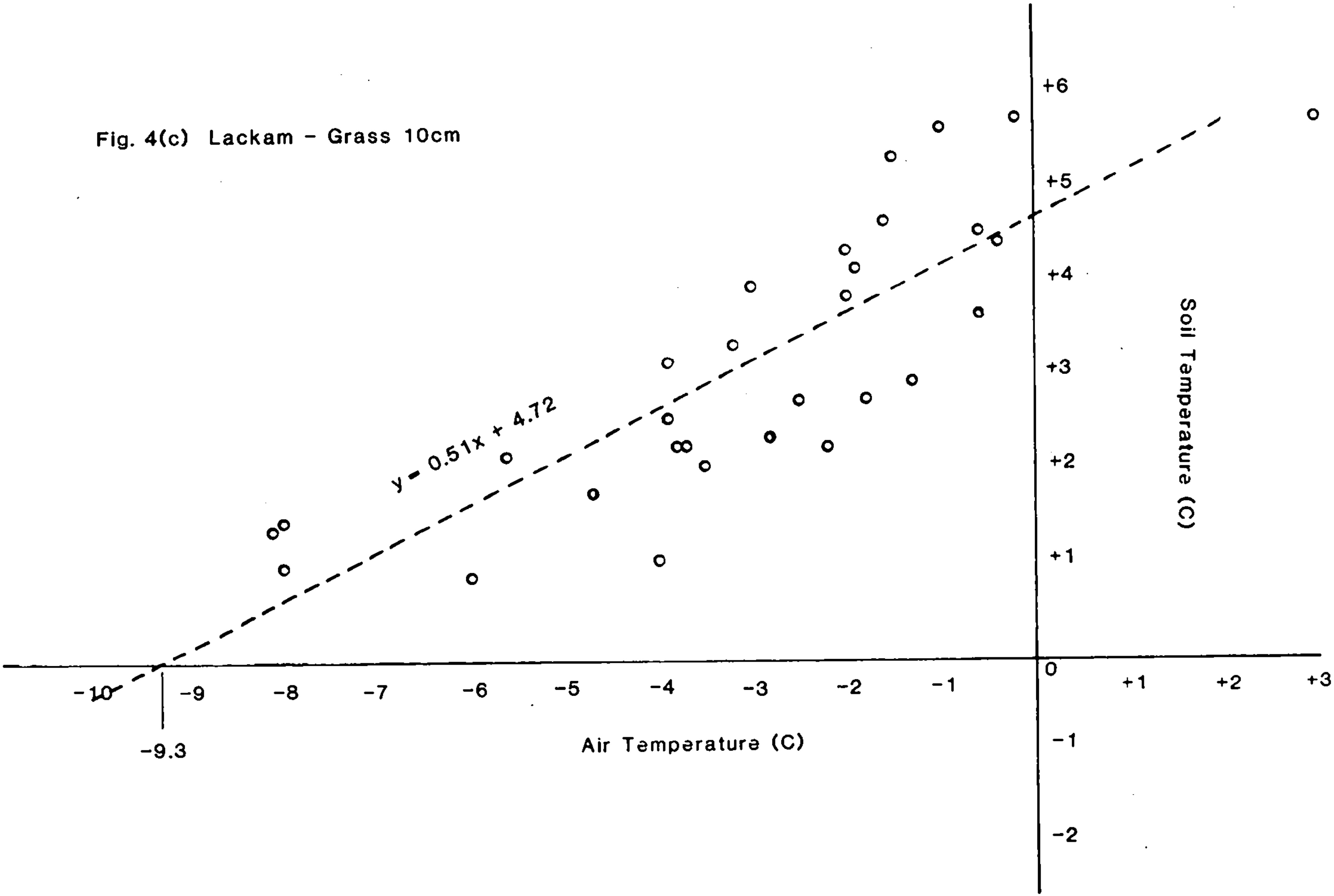


Fig. 4(c) Lackam - Grass 10cm



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