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TITLE OF THESIS. The Relationship Between Soil Temperature and the Plant Cover of a Lichen Dominated Raised Beach System in Subarctic Ontario.

UNIVERSITY. McMaster

DEGREE FOR WHICH THESIS WAS PRESENTED. M.Sc.

YEAR THIS DEGREE GRANTED. 1975

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PERMANENT ADDRESS:

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Thornhill

DATED. April 22, 1975

NL-91 (10-68)

THE RELATIONSHIP BETWEEN SOIL TEMPERATURE AND THE PLANT COVER OF A LICHEN DOMINATED RAISED BEACH SYSTEM IN SUBARCTIC ONTARIO

THE RELATIONSHIP BETWEEN SOIL TEMPERATURE AND THE PLANT COVER OF A LICHEN DOMINATED RAISED BEACH SYSTEM IN SUBARCTIC ONTARIO

By

CAMERON ALEXANDER McGREGOR B.Sc.

A Thesis

Submitted to the School of Graduate Studies

in Partial Fulfilment of the Requirements

for the Degree

Master of Science

McMaster University

May 1975

MASTER OF SCIENCE (1975).

MCMASTER UNIVERSITY
Hamilton, Ontario

TITLE: The Relationship between Soil Temperature and the Plant Cover of a Lichen-Dominated Raised Beach System in Subarctic Ontario

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NUMBER OF PAGES: xi, 155

ABSTRACT

Soil temperature measurements were made under different plant covers to the base of the rooting zone of the raised beaches of the Hudson Bay coastal tundra region to determine the relationship between plant cover and the soil thermal regime. Two methods of description were used for quantitative comparison of temperature; 1) linear regression of daily averages and Fourier amplitudes over the field season to determine near-surface differences in energy entering the soil under different plant covers and 2) a soil temperature model was constructed to separate physical influences over soil temperature from that of the plant cover. It was found that plant density had some control over the amount of energy transferred to the soil, causing a maximum difference of 7°C in the upper layers between different plant covers. From the modelling process it was found that the humus layer had essentially no effect in the transfer of energy throughout the rooting zone during the summer months and it was postulated that the observed difference in soil temperature between sites of different plant cover was due to a differential rate of spring thaw caused by the different thickness of humus between sites.

ACKNOWLEDGEMENTS

I take pleasure in expressing my thanks to several people whose assistance was of great importance to the study.

I would like to thank Dr. K.A.Kershaw, my project supervisor, for his enthusiastic advice and encouragement both in the field and in the laboratory. Also, my thanks to Dr. W.R.Rouse and Dr. R.A.Morton for their useful comments on the literature and the structure of the thesis as well as Miss Jocelyn Voortman who spent exhaustive hours typing the manuscript.

Special thanks go to Chuck Konsky, who ably assisted in the field, as well as the members of the lab for a stimulating work environment.

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LIST OF SYMBOLS

Symbols	Description	Units
A_k	amplitude of the Kth harmonic of the Fourier series	^oC
a	the thermal diffusivity	cm^2/hr
C	the heat capacity	cal/cm^3
G	the soil heat flux	cal/cm^2hr
G_o	the ground heat flux	cal/cm^2hr
H	the sensible heat flux	cal/cm^2hr
$I\downarrow$	the incoming longwave flux	cal/cm^2hr
$I\uparrow$	the outgoing longwave flux	cal/cm^2hr
LE	the latent heat flux	cal/cm^2hr
Q	the direct short wave radiation flux	cal/cm^2hr
q	the diffuse shortwave radiation flux	cal/cm^2hr
R_n	the net radiation flux	cal/cm^2hr
T	temperature	^oC
T_{av}	average temperature over 24 hr.	^oC
t	time	hr
x_m	volume fraction of mineral material in the soil column	
x_o	volume fraction of organic material in the soil column	
x_w	volume fraction of water in the soil column	
z	soil depth	cm
α	albedo	
λ	the thermal conductivity	$cal/cm\ hr^oC$

w	The angular frequency	radians (r)
θ	a positive constant between 0 and 1	
θ_k	the phase angle of the Kth harmonic of the Fourier series	radians (r)

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Section I

INTRODUCTION

Soil temperature, both near the soil surface and throughout the rooting depth zone, is an important factor in the growth of the low prostrate plants which occupy the coastal tundra zone of the Hudson Bay Lowlands. Metabolism of the aerial shoots and leaves is strongly influenced by the near surface temperature while throughout the rooting depth zone, temperature, coupled with soil moisture flow, controls the rate of root metabolism and nutrient uptake.

In studies of the interaction of soil temperature and plant cover, the major concern has been the effect of temperature on the growth of a single plant species, usually of agricultural application; however, to some extent plants can influence the amount of energy reaching the soil surface and the resultant temperature fluctuation throughout the soil profile, so that, in effect, the plant has some control over its physical environment.

Restriction to a single plant species is clearly not practical in the study of a natural system where many species usually compose the plant cover. By segregating species into naturally occurring plant associations it is possible to estimate their influence over soil temperature and it is this empirical description which is the objective of my thesis. The objective is dependent on a relatively homogeneous soil so that physical and plant controlled changes in soil temperature can be easily separated; a situation which will be demonstrated for the Pen Island Site.

(1.2) The Research Area

The research area for the study was located on a fan-shaped series of beach ridges opposite East Pen Island in northwestern Ontario (56°46'N, 88° 46'W) along the southwestern coast of Hudson Bay. The beach ridge series is one of many which occur along the coast from Churchill to Cape Henrietta Maria and for approximately 250 km inland. The area is still undergoing isostatic uplift from the Wisconsin Ice Age and is at present rising at approximately .9 m/century (Weber et al, 1970) which implies that distance from the coast is also a relative measure of chronological age. The coastal tundra zone is composed of the beach ridge series interspersed with muskeg, palsa mounds and other permafrost features and extends from the coast to the treeline which occurs approximately 8 km inland. The ridges are composed of sand with a variable gravel component, overlain by an organic layer, and rise from 1 to several meters above the general lay of the land which slopes to the bay. Ridge crests are lichen dominated (Kershaw, 1973) grading into grass and sedge covered swales (Kershaw, 1974). The entire area is underlain by continuous permafrost (Brown, 1966) which occurs at various depths in the soil depending on soil thermal properties as well as the summer weather conditions. By the selection of beach ridges which are progressively more distant from the coast, not only can a good contrast in vegetation type be provided but it is also possible to determine the influence of factors, such as humus accumulation, on the physical environment of the plant and the consequent change of environment from the coast to near the treeline.

With this in mind, three beach ridges at varying distances from the coast were selected for intensive study (Fig. 1). The front site (1), 1.5 km from the coast, had a complete absence of tree cover while the middle site (2)

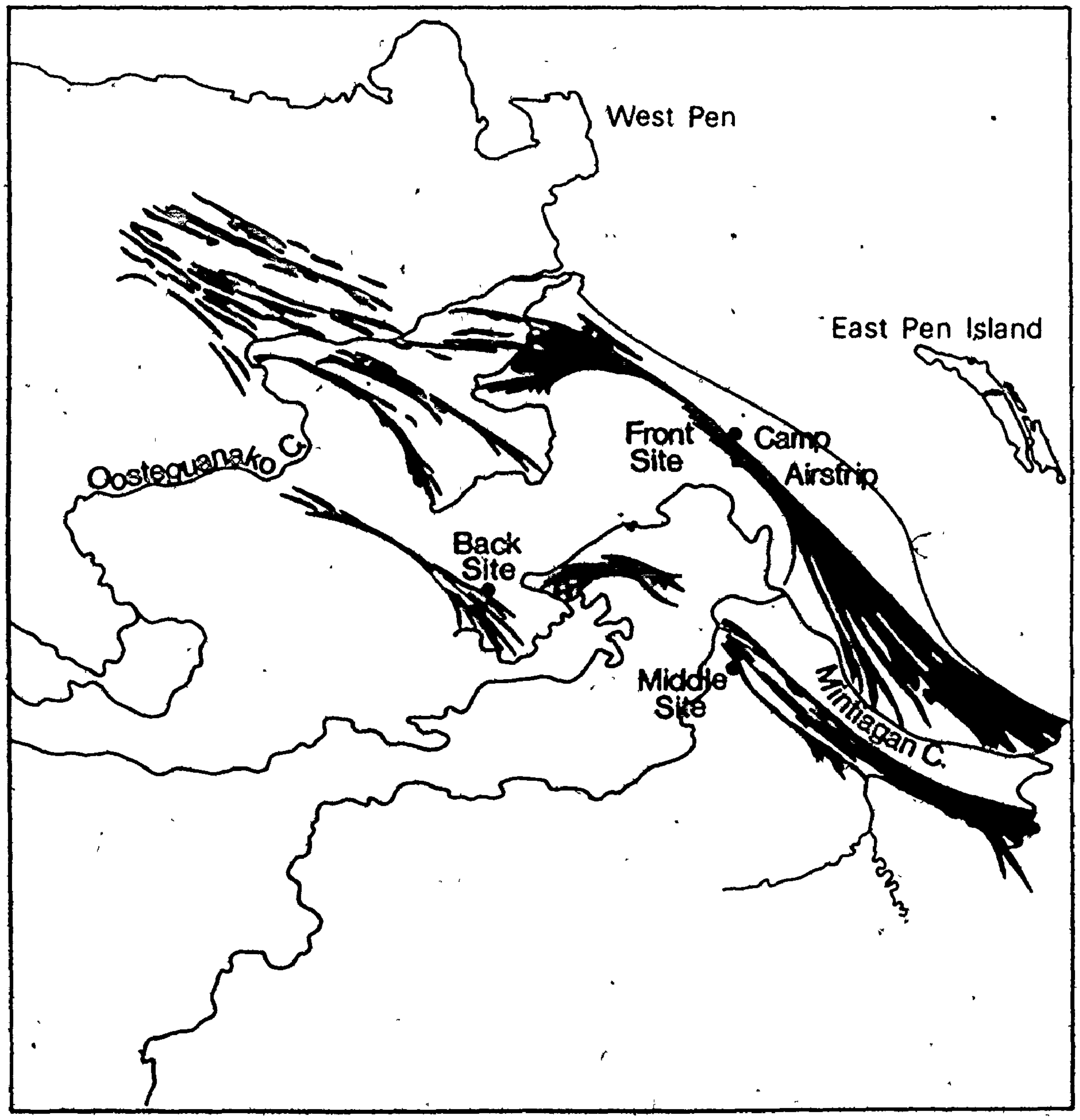


Figure 1. Site Location Map

3 km from the coast, and the back site (3), 4.5 km from the coast, had a sparse cover of Picea mariana. In all cases the flat open ridge crest was selected to eliminate radiation differences due to slope, aspect, or shielding by trees. Two plant associations were evident for each site giving a total of six associations for comparison.

(1.3) Statement of the Problem

To attain the objective of the study, it is necessary to separate changes in the physical factors influencing the soil temperature from the changes in the vegetation. In the next section, those physical differences of importance, such as humus depth and soil moisture, along with the vegetation differences between sites will be presented. Subsequently, in the Theory section (Section III) the relationship of these factors to soil temperature will be divided into two parts; those influencing the above surface transfer of energy to the soil surface and those involved in the relationship of that energy to soil temperature.

By assuming those relationships developed in the Theory section, it is possible to estimate the plant influence over soil temperature. Analysis of the near surface temperatures (Section IV), where all physical factors can be assumed constant and where the largest difference in soil temperature due to plant factors may be expected to occur, will be composed of three parts; 1) a graphical presentation of daily averages to illustrate seasonal differences between associations and profile graphs to illustrate temperature differences in the lower levels of the rooting depth zone, 2) a linear regression analysis of daily averages to quantize differences under changing incoming energy conditions and 3) a linear regression of Fourier amplitudes, which act as a measure of diurnal temperature fluctuation, to determine daily differences over the field season.

In the lower levels of the rooting zone, there is an obvious difference on a physical basis between sites. By the assumption of conduction as the relationship between energy flow and soil temperature and by testing the assumption by the prediction of soil temperature (Section V) it is possible to separate those physical factors influencing the soil temperature from those originating in the plant layer. Conclusions from the soil temperature model (Section V) coupled with those of the descriptive analysis (Section IV) provide the essential components of the relationship of plant association to soil physical environment at the Pen Island Site (Section VI).

Section II

A SITE DESCRIPTION

Separation of plant and physical influence over soil temperature is based on an exact determination of differences in physical factors between sites since humus depth, soil moisture and sand grain size can have appreciable effects on the distribution of heat in the rooting depth zone regardless of the plant cover. Differences in those factors which are important in the Pen Island area will be described in this section and their relationship to soil temperature will be established in the next (Section III).

Each of the three sites (Fig. 1) was chosen to include two contrasting plant associations which were assessed subjectively (Table 1). Recorders for the monitoring of soil temperature were placed two to a site (refered in the tables as recorders a & b) with four profile rods per recorder for the measurement of soil temperature throughout the rooting zone. Four rods were used for each association on each ridge site except for the front ridge where there were only two. Methods for the measurement of soil temperature are contained in Section IV.

(2.2) Methods

1) Vegetation Sampling and Microtopography

A ten foot quadrat was placed around each recorder to include all four rods. The square was gridded into 100 sq. ft. quadrats and microtopography measurements were averaged for each quadrat to give a mean relative height. Vegetation cover was determined for each quadrat using a pin frame of 10 pins.

TABLE 1

SITE AND VEGETATION DESCRIPTION

Site	Location	Number of Recorders	Mnemonic**	Associations*
1	Front ridge 1 km from the coast	1	A D	Arctostaphylos rubra Dryas integrifolia - Alectoria ochroleuca
2	Middle ridge 3.5 km from the coast	2	D R	Dryas integrifolia - Alectoria ochroleuca Rhododendron lapponicum - Alectoria nitidula
3	Back ridge 4.5 km from the coast	2	R C	Rhododendron lapponicum - Alectoria ochroleuca Cladina alpestris

* Associations are determined by dominant species only

** The mnemonic is used for quick reference to association in the Tables and in the text.

For inter-ridge comparison, the cover data was averaged for each recorder and standardized to a total cover of 100% (Table 2). Any species with less than 5% standardized cover was regarded as having little influence over the energy regime and not included in the table.

2) Albedo, Humus depth, and Permafrost

Albedo, or the reflectivity of the surface, was measured once per site, for an all day period, on nearly consecutive days with no cloud cover. Measurements were made of incoming and outgoing shortwave radiation (Sellers, 1965) (.2-3.0μ) using an Eppley 48 junction pyrradiometer for each hour from 10 am to 5 pm Eastern Daylight Time (EDT). The albedo was calculated as the ratio of the outgoing to incoming global and averages of three readings about the solar noon (1.00 EDT) were made for each site, since differences were greatest for this time period (Table 3).

Humus depth was determined for each profile rod by an average of eight measurements around the rod and are listed according to site and rod (Table 4).

Permafrost measurements were made at the beginning and end of the summer using an iron bar (Table 3).

3) Soil Moisture

Soil moisture was measured by the neutron moderation technique (Long & French, 1967) using a Nuclear Chicago neutron probe. Access tubes, stoppered at the top and sealed at the bottom to prevent moisture seepage, were inserted in tight fitting holes augured to the 100 cm level or the permafrost, whichever was reached first. Measurements at the 20-100 cm levels in the soil were made in 10 cm increments using a depth probe while surface moisture measurements were made at ten different locations in a 20' radius and averaged. For the surface measurements the vegetation was carefully removed before each reading to ensure a close fit between the surface and the probe, and then replaced.

Slow neutron counts were made using a Nuclear Chicago scalar with a recording interval of ½ minute. Readings were converted to percent soil moisture by volume using a calibration factor determined from sandy soils at Simcoe, Ont. (Rouse and Wilson, 1972). Measurements for each recorder were taken approximately every four days and graphed for each level and recorder in Figures 2a & b, for the field season.

4) Particle Size Analysis

Soil samples were gathered at various depths within the soil profile, adjacent to the neutron access tube of each recorder in 2 lb. sampling cans. Because of this relatively crude method of gathering undisturbed samples, volume fraction determinations of the solid material were made using Archimedes principle of water displacement and were restricted to the first decimal place in accuracy.

A particle size determination was made at the following sieve sizes using Canadian standard sieves of 2.0 mm, .5 mm, .05 mm with sieving times of approximately 20 minutes.

(2.3) Results

1) Vegetation and Microtopography

Of the vascular plants, only *Dryas integrifolia* was present in high abundance throughout all three sites, with a decreasing cover from the front to the back ridge (Table 2). The only other abundant vascular species of the front site were *Hedysarum mackenzii* and *Arctostaphylos rubra*. Both

TABLE 2

COMPARISON OF PLANT COVER BETWEEN SITES*

	Site 1		Site 2		Site 3	
Species	a (%)	b (%)	a (%)	b (%)	a (%)	b (%)
Vascular						
Arctostaphylos rubra	11.1	7.7				
Dryas integrifolia	20.5	38.1	18.5	11.7	7.2	8.5
Hedysarum mackenzii	15.3	.3	3.2	.1		
Vaccinium uliginosum			2.7	5.8	8.0	6.9
Rhododendron lapponicum			5.6	3.3	6.2	1.5
Empetrum hermaphroditum			.4		5.4	8.3
Total vascular	48.9	46.1	30.3	21.0	26.8	25.3
Lichens						
Alectoria ochroleuca	30.1	29.1	26.2	25.8	12.7	17.8
Cetraria islandica	8.7	2.8		.9	2.0	2.1
Cetraria nivalis	4.0	5.3	11.7	6.3	12.8	9.9
Alectoria nitidula			27.4	27.1	1.3	1.3
Cladina alpestris			2.5	9.7	32.1	31.6
Total Lichens	42.8	37.2	67.8	69.8	61.0	62.8
Total of significant species	89.7	83.2	98.1	90.8	87.7	88.0
Vascular/Lichen ratio	1.1	1.2	.3	.3	.3	.3

*Standardized to 100% of total plant cover for each site.

these species characterize the front site although H. mackenzii occurs in small quantities at the middle ridge.

Vascular species common to the middle and back sites but absent from the front ridge are; Rhododendron lapponicum and Vaccinium vitis-idaea, neither of which show any marked preference for either ridge. Empetrum hermaphroditum, although found in the middle site is abundant only on the back site.

For both middle and back sites the ratio of vascular plant cover to lichen is small with a cover ratio of .3. This compares with a ratio of 1.2 for the front ridge site and effectively summarizes the major vegetation distinction between the front and back two ridges.

Of the lichen cover, Alectoria ochroleuca is the most constant of the lichen species with a high percentage of the total plant cover, decreasing in importance only at the back site. Cetraria nivalis shows the reverse trend increasing in percentage cover towards the back ridge.

The major distinction between the front and middle ridges is the presence of Alectoria nitidula. Although absent on the front ridge, it comprises over 25% of the total cover of the middle ridge but again decreases to low cover in the back site.

Cladina alpestris, present in the middle ridge with a relatively low cover in comparison with Alectoria ochroleuca and Alectoria nitidula is the dominant plant species of the back site with a cover average of over 30% and characterizes this particular ridge crest.

In summary, the front ridge is characterized by a high vascular plant to lichen ratio as well as th presence of A. rubra. The middle ridge is characterized by a high cover of A. nitidula and the back ridge by a high cover of C. alpestris.

The maximum microtopographic variation occurred on the front ridge while the back two sites were roughly comparable. There was no significant correlation between microtopography and species distribution at any site, effectively removing this variable from further consideration. Slope differences from the front to the back of each site were also negligible.

2) Albedo, Humus Depth, and Permafrost

Albedo determinations, averaged over the highest insolation period, showed a similarity between middle and back ridges of .14 and .15 for the middle and back ridges respectively. The front ridge had a slightly higher albedo of .18 for this time period.

The largest difference of humus depth occurred between the front and the back two sites with a difference of as much as 3.5 cm. The middle site had a slightly greater humus depth than the back ridge which was unexpected from the relative distance of the middle and back ridges from the coastline. The duff component varies a maximum of 1 cm for all sites.

There was a difference in the permafrost level at all three sites. At the beginning of the summer the permafrost was closest to the soil surface at the back ridge. The middle site was 16 cm below the back site and the front site, 92 cm below the back site. The rate of decrease over the summer was approximately the same for the middle and back sites and could not be estimated for the front site.

3) Soil Moisture

The back and middle ridges showed a similar surface water content of 13 percent by volume while the front site was slightly drier at 9%. (Fig. 2a). All sites had a similar moisture profile from the 20 to 70 cm levels, although

TABLE 3

Permafrost Depths, Albedo, and Microtopography

Site	Permafrost (cm below surface) Start[1]	Finish[2]	Albedo	Slope (m/m)
1a	≈160	below 200	.18	.01
1b				.01
2a	84	162	.14	.03
2b				.02
3a	68	147	.15	.01
3b				.01

1 Start of the field season
2 Finish of the field season

TABLE 4

A COMPARISON OF THE THICKNESS OF HUMUS AND DUFF LAYERS BETWEEN SITES (cm)

Site 1

	D1	A2	D1	D2
Humus	.5	.5	1.4	1.1
Duff	1.1	.9	1.2	.4

Site 2a

	D1	D2	R1	R2
Humus	3.9	3.3	3.6	3.7
Duff	2.6	1.0	1.8	2.0

Site 2b

	D1	D2	R1	R2
Humus	4.8	3.8	4.8	4.5
Duff	2.0	2.5	2.1	2.1

Site 3a

	C1	C2	R1	R2
Humus	2.1	2.4	2.7	1.6
Duff	1.0	1.1	1.9	1.9

Site 3b

	C1	C2	R1	R2
Humus	3.4	3.0	4.0	5.1
Duff	1.1	1.5	1.4	1.8

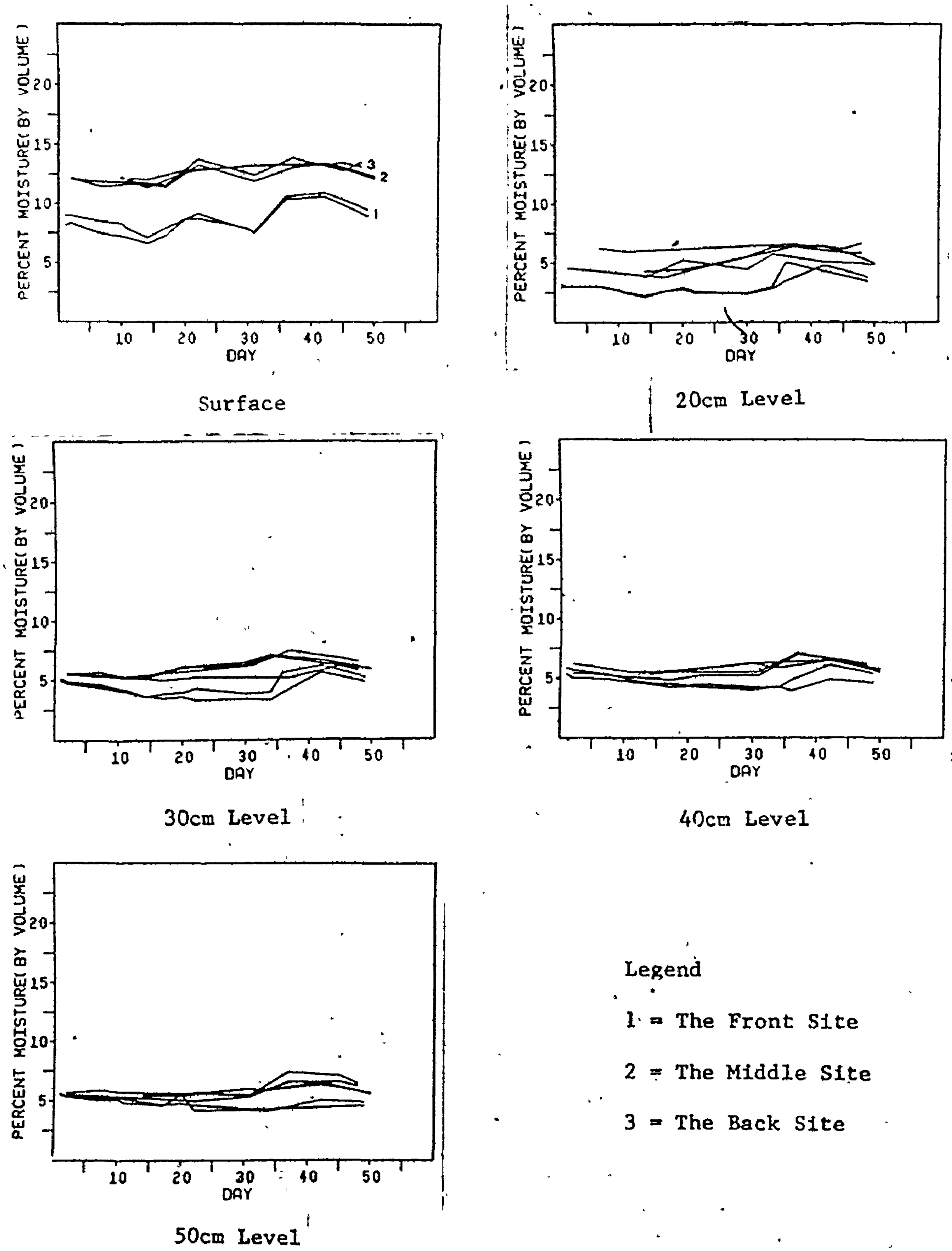


Figure 2a. Soil Moisture Measurements over the Field Season: The Surface to 50cm Levels

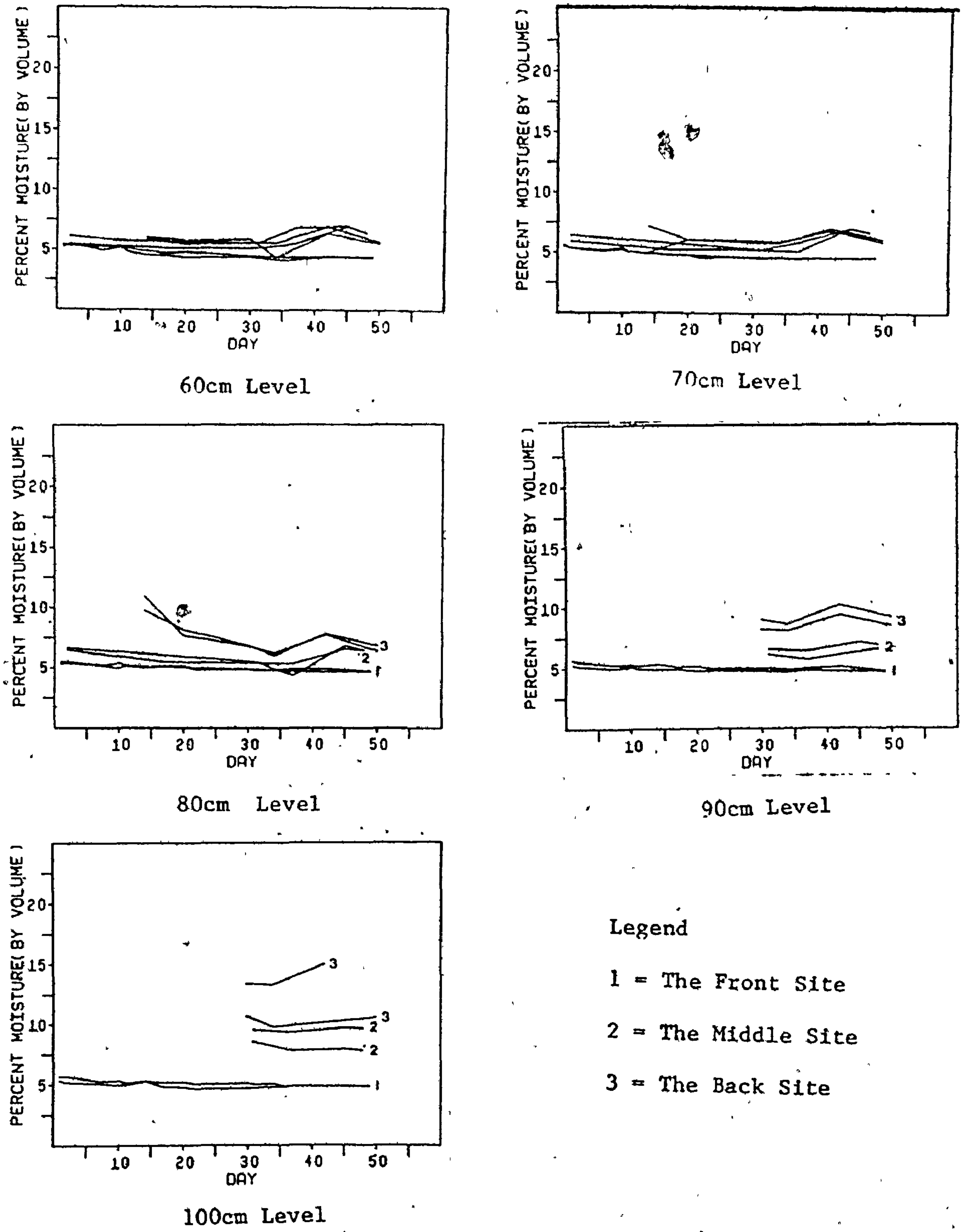


Figure 2b. Soil Moisture Measurements over the Field Season:

The 60cm to 100cm Levels

the front ridge was always 1% drier.

At 80- 100 cm, (Fig. 2b) soil moisture contents diverged according to site. The front site clearly is much drier than the other two sites with soil moisture of 6% at the 100 cm level and an almost linear soil moisture profile from the surface down to the 100 cm level throughout the study period. Soil moisture at site 2 averages 9% at the 100 cm level, 2% higher then measurements up to the 70 cm level and the back site show a large increase in soil moisture of 10-13% at the 100 cm level.

This difference in soil moisture at the lower levels in the soil profile is not due to a changing moisture characteristic since these have been shown to be constant over the research area for all levels including that of the 100 cm level (Rouse and Kershaw, 1973). Rather, the difference is due to the different permafrost levels at each site. In the back ridge the permafrost is 20 cm closer to the surface than the middle site and at least 80 cm closer than the front site. Permafrost is impenetrable to water and acts as the base of the water table, thus raising the table of the back site compared with that of the middle or front and accounts for the different soil moisture at measured levels.

This difference occurs below the bottom level of temperature measurement and since moisture near the surface is correlated with the depth of the organic layer (Rouse and Kershaw, 1973), there is little moisture variation between sites except with humus depth, during the field season.

4) Particle Size Analysis

A soil particle size analysis showed a slight variation in the gravel component (> 2.0 mm) of the mineral soil material between sites and between different levels of the same site. The quantities of coarse and medium sands were approximately equal in both the surface and subsurface layers of the two back ridges while the front site had an increased proportion of medium sand at all levels. The amount of fine sand at all sites was negligible.

TABLE 5

SOIL PARTICLE SIZE ANALYSIS

Site	Level (cm)	Gravel (> 2.0 mm)	Coarse Sand (2.0-.5 mm)	Medium Sand (.5-.05 mm)	Fine Sand (< .05)
1a	S	.08	.13	.79	.003
1a	40	.26	.15	.59	.009
1b	40	.52	.16	.28	.002
1a	60	.17	.20	.60	.03
2a	S	.24	.38	.37	.009
2a	40	.61	.20	.19	.002
2b	40	.47	.27	.26	.002
2b	80	.13	.30	.58	.001
3a	S	.45	.26	.28	.005
3b	40	.32	.33	.35	.003
3b	80	.57	.16	.28	.001

Sand Fraction

Bulk Density = 1.90

Volume fraction = .7

(2.4) Summary

Vegetation differences are clear cut between sites. The front ridge is characterized by its low lichen to vascular plant ratio as well as the occurrence of Arctostaphylos rubra. The back two ridges differ in the high level of abundance, of Alectoria nitidula on the middle ridge and Cladina alpestris on the back ridge.

There is also a clear cut difference between the front and back two ridges on the basis of humus, permafrost depth, albedo and soil moisture; however, the only distinctions between the middle and back ridges are on the basis of permafrost depth and soil moisture.

Section III

THEORY

The relationship between those factors, which were measured in the last section, and soil temperature can be divided into two parts; 1) Above surface factors which affect the transmission of energy to the soil and 2) those factors which affect the distribution of that energy in the soil profile. By establishing these two components it is possible to separate the influence of plant cover over soil temperature from physical differences between sites.

(3.2) Energy Transfer to the Soil Surface

1) The Radiation Balance

The source of energy for all natural processes is the sun, and any site to site comparison of plant cover must take into account differences in the radiation flux due to plant-independent factors. The radiant energy flow at the soil surface can be split into the following components (Sellers, 1965).

$$R_n = (Q + q)\ (1-\alpha) + I\downarrow - I\uparrow \qquad (cal/cm^2 sec) \qquad (1)$$

where

R_n = the net radiation flux

Q = the direct solar radiation (.3-3.0μ) incident on the earth surface

q = the diffuse solar radiation

α = the albedo

$I\downarrow$ = the incoming longwave radiation (3.0-100.u)

$I\uparrow$ = the outgoing longwave radiation

i) The Short Wave Flux

Differences in the incoming short wave flux, $Q + q$, between sites are dependent only on cloud cover for the coastal tundra zone. In the study area, cloud differences between sites average out during the diurnal cycle but on a shorter time interval may cause some differences in the energy transmitted to the soil therefore for the purposes of this study it is necessary to make an inter-site comparison with daily representative data.

ii) Albedo

Albedo can be defined as the reflectivity of the earth surface to shortwave radiation and is a function of the angle of incidence of the radiation and the reflective characteristics of the surface. Since reflective characteristics are largely a function of plant cover, in this instance only the angle of incidence need be kept constant between sites and this is achieved by restricting the site to the flat ridge crest.

iii) The Long Wave Flux

The net long wave flux $(I\downarrow - I\uparrow)$ is composed of an incoming and outgoing component. On a diurnal basis the incoming component is relatively invariant in a site to site comparison but the outgoing component, because of the dependence of the long wave flux on the Stephan-Boltzmannlaw (Sellers, 1965), is determined by the surface temperature and may vary from site to site. This difference in surface temperature is ultimately a result of the amount of energy transmitted to the soil surface and the thermal characteristics of the underlying soil, and, as such, is included within the objectives of the study.

By calculation of the maximum difference in the outgoing longwave flux between sites it was determined that these differences were only a small portion of the net radiation flux over a day which, in effect, implies that the critical factor influencing the net radiation flux at each site is the reflective characteristics of the plant surface.

2) The Energy Balance

The partitioning of the net radiation at the earth surface is governed by the general energy balance equation (Sellers, 1965) in which

$$R_n = H + LE + G_o \qquad (\text{cal/cm}^2\text{hr}) \qquad (2)$$

where

R_n = the net radiation flux

H = the sensible heat flux

LE = the latent heat flux

G_o = the ground heat flux

An expression of the changes in G_o, the amount of energy entering the soil under different plant covers, is one of the objectives of this study and will be discussed in the next subsection (3).

The fluxes of the equation have been studied in the Pen Island research area (Rouse and Stewart, 1973) and, by a modification of the Slatyer-McIlroy equilibrium model (Slatyer and McIlroy, 1961) the latent heat flow has been predicted by a combination of net radiation, ground heat flux and screen height temperature measurements. The prediction accounted for 91% of the measured latent heat flux and implies that water availability at the surface is not an important consideration in the study area, as is usually the case.

By applying the model on geographically separate areas as well as the same area for two summers, it was shown to accurately predict the latent heat flux for all ridge crest sites. Since screen height temperatures do not deviate significantly over the study area, changes in the latent heat flux in a site to site comparison will be a function of net radiation and ground heat flux only. For a study of differences in ground heat flux, this implies that the major concern is differences in the net radiation term which, as long as aspect and slope are controlled, reduces to differences in the reflective characteristics of the surface for the field season.

By restricting the discussion to the field season, differences in albedo due to changes in the reflective surface by an agent other than plant cover, eg. snow cover, have been ignored. If one site is covered by snow for a longer period during the spring melt than another, this could make a difference in the temperatures of the rooting zone even though soil thermal characteristics and the energy transferred to the soil surface were the same throughout the field season. This factor can only be qualitatively treated in the thesis since it could not be measured or controlled.

(3.3) Energy Flow in Soils and Soil Temperature

1) Mechanisms of Heat Transfer

Flow of energy in soils is predominantly by the mechanism of heat conduction and forms the relationship between soil temperature and the ground heat flux; however, other modes of energy transfer such as radiation, convection and chemical heat transfer also occur and can become critical considerations in many soils.

Radiation transfer is unimportant in all soils since it occurs only in the first few millimeters. Convectional heat transfer by the movement of water through the soil after rainstorms or under strong thermal gradients can be important because of the high heat capacity of water; however, redistribution of water under thermal gradients is negligible in coarse sandy soils (deVries, 1966), such as those which occur at Pen Island, and convection heat transfer after rainfall occurs only for a short period of time in the rooting zone because of the high hydraulic conductivity of the beach ridges (Rouse and Kershaw, 1973).

Chemical heat transfer in soil occurs through the phase changes of water. The transfer of energy due to thawing and freezing is an important consideration in a continuous permafrost region such as the coastal tundra zone (Brown, 1966); however, since the permafrost lay below the rooting depth zone during the field season, its influence on the measurements of this study was small.

Heat transfer due to the evaporation and condensation of water vapour is reported to be of small concern in coarse textured soils such as occur at Pen Island, especially when they are below field capacity (deVries, 1966). Recent evidence in finer soils (Rose, 1968, Jackson et al, 1973 Wieranga et al, 1969 and Westcott and Wieranga, 1974) have indicated that vapour transfer out of the soil system may be an important consideration during peak temperature periods, ie. at noon. In soils corresponding to those at Pen Island (Nakano and Brown, 1972) some emphasis was placed on the importance of vapour transfer out of the organic layer so that vapour transfer may be of importance during the middle of the day in the field area. For the most part however, conduction may be considered as the mechanism of heat transfer in the Pen Island soils.

2) The Theory of Heat Conduction

At the soil surface, the heat flux through an infinitesimal depth dz. is given by

$$G_o = -\lambda \frac{\partial T}{\partial z} \qquad (\text{cal cm}^{-2}\text{hr}^{-1}) \tag{3}$$

where

G_o = the ground heat flux

λ = the thermal conductivity (cal cm^{-1} hr^{-1} $^oC^{-1}$)

∂T = the temperature increment

∂z = depth increment

and assumes that vertical transfer into the soil is the only direction of heat flow.

This can be generalized for any level in the soil regime such that:

$$G = -\lambda \frac{\partial T}{\partial z} \qquad (cal\ cm^{-2}hr^{-1}) \qquad (4)$$

where

G = the soil heat flux

If there is a change in the heat flux over a depth increment, dz then the change is equal to the amount of heat stored in the increment assuming heat transfer by conduction. This is given by:

$$C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(-\lambda \frac{\partial T}{\partial z}\right) \qquad (cal\ cm^{-3}hr^{-1}) \qquad (5)$$

where

C = the heat capacity (cal cm^{-3} $^oC^{-1}$)

The left hand side of the equation represents the amount of heat stored in the depth increment in a specified time increment, dt, and the right hand side is the change in the heat flux through the depth increment, dz. Small fluctuations in the heat capacity, C, and the thermal conductivity, λ, can be used to include small changes in heat transfer due to other transfer mechanisms.

If it can be further assumed that the thermal conductivity does not change over the depth increment, Equation 5 can be rewritten as:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial z^2} \qquad (cal\ cm^{-3}sec^{-1}) \qquad (6)$$

where

$a = \lambda/C$ = the thermal diffusivity

Equations 5 and 6 form the Fourier equations for heat conduction in one dimension.

The usefulness of Equation 3 to 6 is dependent on the accuracy to which each of the thermal properties of thermal conductivity, thermal diffusivity and heat capacity can be defined within the soil, so that a separate discussion of each is necessary.

i) The Heat Capacity

The amount of heat stored in a soil column is determined by the relative proportions of its soil, water, and air components. Because air has a small heat storage capacity (.0003 cal/cm^3) compared to that of soil and water, it can be neglected.

The heat capacity of the constituents which make up the soil material is the product of their specific heat and density. This is relatively invariant for both mineral and organic soil material (Kersten, 1949, deVries, 1966) and does not vary appreciably with temperature (Kersten, 1949), so that the following equation describes the heat capacity of any soil.

$$C = .46x_m + .60x_0 + x_w \quad (7)$$

where

x_m = the mineral volume fraction

x_o = the organic volume fraction

x_w = the water volume fraction

From this equation, increases in the volume fraction of water can significantly increase the heat capacity and emphasizes the importance of soil water measurement in this study.

ii) The Thermal Conductivity

Thermal conductivity cannot be accurately predicted by theoretical means so that a more empirical approach must be used. Temperature and density changes have only small effects (Kersten, 1949) the most significant factors being changes in soil moisture and soil constituents.

The effects of soil moisture changes are greatest in sands and silts when these are very dry as is the case at Pen Island. Changes as small as 5 volume percent in water content can double the value of the conductivity (Table 6) while similar changes in water content of organic soils such as peat, (Table 7) have only small effects (Kersten, 1949).

From these two examples it should be noted that there is a considerable difference in the conductivity of sand and peat. Since the peat classification is roughly comparable to humus, this establishes the importance of the humus layer in the distribution of heat energy to the lower levels.

Experimental determination of the thermal conductivity in the field (Janse and Borel, 1965) and in the laboratory (Kersten, 1949) must be made over relatively large depth increments in the soil so that small fluctuations are ignored. A more usual approach is made by the solution of Equation 5 for λ, using soil temperature values for selected periods of time (Carson, 1963). This is termed the apparent thermal conductivity.

iii) The Thermal Diffusivity

From Equation 6, the thermal diffusivity is the ratio of the thermal conductivity to the heat capacity. It defines the rate at which heat is passed through the soil column relative to the amount that is stored.

The change of thermal diffusivity with changing moisture content is much less than the corresponding change in thermal conductivity since both conductivity and heat capacity have a similar response to soil moisture. This

TABLE 6

THERMAL CONDUCTIVITY*
FAIRBANKS SAND

Percentage Volume of Water	Thermal conductivity (cal $cm^{-2}hr^{-1}$)
3	10.3
5	15.4
12	18.9
20	21.9

TABLE 7

THERMAL CONDUCTIVITY*
FAIRBANKS PEAT

Percentage Volume of Water	Thermal conductivity (cal $cm^{-2}hr^{-1}$)
3	.54
14	.79
25	1.19
38	2.16

* from Kersten, 1949.

makes the application of Equation 6 to the solution of the soil thermal properties easier than Equation 5 unless the relationship between conductivity and the soil moisture fluctuation is known.

(3.4) Summary

From the discussion of the energy transfer to the soil surface, it was established from the standpoint of the net radiation flux (Equation 1) and the energy balance (Equation 2), that the critical consideration was the change in the albedo due to differences in the reflective characteristics of the vegetation. Control of physical factors above the soil surface was achieved by locating on the flat ridge crests.

Within the soil it was assumed that heat conduction was the dominant mode of heat transfer although the relative influence of rainfall and vapour transfer could not be specified. By application of conduction theory to the prediction of soil temperature the relative importance of these modes of energy transfer can be ascertained.

From the discussion of the thermal conductivity it was shown to be sensitive to changes in the sand to peat components and to the fluctuations of soil moisture. This sensitivity can be reduced by using the thermal diffusivity in the modelling process.

Section IV

THE NEAR- SURFACE TEMPERATURE FLUCTUATION UNDER DIFFERENT VEGETATION COVERS

In any comparison of soil temperature under different plant covers, the largest differences should occur near the soil surface before the energy received at the surface is dissipated throughout the soil profile. For the three intensive study sites, near surface measurements were, for the most part, contained in the humus layer, so that it is reasonable to assume that thermal properties are the same for all sites in the upper levels. This implies that the differences in energy received at the soil surface and near-surface temperature are a function of the reflective characteristics of the plant cover alone.

The section will be divided into three parts: 1) field methods of soil temperature measurement,* 2) a graphical description of the seasonal temperature fluctuation and 3) the application of linear regression for a quantitative description of soil temperature fluctuation for the season.

(4.2) Methods of Soil Temperature Measurement

The nature of the terrain and the problems in travelling over it to sites several miles distant required that the equipment used for soil temperature measurement be automatic, able to withstand backpacking and, once in the field, be able to operate for long periods of time without servicing. For this purpose recorders made by Grant Co., Toft, Cambridge were used to record temperature fluctuations using thermistors manufactured specifically for these recorders by the same company.

Thermistors are ceramic semi conductors with a negative temperature coefficient proportional to square of the change in temperature and do not change their calibration characteristics appreciably over a year (Tanner, 1963). The thermistors used in this study were calibrated at the beginning and end of the field season and showed no change. Their response to a 10°C temperature change was 5 sec or 2°C/sec which is quite adequate for the conservative temperature changes found in soils.

The recorders, Grant model no. LT-4, required a small 5.4 V battery as an energy source and had an automatic time scanner for continuous ¼, ½, and 1 hour time intervals. This, combined with their light weight makes them ideal for field studies over large areas although they are somewhat sensitive to rough handling.

Current changes due to the temperature dependent resistance of the thermistors were measured by a light weight galvanometer. A stepping switch inside the recorder allowed a scan of a maximum of 28 signals in 3 minutes. Calibration of the galvanometer to maximum and minimum current from the battery was made by two variable resistors. Because of the temperature dependence of the battery current, which could not be controlled in the field, small errors in the recorded signal occurred throughout the measurement period.

The second order temperature response of the thermistor was linearized for three temperature ranges by resistors within the recorder. The temperature range from 0-20°C was used for this study.

Calibration at 4 temperatures; 0, 5, 10, and 15°C, were made using a Lauda K-2/R water bath and a calibrated platinum resistance thermometer. All probes consistently over or under predicted for all temperatures except that of one recorder where the temperature response near 0. was alinear with the rest of the calibration temperatures. Those recorders with a response of $.3^{o}C$ above or below the platinum resistance thermometer were corrected in the data assembly.

Because of the inaccuracies of this calibration procedure as well as the problem of calibrating the recorder in the field, accuracy can only be claimed to $\pm .3^{o}C$.

Two recorders were used per site, with four rods of six sensors each attached per recorder. Rods were made of 3/4 inch dowling and sensors were taped to lie at the 2, 5, 10, 15, 30 and 50 cm levels in the soil. Measurement took place on an hourly basis over a 51 day period starting at June 26 and ending August 15. Synchronization of the recording times between recorders could not be made since the timer device could not be set manually so that comparisons of associations were made for each recorder of the site.

Several problems were found in the data collection procedure resulting in the loss of data from one front ridge recorder for the entire field season and considerable portions of several others.

(4.3) <u>Graphical Description of Seasonal Soil Temperature Fluctuations</u>

1) Methods

The hourly data was averaged over a 24 hour period starting at 1.00 pm EDT for all days, rods and levels measured. Averages were calculated only if there were 6 or less missing values over a 24 hour period.

Averages were plotted according to site and recorder (a or b) for each rod for the 2 cm level using a Behnson-Lehner offline plotter programmed by the CDC computer. Actual dates were converted into day numbers out of the total 51 day field season to facilitate computing.

For an initial approximation of the daily differences between associations on both an intra-site (between recorders) and inter-site level, profile graphs, including the six measured levels, were drawn for the time periods of 6 pm, 12 am, 6 am, and 12 pm EDT. It should be noted that these times are only approximately the same between recorders.

2) Results

i) Daily Average Graphs

Graphs of daily averages for the field season are given for the 2 cm level in Fig. 3. The 2 cm level shows a great similarity in temperature between sites and recorders. The front ridge recorder shows a small difference between associations on warming days but for periods when the average temperature is decreasing there is no difference. The middle ridge recorders show almost no distinction between measurements on either warming or cooling days except at the beginning of the season with averages slightly less than the front ridge. The back ridge recorders show a large difference between measurements especially on warming days where differences are as great as 3°C, however, there is no obvious grouping into associations. Cooling days show the same trend as the other two sites, ie., the difference between measurements is small. On observation of the entire temperature curve for each site it is apparent that the front site is more sensitive to changes in the incoming energy than the other two sites.

At the 50 cm level differences between measurements are small in all recorders so that the graphs were not included. Temperature variation at this level has a maximum fluctuation over the summer months of 2°C. The front site has the highest average temperature at this level at 5°C, the middle site averages 3°C and the back site, 2°C.

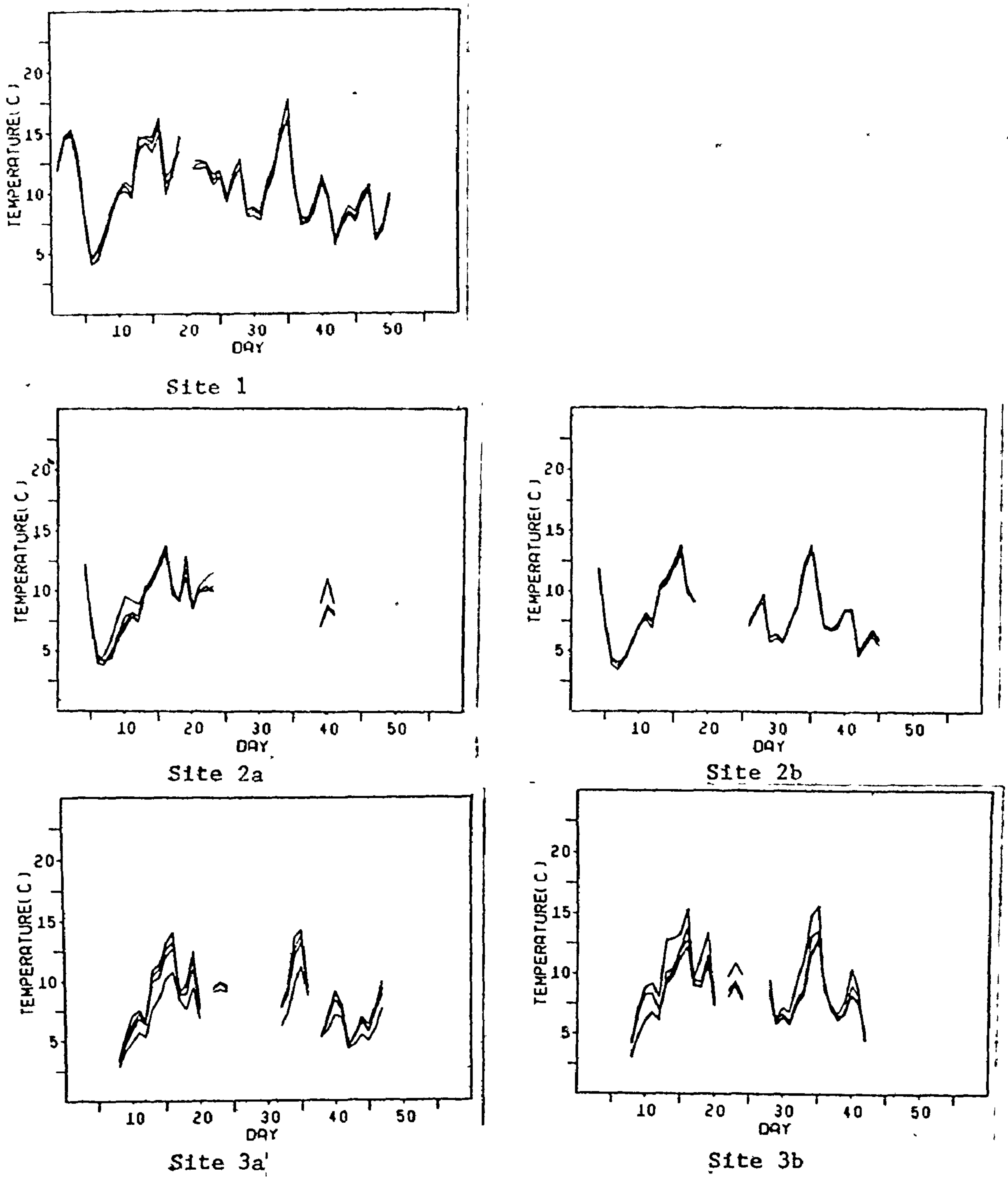


Figure 3. The Daily Average Temperatures at the 2cm Level over the Field Season.

ii) Characteristic Profiles

Graphs of Day 9, a day of bright sunshine followed by a cloudless night, are presented for all recorders as representative of the trends observed throughout the summer.

The 12 pm Profile (Fig. 4a)

In a comparison of the profile shape, the middle and back ridges have a much faster decrease in temperature in the 2-10 cm levels than the front site, illustrating the insulating properties of the deeper humus layer. From the 15-50 cm levels the middle and back ridge profiles are $3^{o}C$ colder than the front ridge.

On the front site, there is some distinction in temperature between associations which, although not observable at the 2 cm level, is as much as 1 - $1.5^{o}C$ at the 15 cm level. All other recorders show differences between profiles which cannot be attributed to association differences.

The middle site profiles are all similar except for one profile of 2a under the Rhododendron lapponicum-Alectoria nitidula association with a 2 cm temperature which is much higher than the rest but which is not different at any lower level. On the back site the highest and the lowest readings at the 2 cm level are under the R. lapponicum - A. ochroleuca association with a temperature difference of $12.5^{o}C$ on the 3b recorder demonstrating the large association-independent variation at these two sites.

The 6 pm Profile (Fig. 4b)

The middle and back ridge recorders show a much wider variation in 2 cm temperatures than the front site although this is not the case at the 5 cm level and below. Below the 15 cm level temperatures of the front ridge are consistently $3^{o}C$ warmer than the middle or back ridge sites.

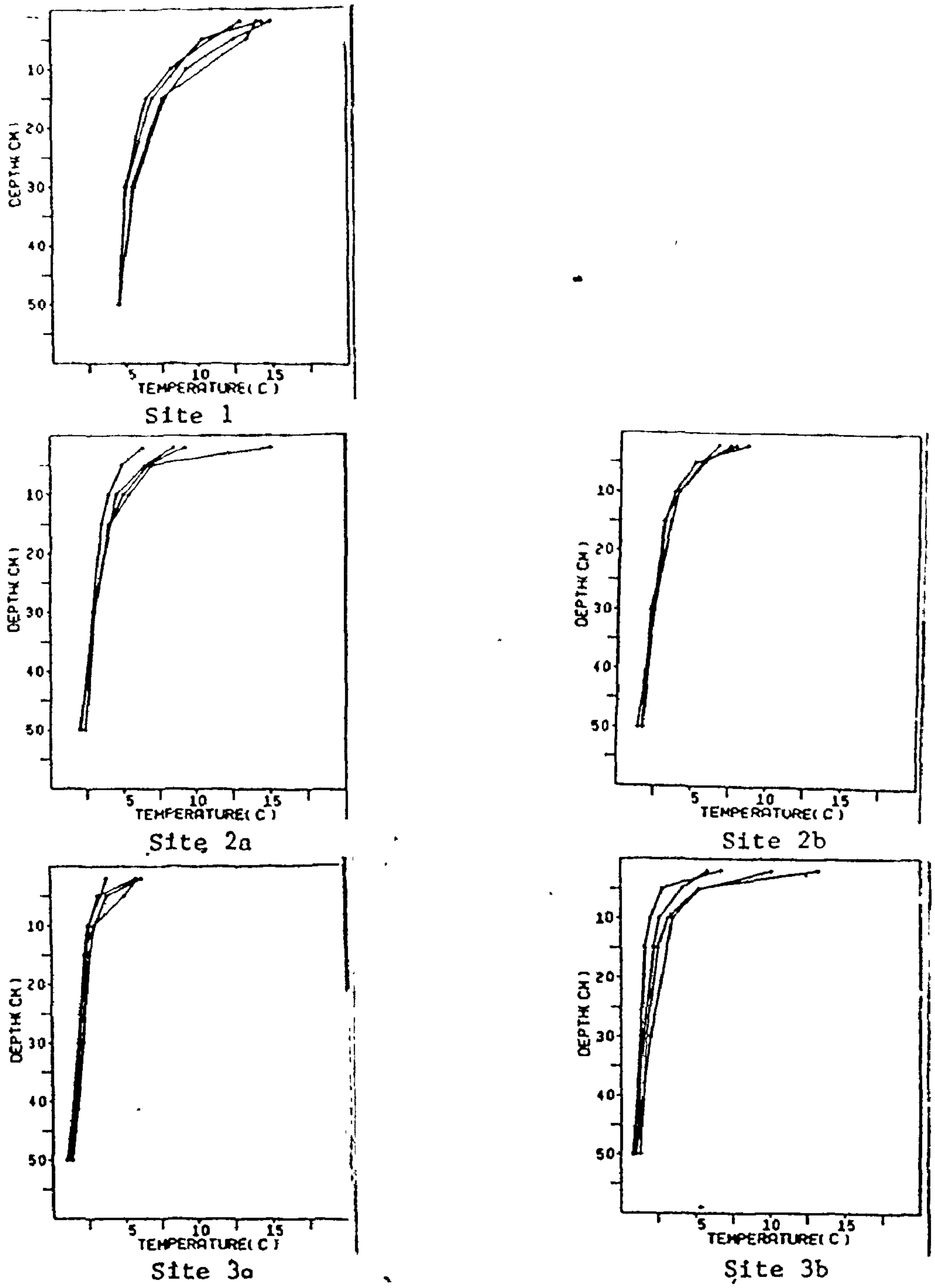


Figure 4a. The 12pm Temperature Profile

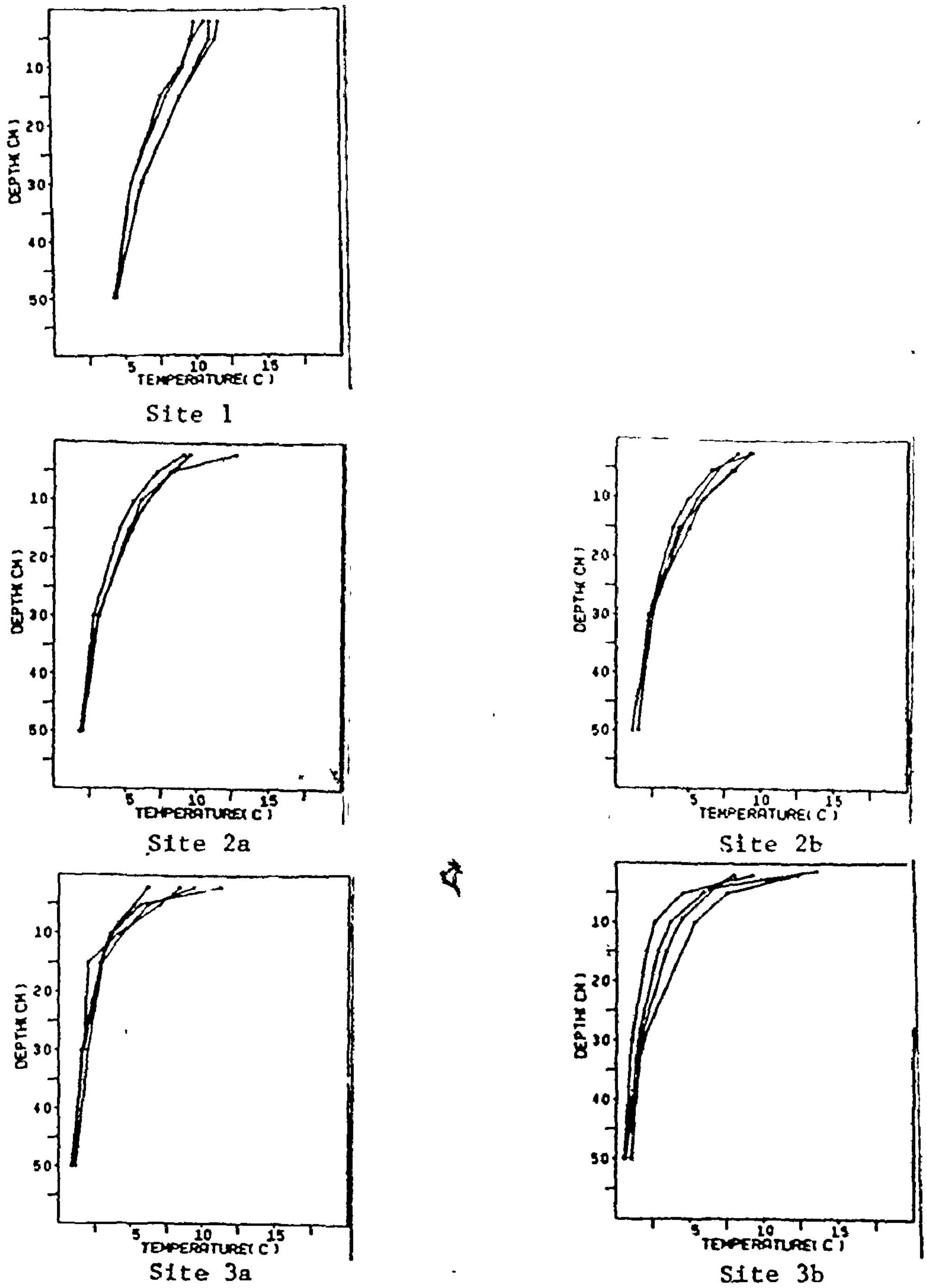


Figure 4b. The 6pm Temperature Profile

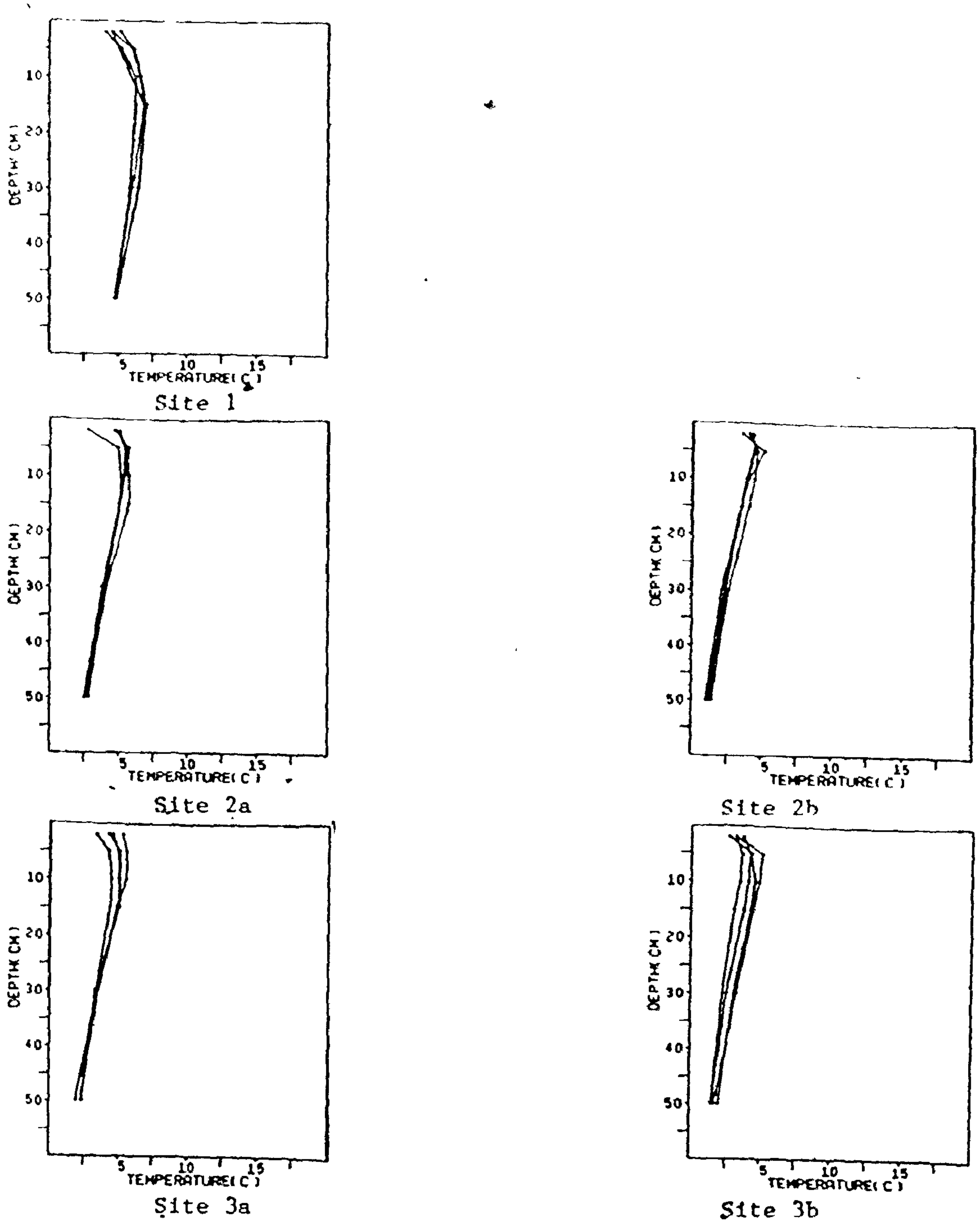


Figure 4c. The 12am Temperature Profile

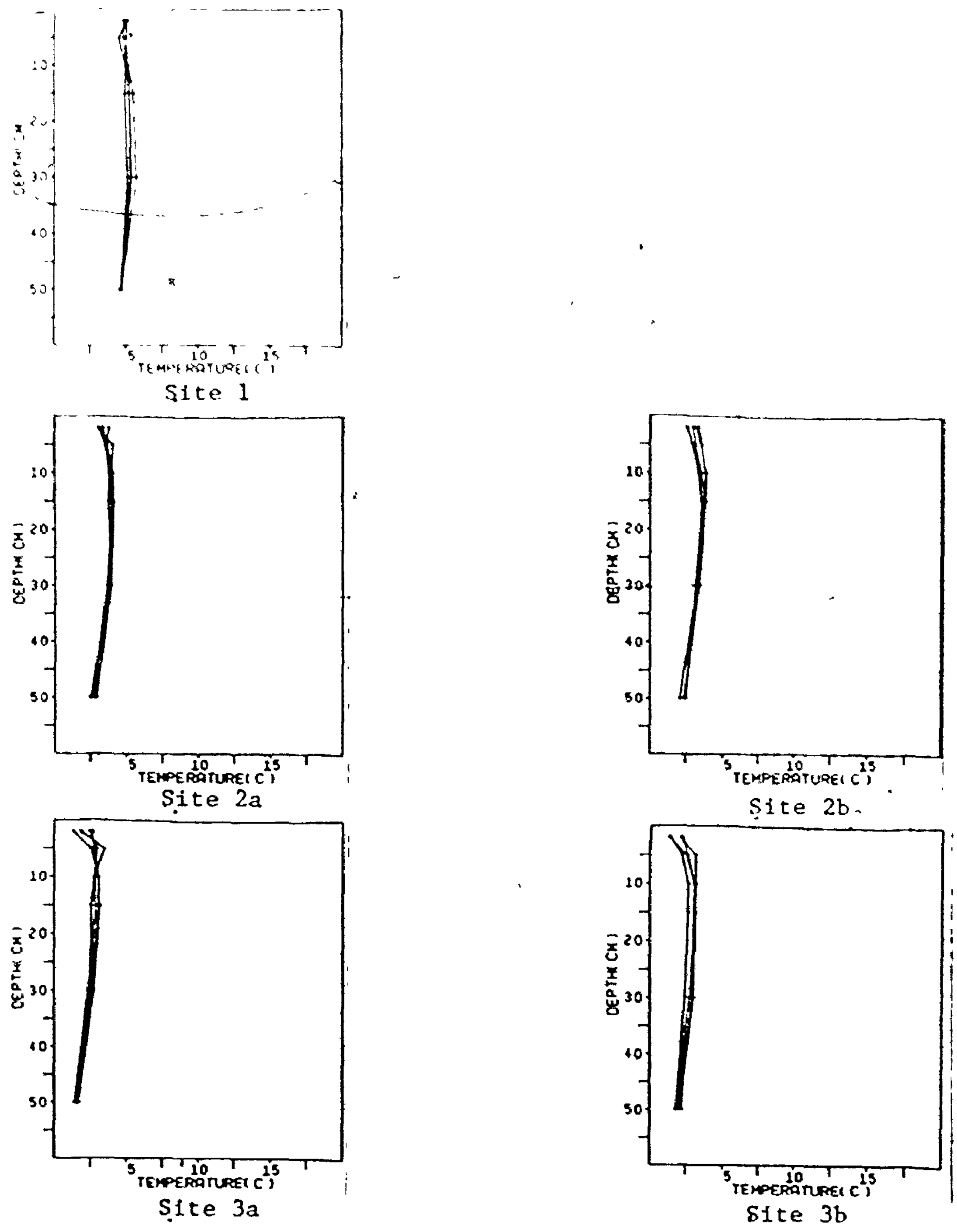


Figure 4d. The 6am Temperature Profile

The relationship between the recorders and associations is much the same for this time period as at 12 pm with one slight difference at the back ridge where the range of temperature of recorder 3a at the 2 cm level is similar that of 3b. The two extreme temperatures of each recorder occur under the Rhododendron lapponicum-Alectoria ochroleuca association with differences as great as 11°C.

The 12 am Profile (Fig. 4c)

In a comparison of the entire profile the front ridge is consistently warmer than the middle or back sites by as much as 3°C from the 15-20 cm levels and as little as .5°C at the 5 cm level. All associations show similar profiles for this time period illustrating the conformity of each association under low energy conditions.

The 6 am Profile (Fig. 4d)

The change in the surface temperatures from the 12 am profile demonstrates the change from negative to positive net radiation however the same similarity between rods is found for this time period as at 12 am.

3) Conclusions

There are three major trends which are evident in these results. 1) From the averaged temperature plots for the field season (Fig. 3) the largest differences between measurement occur during days when the average temperature is increasing, especially at the back site, implying that any further analysis should break the data into warming and cooling days to detect the maximum differences between associations. This is to be expected since the largest difference in G_o should occur during days of high positive net radiation. 2) Under high incoming energy conditions, the large differences detected at the 2 cm level under the Rhododendron lapponicum dominated association cannot be explained in simple terms such as an albedo difference since the largest differences occured between measurements of the same association. The consistency of this result as well as the variability in other associations must be determined before any hypothesis can be formulated.

3) The consistency noted in the average graphs of the 50 cm level is also found in the profile graphs occuring up to the 15 cm level of the back and middle ridges. The front ridge shows some separation of the profile according to association down to the 30 cm level, however the difference is 1°C or less.

In conclusion the differences detected by this graphical approach point to an intra-association different unexpected from the field design of the project and imply that some unmeasured parameter, either physical or plant related, is influencing the absorption of energy at the soil surface.

(4.4) Linear Regression of Near Surface Temperatures

1) Methods

i) Interpretation

The regression analysis serves two purposes in the description of the soil temperature fluctuations in the upper levels of the soil, in this case taken as the 2 cm level: a) a simple description of the temperature difference between associations under different energy conditions and b) a method of determining plant control over the ground heat flux.

a) By a combination of the slope, intercept, and temperature range of the regression it is possible to describe the difference between sites as an absolute temperature difference under a changing ground heat flux. For example, if the regression coefficient is 1.2 with an intercept of 0.0 over a 10°C range the dependent site of the regression is 2°C warmer under maximum ground heat flux than the independent site and is exactly the same as the independent site when ground heat flux conditions are at their minimum. This interpretation makes no distinction between physical and plant controlled differences in the soil temperature so that no assumption of any particular relationship of physical factor to soil temperature need be made. b) By assuming that the relationship between physical factors and soil temperature is described by the Fourier heat conduction equation (Equation 6) it is possible to determine the extent of plant control over the ground heat flux. Since the humus layer extends to the 2 cm level in all sites except for the front site, it is reasonable to assume as a first approximation that the thermal properties to the 2 cm level of each site and association are the same. From this assumption the only factor controlling the energy transmitted to the 2 cm level is the reflective characteristics of the plant surface during the field season. Assuming the above the following cases can be made for the interpretation of the regression.

Case 1: If the reflective characteristics of the surface are the same for the year then temperatures at the 2 cm level will be exactly the same in a comparison, and the slope of the regression will be 1 and the intercept will be 0.

Case 2: If the reflective characteristies of the surface are the same throughout the field season but are different through some other portion of the year (differential snow melt for example) then there will be a constant difference between temperatures. The regression coefficient will be 1, but the intercept will be equal to the temperature difference. In this case, it is unlikely that the plant cover has any effect over the ground heat flux.

Case 3: If the reflective characteristics are different, the regression coefficient will deviate from 1, however, if the difference is constant throughout the field season, the standard deviation of the regression will be small. If the difference changes throughout the season or over a day, the

the standard deviation of the regression coefficient will increase.

For all these cases an increase in the standard deviation of the regression coefficient implies some fluctuation in the reflective characteristics of the plant surface over the field season.

ii) Average Temperature Regression

Linear regression of daily averages (calculated in Graphical Methods) were made at the 2 cm level for the entire season. From the graphical description some difference was found in the temperature response between sites when temperatures were increasing so the data was split into days of increasing and decreasing temperature and regressed again. Because of the large number of regressions that this entailed, results are given in Appendix A. Only the observed trends will be presented here.

iii) Fourier Amplitude Regression

From the linear regression of averaged temperatures it is possible to determine changes in the soil heat flux over the field season but not for the diurnal period. Comparison using actual hourly data cannot be made since differences from site to site are no longer solely a function of plant cover. To simplify the diurnal variation to a single variable, Fourier series were applied to the actual temperature data. This is based on the observation that diurnal temperature fluctuation is very similar to a sine function. By applying a series of sine and cosines to the actual temperature data, of the form

$$T(t) = T_{AV} + \sum_{k=1}^{n} a_k \cos(kwt) + b_k \sin(kwt) \quad (8)$$

where
T(t) = temperature at time t

T_{AV} = average diurnal temperature

k = harmonic

w = angular frequency = 2π/period

a_k, b_k = Fourier coefficients

n = maximum number of harmonic to be fit

succesive approximations of the actual temperature can be made. The coefficients a_k and b_k can be accurately approximated for several harmonics (van Wijk, 1966) by:

$$a_k = \frac{2}{N} \sum_{i=1}^{N} T(t_i) \cos (kwt_i) \qquad (9)$$

b_k is caluclated by the substitution of sine for cosine in Equation 9.

This can be converted into the more interpretive form:

$$T(t) = T_{AV} + \sum_{i=1}^{n} A_k \sin (kwt + O_k) \qquad (10)$$

A_k = the amplitude of the kth harmonic

O_k = the phase angle of the kth harmonic

by the substitution of

$$A_k = \sqrt{a_k^2 + b_k^2} \quad . \quad O_k = \text{arct } (a_k/b_k)$$

When the first harmonic of the series accurately approximates the actual temperature wave, then the Fourier amplitude can be used to represent the daily fluctuation of temperature at each level. To estimate the accuracy of the first harmonic Brunt's completeness criterion was used of the form.

$$\text{Percent Variation} = \sqrt{100 \frac{\frac{1}{2}\sum_{i=1}^{n} (A_i)^2}{\sum_{j=1}^{N} (T_j - Tav)^2}} \qquad (11)$$

The first harmonic of the Fourier series was calculated for all days and recorders. When it accounted for 80% or more of the variation, the value was used in a linear regression of Fourier amplitudes between different associations and sites. In this manner seasonal trends in the diurnal variation could be established according to the regression interpretation already given. Fourier amplitudes were calculated and regressed for two levels; at the 2 cm level to determine differences under each association and at the 5 cm level to determine the transport of any differences into the lower soil layers.

Differences detected by the daily average regressions are essentially independent of the Fourier amplitude differences so that it is possible to add the average and Fourier differences to produce a combined temperature difference between associations.

2) Results

In each comparison results are quoted to one significant digit after the decimal place. Comparison for all sites and recorders were made on an inter- and intra- association basis and are included in Appendix A.

i) <u>The 2 cm Level; Total Data</u>

The Front Site

Regression coefficients varied from 1 - 1.1 with a standard deviation of .0 for all comparisons of daily averages (Table 1, Appendix A). No inter-association differences were detected and the intra-association difference under the <u>Arctostaphylos rubra</u> association was as much as .9°C at low soil temperatures to .1°C at the highest soil temperature, clearly a negligible difference.

A variation of .9 - 1.0 was observed in the regression coefficients of the Fourier amplitude comparison with (Table 5, Appendix A) with a standard deviation of .0 for all comparisons. This implies a maximum difference of .5°C in amplitude over a range of 5°C which is also clearly negligible so that it may be concluded that the front site temperature differences are so small that it is not possible to distinguish the influence of plant cover over the soil temperature. Because there was some variation in the humus depth above the 2 cm level in this site, it is also concluded that small differences in humus depth of less than 1 cm has no measurable effect on soil temperatures.

The Middle Site:

The intra-site variation between 2a and 2b recorders causes some problems in interpretation of this site. Site 2b shows a similar variation in the regression coefficients of the daily averages to the front site (1 - 1.1) with a standard deviation of the regression coefficient of 0, which implies a negligible difference on both the inter-association and intra-association comparisons; however, regression of the Fourier amplitudes (Table 5) points to some differences between the association dominated by Rhododendron lapponicum and Alectoria nitidula with differences as great as 2.0°C in the amplitude of temperature variation on a sunny day.

There is an increase in the standard deviation of the regression coefficient in Site 2a which is only partly accounted for by the small number of measurements of this recorder (Fig. 4b). Regression coefficients of daily averages vary from .9 - 1.1 with standard deviations of .1 - .2. Average temperature differences are therefore small between associations however regression of the Fourier amplitude show a difference on an intra-association basis of as much as 4°C under the Rhododendron lapponicum - Alectoria nitidula association. The large standard deviation (of as much as .5) can be partly accounted for by the small number of comparisons of this analysis. By graphing the comparisons (not presented) this fluctuation was of a random rather than a functional nature.

It is evident from the 2 cm description of this site that a constant temperature difference between associations was not found. Distinction between associations can be made on the basis of intra-association variation alone. Measurements of the Dryas integrifolia-Alectoria ochroleuca dominated association are nearly equal while Rhododendron lapponicum-Alectoria nitidula dominated measurements are considerably more variable.

The Back Site:

There was a considerable variation in the regression coefficients in both of the back ridge recorders even in the comparisons of averaged data. Coefficient variation of daily average regressions was .7 - 1.1 in recorder 3a with standard deviations from .0 - .1. The largest difference occurred under the Rhododendron lapponicum-Alectoria ochroleuca dominated association with differences as great as 3°C on a sunny day. Regression of the Fourier amplitudes showed a larger difference on the intra-association scale under Rhododendron with an amplitude difference as great as 4°C. Combined, differences on the intra-association scale under Rhododendron were 7°C on a sunny day.

A similar difference between measurements under the Rhododendron lapponicum-Alectoria ochroleuca association occurred in recorder 3b, however, there was also intra-association variation under Cladina alpestris, with differences as great as 4°C on a sunny day. This difference was mostly accounted for by a large difference in the Fourier amplitude of diurnal temperature fluctuation.

Association controlled differences in this site are a minor consideration compared to the large intra-association found. Differences under the same Rhododendron association were as great as 7°C, clearly indicating that some unmeasured factor besides the specific plant association is also affecting the reflective characteristics of the plant surface.

ii) The 2 cm level: Increasing and Decreasing Temperatures

There was no change in the relationship between associations of the front site under sunny or cloudy conditions or in one of the middle site recorders (2b), however, for the other middle ridge recorder there was some differences in the relationship between associations depending on the incoming energy. Measurements under the <u>Rhododendron lapponicum</u> dominated association of both ridges have approximately equal average temperature is increasing, there is a wide divergence in temperature. This points to some difference in the energy transmitted to the soil which is not consistent for both cloudy and sunny days. An explanation of this factor cannot be made from this analysis and its solution must wait until the next section.

iii) Differences between Sites (Table 7-10)

For the purposes of this comparison, the data from all measurements for each recorder were averaged and then compared with the averaged data of all other recorders.

From the regression of the 2 cm averaged data, there is a variation in the regression coefficient from .8 to 1.2. The front site rises 1°C more than the middle or back ridge sites over a 10°C range. Recorders 2b, 3a and

3b have approximately the same average temperatures throughout the season while recorder 2a shows some variation with the other middle and back ridge recorders.

Regression of average temperatures at the 50 cm level shows the front site more variable and at least 2°C warmer than the back and middle sites while comparisons between the middle and back ridge sites are somewhat inconclusive since the regression was over a very small temperature range for these recorders.

Regression of the Fourier coefficients of the 2 cm level show a wide variation between sites and recorders the only conclusive trend being the greater variability of the front site to changes in the incoming energy conditions. Fourier amplitudes at the 5 cm level are up to twice as large under the front site than at either the middle or back sites. Comparison of the Fourier amplitudes at the middle and back sites shows that much of the variation occurring at the 2 cm level is damped by the time it reaches the 5 cm level, however results are not conclusive because of the small range of the regression.

(4.5) Discussion

From both the graphical and linear regression analysis there was very little difference between associations on the front ridge. Because of the small variation in regression coefficients and standard deviation it was also concluded that the small differences in humus depth of this site had no appreciable effect on the soil temperature.

From the regression analysis between sites, the front site has a greater temperature fluctuation at the 2 cm level than the middle or back site which was unexpected. The front site has a greater albedo than either the middle or back which implies that less energy should be transferred into the soil. Also, the sand layer which occurs just beneath the 2 cm level conducts heat faster and has a higher heat storage because of its large volume fraction, than the corresponding humus at this level in the middle and back sites. This should decrease the daily temperature fluctuation at the 2 cm level of the front site compared to the back two. Since the opposite effect was observed there is some factor as yet unaccounted for.

There was an increase in the variation of the regression coefficient and standard deviation in the middle and back sites which is mainly due to the variation observed under the Rhododendron lapponicum dominated associations of both sites. From the interpretation given at the beginning of the regression analysis this implies that there is a change in the reflective characteristics between measurements of the same association as well as a variable component which changes throughout the field season.

One of the factors contributing to this difference is the changes in plant density above the soil surface. As plant density increases, more of the incoming radiation is absorbed by the plant layer and is convectively transferred into the soil or into the atmosphere. Under a species with an open branching pattern such as Rhododendron lapponicum some of the incoming radiation will be absorbed by the branches and some will pass through to the soil surface. Since it is to be expected that the absorbing surface will change with sun angle there will be some variation in G_o throughout the day as was observed in the increase of the standard deviation of the regression coefficient.

The divergence in absorbed energy by the soil surface points to a change in the energy balance for different plant densities and appears to contradict other findings in the area (Rouse and Stewart, 1973). However since their measurements were made at the 1 m level it is likely that the small density differences found are averaged out above the plant surface.

The effect of plant density may also explain the unexpected high temperatures fluctuation of the front site when compared to the back and middle sites. Because of the relatively thin vegetation covering of the front ridge, much of the incoming radiation is absorbed directly onto the soil surface, increasing the amount of energy transmitted to the soil, rather than convectively exchanged with soil and air as in the middle and back sites.

Therefore, it is concluded that there are differences between associations mainly due to density differences above the soil surface which can effect the 2 cm temperature fluctuation by as much as 7°C on a sunny day.

The change in the temperature fluctuation of the Rhododendron association when conditions are cloudy and when they are sunny is as yet unexplained. It implies that some factor which changes depending on high or low incoming energy conditions is causing the difference. From this analysis it is not possible to determine whether the factor is contained in the plant or soil layer.

Section V

PREDICTION OF SOIL TEMPERATURE

(5.1) Introduction

Changes in the thermal properties of the Pen Island soils, either on a diurnal or seasonal time scale, can potentially invalidate the interpretation and discussion of the last section (Section IV). As well as the obvious utility of an accurate model of soil temperature in the study of physiological responses of subarctic plants, the modelling process of this section provides the essential validation of the assumption of heat conduction for the Pen Island soils.

1) Methods of Solution

Two types of model were investigated as a solution of Equation 6: an analytic solution, using a sine curve to define the upper boundary condition (van Wijk, 1966) and a finite difference approximation to the equation using actual data for both the initial and upper boundary conditions (Nakano and Brown, 1972).

To derive an analytic solution for the soil heat flux equation it is necessary to approximate discrete actual data by a continuous function to determine the upper boundary conditions. Since of necessity this is only an approximation some accuracy from the original data must be lost.

In most applications of the analytic model the upper boundary is approximated by an annual and diurnally fluctuating sine curve of which only the diurnal wave may be calculated from this study. This requires that initial conditions must be specified for the field season data thus losing the advantage of the analytical solution over the finite difference approximation. Also, not all days can be approximated by a sine wave necessitating the use of some other function to specify the temperature fluctuation for these time periods. Finally, incorporation of a step change in the diffusivity to account for the different layers of humus and sand in the profile adds a considerable mathematical complication to the model (van Wijk and Kerksen, 1966) so that application to the current research was not attempted.

Implimentation of the finite difference model to the problem will be described in three parts; a description of the mathematical basis of the model followed by a literature review. Subsequently, the methods of inputting the model requirements for prediction will be discussed including sensitivity testing and tests for goodness of fit.

Results will be presented in four parts; prediction of soil temperatures using literature values for diffusivity, the determination of "best fit" diffusivities for a single day throughout the profile, testing the "best fit" diffusivities on different days and finally testing the "best fit" diffusivity over a several day period.

(5.2) The Finite Difference Model of Soil temperature

The finite approximation of the Fourier heat conduction equation is made by changing the differential into discrete time and depth increments. This is best represented as a grid of points (Fig. 5) where the ith column refers to the time $i\Delta t$ and the jth row refers to the depth $j\Delta t$.

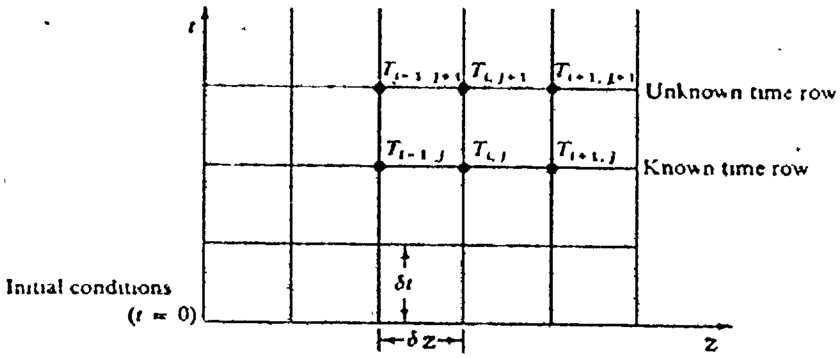


Figure 5. Mesh Points of One-Dimensional Finite Difference Scheme

The left hand site of the Fourier equation can be approximated by a forward difference formula while the right hand side is approximated by a central difference formula, of the form:

$$\frac{T_{i+1,j} - T_{i,j}}{\Delta t} = a \frac{T_{i,j+1} - 2T_{i,j} + T_{i,j-1}}{\Delta z^2} \tag{12}$$

This forms the explicit solution of the equation where three elements of the ith time column are used to predict one element in the i+1 time column.

There is a problem of instability in this solution when $\Delta t/\Delta z^2$ is greater than ½. When this occurs errors due to the finite approximation accumulate to make the solution highly inaccurate after about twenty forward steps in the solution (Bayley, Edgar, and Owen, 1972). For long time increments this restricts the size of depth increment and for large depth and time increments the finite approximation of Equation 6 is inaccurate.

To stabilize the solution, a central difference formula of the i+1 time column is used instead. This is the form:

$$\left(\frac{T_{i+1,j} - T_{i,j}}{\Delta t}\right) = a\left(\frac{T_{i+1,\ j+1} - 2T_{i+1,j} + T_{i+1,j-1}}{\Delta z^2}\right) \qquad (13)$$

Use of this equation instead of Equation 12 in the Fourier equation results in the fully implicit solution in which three temperatures in the i+1 time column are predicted by one temperature of the ith time column. This results in a set of simultaneous equations of the form:

$$A(T_{i+1,j+1}) + B(T_{i+1,j}) + C(T_{i+1,j-1}) = D$$

and can be solved with set initial and boundary conditions by Gaussian elimination.

In this study a combination of the explicit and the fully implicit solution was used (Crank and Nicholson,1949) and this is of the form:

$$\frac{T_{i+1,j+1} - T_{i,j}}{\Delta t} = \left[\frac{(a_{j+\frac{1}{2}}(\Theta)(T_{i,j+1} - T_{i,j}) + (1-\Theta)(T_{i+1,j+1} - T_{i+1,j}))}{\Delta z^2}\right] + \left[\frac{(a_{j-\frac{1}{2}}(\Theta)(T_{i,j-1} - T_{i,j}) + (1-\Theta)(T_{i,j-1} - T_{i,j}))}{\Delta z^2}\right]$$

where Θ varies from 0-1.

When $\Theta > \frac{1}{2}$ the solution is unconditionally stable (Mitchell, 1968).

(5.3) Literature Review

The first application of the finite difference model (Hanks et al, 1970) was of the fully implicit form and was applied to hourly temperature data from a Milleville silt loan in California using thermal properties obtained by theoretical methods (deVries, 1966) and errors were as great as 1°C for a 24 hour simulation at the 6 cm and 16 cm levels with an increase to a maximum of 2°C in the lower levels after two days of simulation. It was noted that there was little sensitivity of the model over the 24 hour interval to small changes in the calculated thermal properties.

Application of a resistance model (Weiranga and deWit, 1970) using data collected at 10 minute intervals was shown accurate for moist soils of Yoho silt loam although it was noted that at the end of the 24 hour simulation observed soil temperatures were generally higher than the predicted temperatures, especially the two top levels at 2 and 10 cm. It was also demonstrated that, for a dry soil, prediction was less accurate, especially at peak temperatures in the upper layers where the simulated temperatures overpredicted the actual by as much as 2.5°C. This was attributed to vapour mass transfer out of the soil during high incoming energy periods.

Application of the finite difference model to tundra soils was made at Point Barrow, Alaska (Nakano and Brown, 1972) and was used to predict the thawing rate of permafrost over several months from data collected at half-hourly intervals using literature values for thermal properties (Kersten, 1949). The assumption of a constant thermal conductivity for the upper layers of the soil (above 15 cm) is more accurate in a prediction over a long time scale (Carson, 1963) as demonstrated by their outstanding prediction of permafrost levels. Prediction over a four day period with a diffusivity value constant over time for the upper levels showed an over prediction at peak temperature periods of as much as 1.5°C which was attributed to a diurnal vapour mass transfer in the organic layer.

Each one of these studies used thermal diffusivity values derived from the literature and except for peak incoming energy time periods showed good simulation of actual temperature variation, however they could not be applied to the present problem for the following reasons. Firstly, there was no method other than visual for determining the goodness of fit of the simulated curve. For the project the number of graphs this would produce is prohibitive so that it is necessary to derive other criteria to determine goodness of fit and secondly, each one of these studies was performed on a bare soil surface where there was no interception of radiation by vegetation so that results obtained are not completely applicable.

(5.4) Methods

The accuracy of prediction of the model is dependent on several factors, the upper boundary condition, the lower boundary condition, the initial conditions and the correct thermal properties. In the following section the implementation of the model to the Pen Island data will be discussed. The mathematical formulation for the purposes of computation are given in Appendix C.

1) Input Parameters

i) The Upper Boundary Condition

Upper boundary conditions were described by the actual hourly data at the 2 cm level. A shorter time interval was used to increase the accuracy of prediction by a Fourier approximation to the 2 cm data using the first 4 harmonics and interpolating to ten minute intervals, however accuracy was not increased while computer time increased significantly so that hourly data was used for the rest of the analysis.

ii) The Lower Boundary Condition

The lower boundary condition was set at the 20 m level below the soil surface where the annual temperature variation approaches zero (Lachenbruch, 1962). Since the actual temperature at this level could not be measured, several different temperatures were tested to determine the effect of the base temperature. Temperatures from -20°C to -100°C in 20°C increments were tested for one of the rods of the front ridge and only the bottom measurement level at the 50 cm level was affected with a change in average temperature of .2°C, clearly insignificant, so that for the remainder of the analysis -40°C was used as the lower boundary condition.

iii) Initial Condition:

To increase the accuracy of the finite difference approximation to the Fourier heat conduction equation it is necessary that a small increment size be used, especially in the upper levels where the temperature change with depth is great. For the analysis an increment size of .2 cm was used for the first 100 cm and an increment size of 1 m was used to the 20 m level.

Temperatures intermediate to those measured were interpolated from a polynomial fit of the second and third order as well as a linear fit between measured levels. Polynomial approximation only marginally increased the accuracy to the 15 cm level while substantially decreasing the accuracy in the lower levels, probably due to the few measurement points to be fitted, so that linear interpolation between measured levels was used.

Two time periods were tested for accuracy of fit for linear interpolation; 6 am, when the profile was near linear and 12 pm when the profile was distinctly non-linear and it was found that there was no difference in the accuracy of solution for a daily or several day period. Accordingly it was concluded that any time period could be used for the initial conditions using linear interpolation.

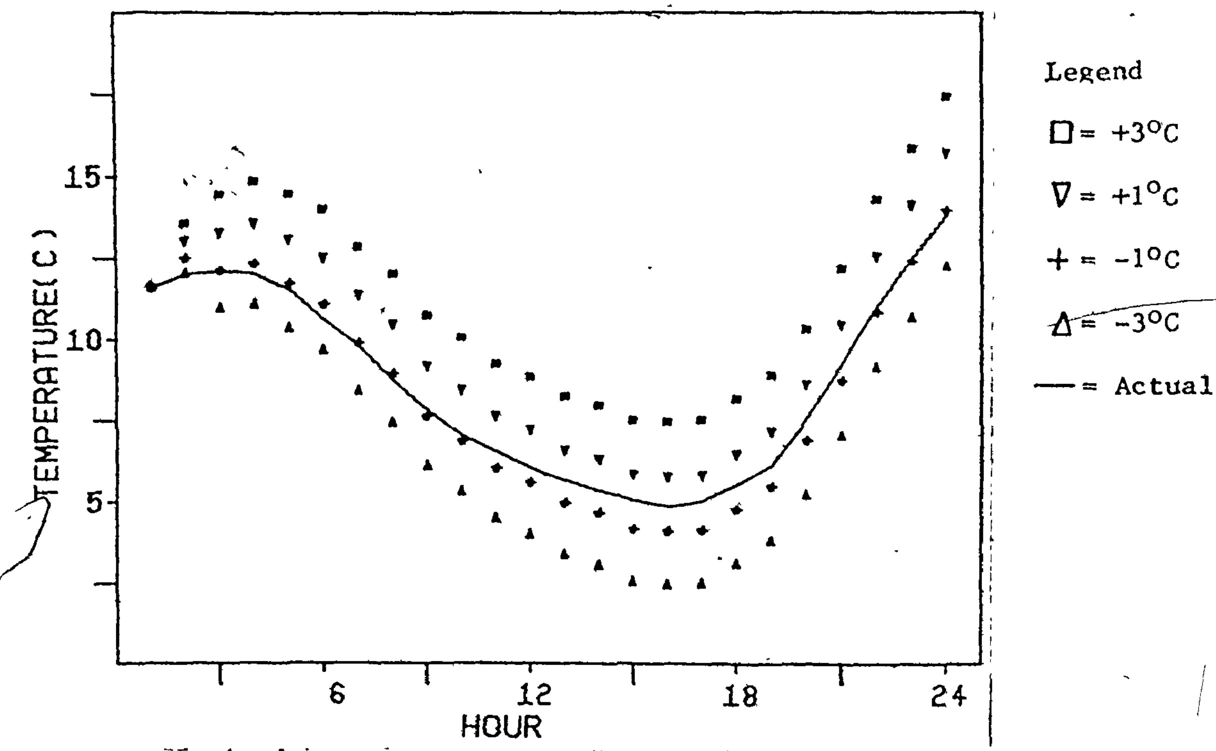
2) Sensitivity of the Model to Input Parameters

i) The Upper Boundary Condition

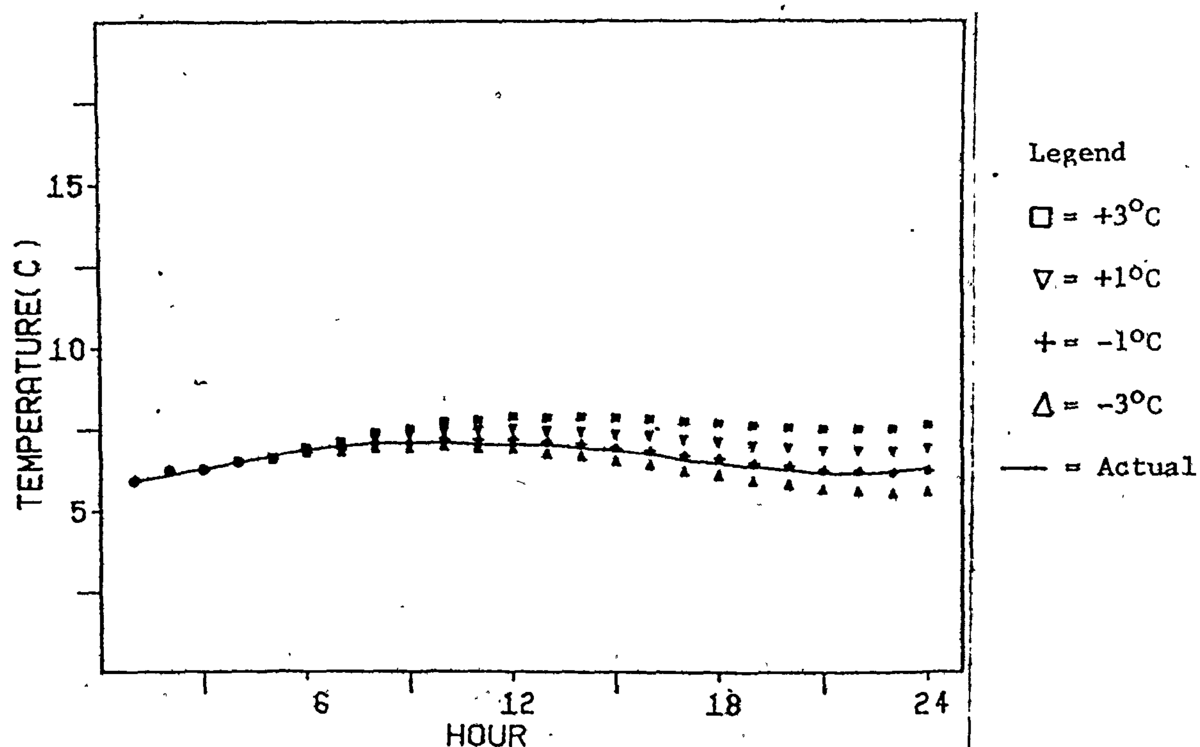
Two tests were applied to the upper boundary to determine their effects on the accuracy of prediction of the model; a) the entire 2 cm wave was raised or lowered 1°C and 3°C and, b) the amplitude of temperature variation was changed by ½ to 1½ times its actual fluctuation.

a) At the 5 cm level (Fig. 6a) the increase or decrease in the upper boundary condition is exactly mimicked after 3 forward steps in the model. Comparison with the actual wave at this level (A1, Site 1) shows some deviation from that expected however. Ideally the actual wave should occur exactly between the 1°C increase and decrease in the upper boundary conditions and although this is the case for the trough of the wave, there is some deviation during the daylight portion. This finding is not consistent for other rods of the same site, however it demonstrates a slight variation in the diffusivity over the diurnal period. At the 30 cm level (Fig. 6b) the temperature wave is not affected until about 8 forward steps in the solution. Divergence is slow after this point to about .5°C difference after 24 hours for different upper boundary conditions. Fit of the -1°C curve is very close to the actual temperature wave at this level also indicating a change in diffusivity over a diurnal period which is consistent with the rest of the rods at this level.

Change in amplitude of the upper boundary conditions results in an immediate displacement of the 5 cm level (Fig. 7a) but does not affect the 30 cm level until almost 12 hours later (Fig. 7b). Changes at the 30 cm level are similar to those after an average temperature change in the upper boundary however a similar change in amplitude has less of an effect at these lower levels.

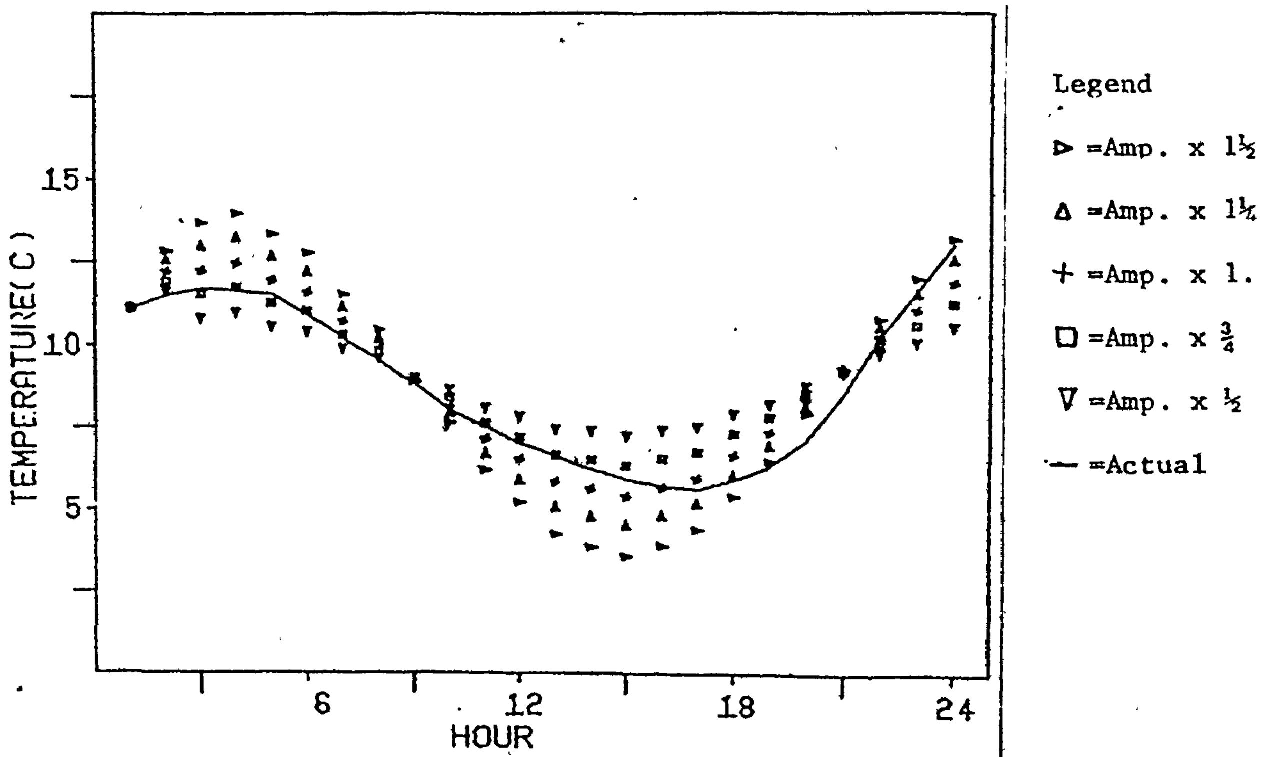


6a. Prediction of the 5cm Level

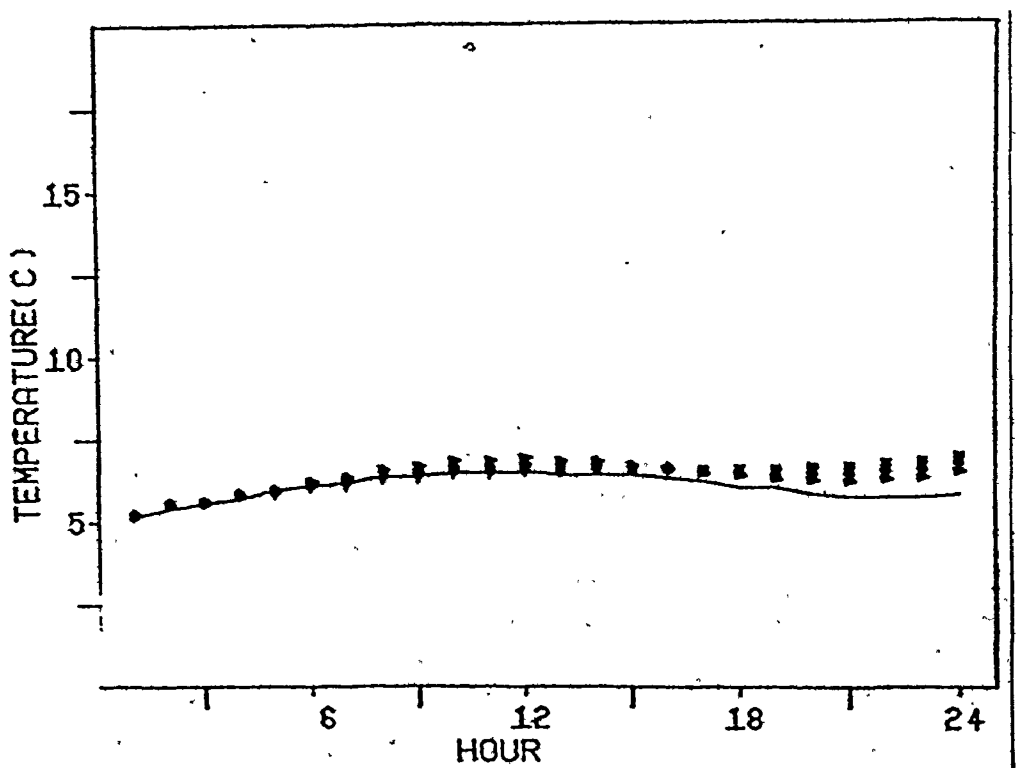


6b. Prediction of the 30cm Level

Figure 6. Sensitivity of the Model to an Average Change in the Upper Boundary Condition



7a. Prediction of the 5cm Level



7b. Prediction of the 30cm Level

Figure 7. Sensitivity of the Model to Changes in the Amplitude of Temperature Fluctuation of the Upper Boundary

ii) The Initial Condition

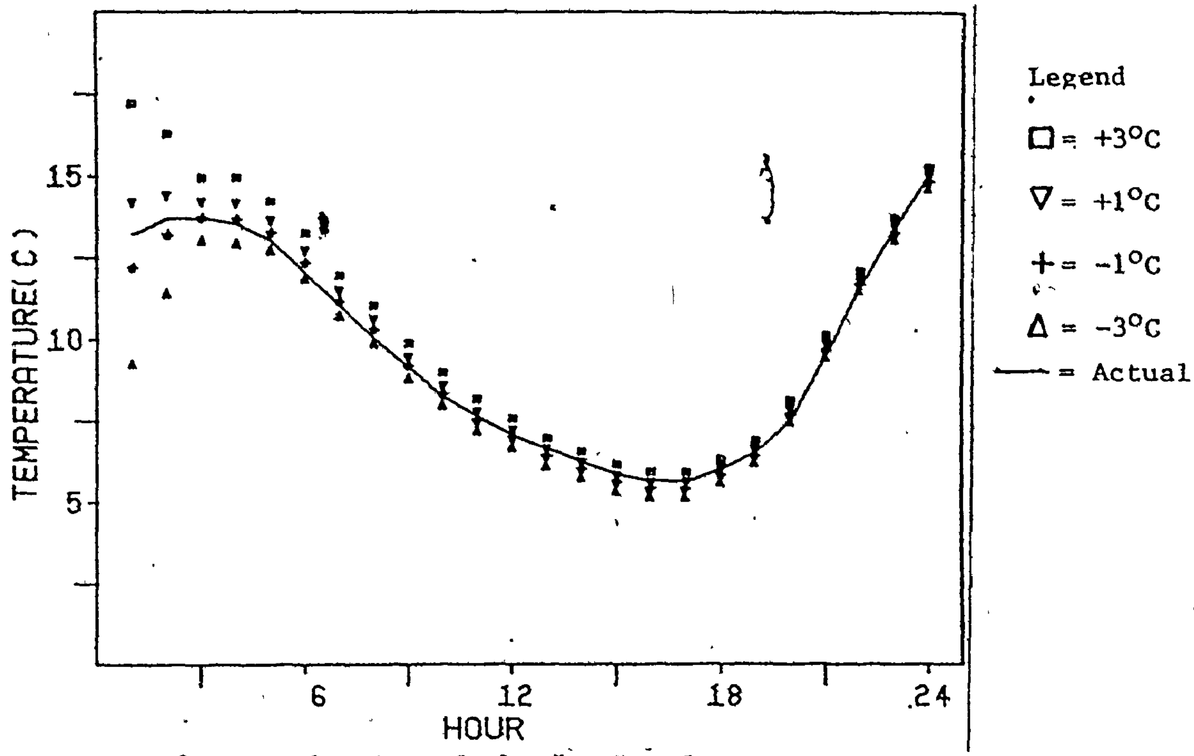
The initial conditions were changed 1°C and 3°C to determine the effect on the accuracy of the solution. In a comparison of two of the front site rods (Fig. 8a,b) of the 5 cm level, it can be seen that some rods have a very fast convergence to the actual solution while others are somewhat slower. This illustrates that convergence is fastest when there are large temperature differences between measurements in the diurnal temperature wave. At the 30 cm level (Fig. 8c) convergence is very slow demonstrating the dependence of these levels on the proper initial conditions for accuracy.

3) Testing the Accuracy of the Prediction

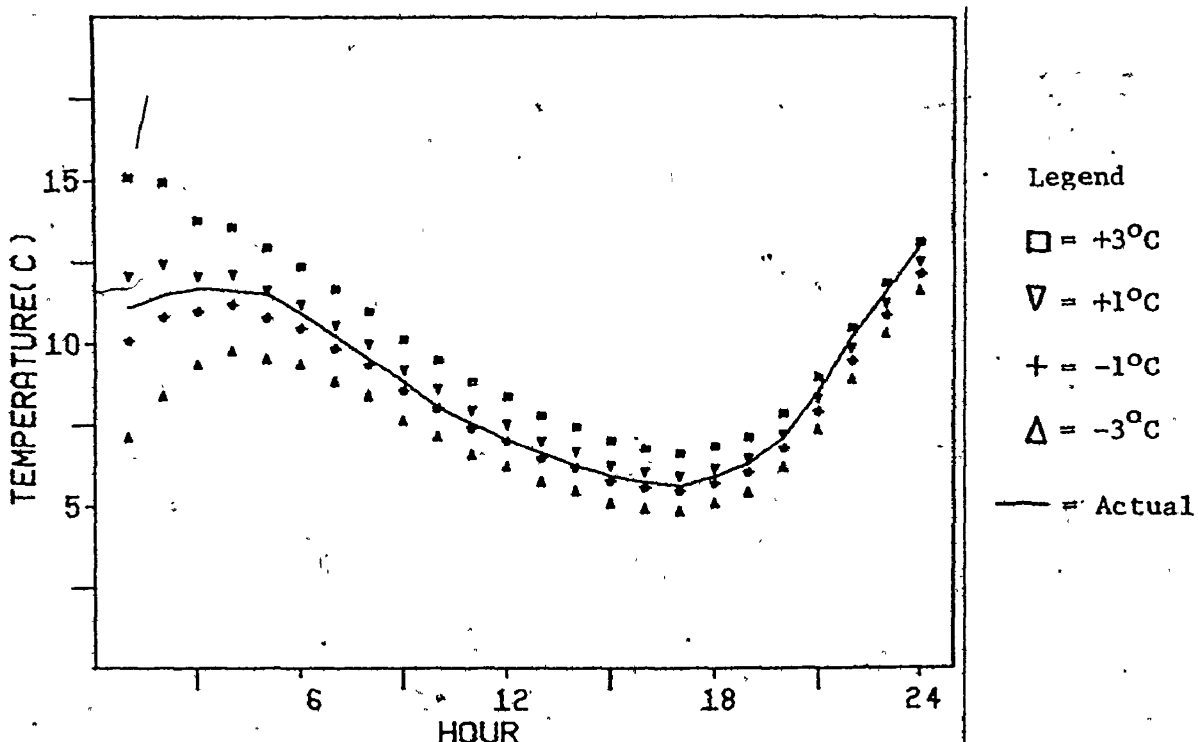
Of great importance for this study is the determination of the accuracy of fit of the predicted to actual, firstly to determine the accuracy of the conduction assumption and secondly to determine the accuracy in the prediction of the temperature fluctuation for studies of physiological responses of plants.

Three indexes were used: average differences over 24 hours, and Fourier amplitude and phase angle differences of the first harmonic over 24 hours.

Application of the Fourier coefficients as an index is based on the assumption that the first harmonic approximation of the actual wave is accurate so that, for the purposes of the study, analysis will be restricted to days which the approximation of the surface wave accounted for 90% or better of the observed temperature variation as determined by Brunt's Completeness criterion.

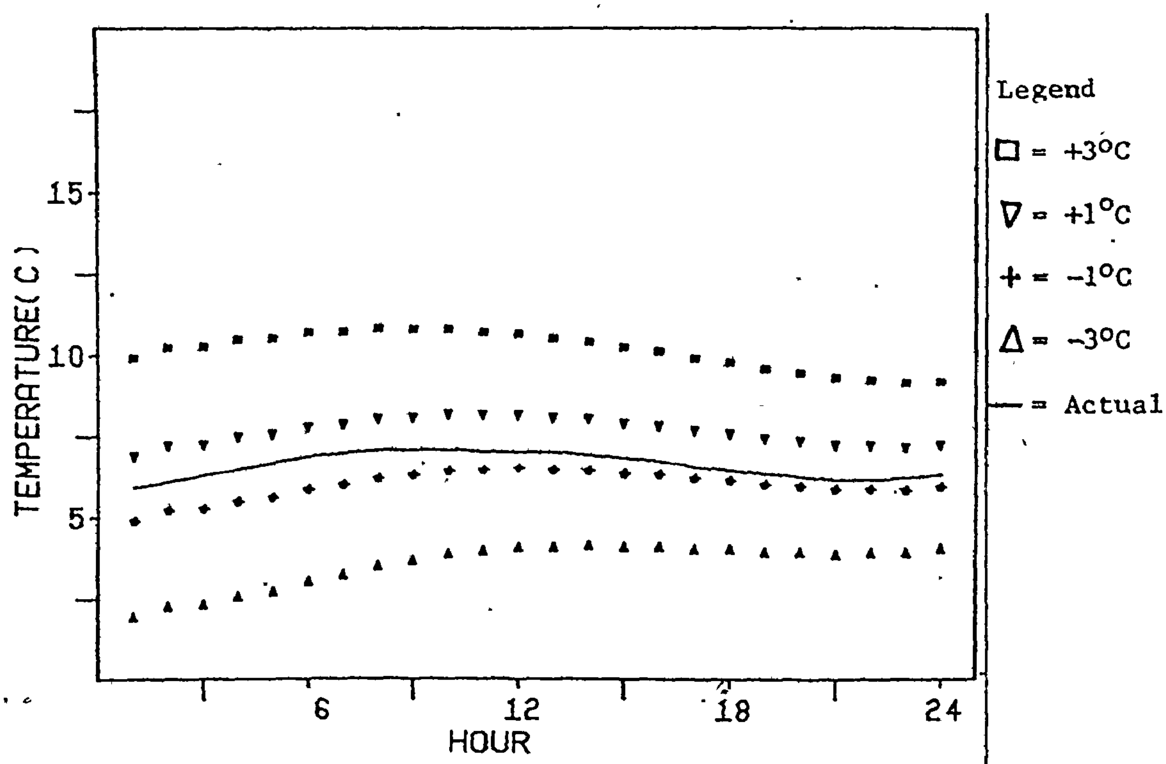


8a. Prediction of the 5cm Level



8b. Prediction of the 5cm Level

Figure 8, Sensitivity of the Model to a Change in the Initial Condition



8c. Prediction of tRe 30cm Level

Table 8

Maximum Error for an Amplitude of $1^{\circ}C$ due to Phase Displacement

Maximum error ($^{\circ}C$)	Phase Displacement (hr)
.25	1
.4	2
.7	3
.88	4
.98	5
1.0	6

Amplitude deviations between predicted and actual are readily interpreted in ^{o}C however deviations in the phase angle result in a time displacement which alters the difference between predicted and actual from time interval to time interval but is not readily interpreted as a temperature difference at first glance. For the purposes of the study only the maximum deviation need be considered and this occurs at $12 + \Delta\phi /2$ hours where $\Delta\phi$ is the phase displacement. For an amplitude of $1^{o}C$, maximum temperature differences resulting from phase displacements of 1-6 hr are listed (Table 8) and can be converted to any size of amplitude by multiplying by the amplitude so that phase shifts are most important for the determination of absolute error in the upper levels where the amplitudes of temperature fluctuation are large.

Because of the large number of indexes calculated, they will appear in a separate appendix (Appendix B) but for the purposes of the discussion of the results the error determined by each of the three indexes will be summed and where one index is responsible for a major part of the error this will be stated.

Differences are given in the Appendix B as ^{o}C for average and amplitude differences and in hours for the phase displacements. Actual amplitudes and averages are given in ^{o}C while actual phase angles were left as calculated in radians.

Use of graphs is restricted in this presentation because of the large volume of the comparisons and will be used only to illustrate the information determined by the other three indexes.

(5.5) Results

1) Diffusivities from Literature Values

A field determination of the thermal properties could not be made for the Pen Island soils, so that in the first approximation, literature values were used. The only extensive study of thermal properties (Kersten, 1949) used a steady state principle for the determination of thermal conductivity which has been shown to be less than accurate, so that some problems were anticipated by the assumption of these values.

The thermal conductivity of Fairbank's sand (15.4 cal/cm^{2}hr) and Fairbank's peat (1.19 cal/cm^{2}hr) were chosen as those best corresponding to the Pen Island soils. The substitution of the conductivity of peat for that of humus has already been shown to be successful in other tundra soils (Nakano and Brown, 1972) and the particle size analysis of the Pen Island sand corresponded with that of the Fairbank's sand.

Conductivities were converted to the thermal diffusivities by division of Equation 7 resulting in a diffusivity of 3.16 cm^2/hr for humus and 41.25 cm^2/hr for sand.

Using these values in a two layer model of Equation 14 with the measured depth of humus as the boundary betweeen the two layers, the soil temperatures for one rod of each site were predicted for day 10 (Table 1, Appendix B). Agreement with measured values was not good with a tendency to over predict on the front site and under predict at the back site. Differences were as great as 2.5°C at the 5 cm level.

2) Optimizing the Fit

To determine better diffusivity values it was decided to optimize the fit for one day and then retest on several different days. Since the humus layer occurred only above the 5 cm level, the diffusivity of the 2-5 cm level was allowed to vary independently of the rest of the Profile.

i) The 5-50 cm levels

Different diffusivities were supplied for the lower levels soil after first fitting the 2-5 cm level as exactly as possible. Diffusivities were varied from 10-40 cm^2/hr in intervals of 10 cm^2/hr and the best fit determined by the fitness criteria previously described.

Best fit for most levels was achieved with a diffusivity of 20 cm^2/hr, less than ½ the literature value but comparable with that used in other tundra soils (Nakano and Brown, 1972).

Step changes in the diffusivity between levels increased the accuracy of prediction for the lower levels (30-50 cm) however, the improvement was not consistent for all rods and only increased the accuracy by .1°C over all. Since this could not be correlated to any observed change down the profile, such as moisture or density differences a constant diffusivity of 20 cm^2/hr was assumed for the rest of the analysis.

ii) The 2-5 cm Level

Diffusivities varying from 3. to 20. cm^2/hr were tested for all rods of each site using a constant 5-50 cm diffusivity of 20 cm/hr for Day 10, in which the average temperature was increasing (Table 3, Appendix B). Judgement of best fit was not restricted to accuracy in the prediction of the 5 cm level alone but for the entire profile. Results are summarized according to association and site in Table 9.

Prediction of the 5 cm level was accurate to a maximum error in prediction of .4°C over 24 hours as determined by the sum of the amplitude, phase and average differences. The greatest sensitivity to diffusivity change was found in those rods with a low optimized diffusivity (3.-4. cm^2/hr)

Table 9

Optimized Diffusivities for Day 10
All Associations

1	A1 10.	A2 14.	D1 18.	D2 24.
2a	D1 12.	D2 10.	R1 10.	R2 5.
2b	D1 12.	D2 14.	R1 8.	R2 10.
3a	C1 8.	C2 8.	R1 4.	R2 12.
3b	C1	C2 10.	R1 3.	R2 4.

with an increase in maximum error of as much as 1.^{o}C for a diffusivity change of ± 4. cm^{2}/hr. Sensitivity of high optimized diffusivities was .1^{o}C for the same diffusivity change.

Of interest is the fluctuation in the diffusivity between two measures of the same association dominated by Rhododendron lapponicum and the relative similarity between the diffusivities of other associations irrespective of the fact that there is a difference of 4-6 cm of humus between the front and back two sites. The consistency of these results remains to be tested before any interpretation can be given.

There was some increase in the maximum error of the solution at the 10-15 cm levels for some of the profiles of the front site by as much as .4^{o}C which is mainly accounted for by an average temperature difference between predicted and actual.

In the 30-50 cm levels there is a decrease in the accuracy of fit for both the phase and amplitude tests especially in the middle and back sites where the predicted phase angle lags the actual by as much as 3 hours and the predicted amplitude underestimates the actual temperature fluctuation by as much as .4^{o}C although a more common difference is .2^{o}C. This implies that the assumed diffusivity of 20 cm^{2}/hr for the 5-50 cm levels is inaccurate. This could be accounted for, in part, by a change in the conductivity due to the increased proportion of coarse sand in the middle and back ridges. However, on the front site the predicted and actual amplitudes at the 50 cm level are equal but there is a phase lag of 1.2 hours indicating that some other factor, perhaps a time variation in the thermal diffusivity over a diurnal period is affecting the distribution of heat to the lower levels in the profile. The absolute difference in temperature prediction caused by this inaccuracy is negligible because the small temperature variation in the lower levels.

A visual representation of the effects of changes in the diffusivity of the 2-5 cm level is presented in Fig. 9, of rod A1 of the front site.

From the 5 cm graphs it can be seen that there is some differences in the shape of the predicted curve to the actual. Although this results in a maximum error of .2°C in the predicted value, this implies that there is a change in the thermal diffusivity with time over a diurnal cycle.

By inspection of the 50 cm level it can be seen that there is some divergence of the solution near the end of the 24 hour period. Since this is more pronounced after a simulation over several days this will be discussed later in this section.

3) Testing the Fit on Different Days

Three days were selected to test the values determined from the analysis of day 10; day 17, a day of alternating sun and cloud with temperatures at the 2 cm level decreasing on average after a long period of sunny weather, day 38, a day of sun with increasing temperatures on average after a long period of cloudy and wet weather, and day 40, a predominantly sunny day after a short period of sunny weather.

The initial analysis used a constant diffusivity of 8. cm^2/hr for the back two sites for each rod for the purposes of comparison. Then the optimized diffusivities calculated from day 10 were substituted and the goodness of fit compared for at least two rods under different associations of each recorder (Table 5, Appendix B).

The worst fit occurred on day 17 for the back and middle ridges with most of the differences occurring under the Rhododendron lapponicum dominated association. In site 2a, using a diffusivity of 4. cm^2/hr the amplitude of variation was underestimated by 1.0°C while a diffusivity of

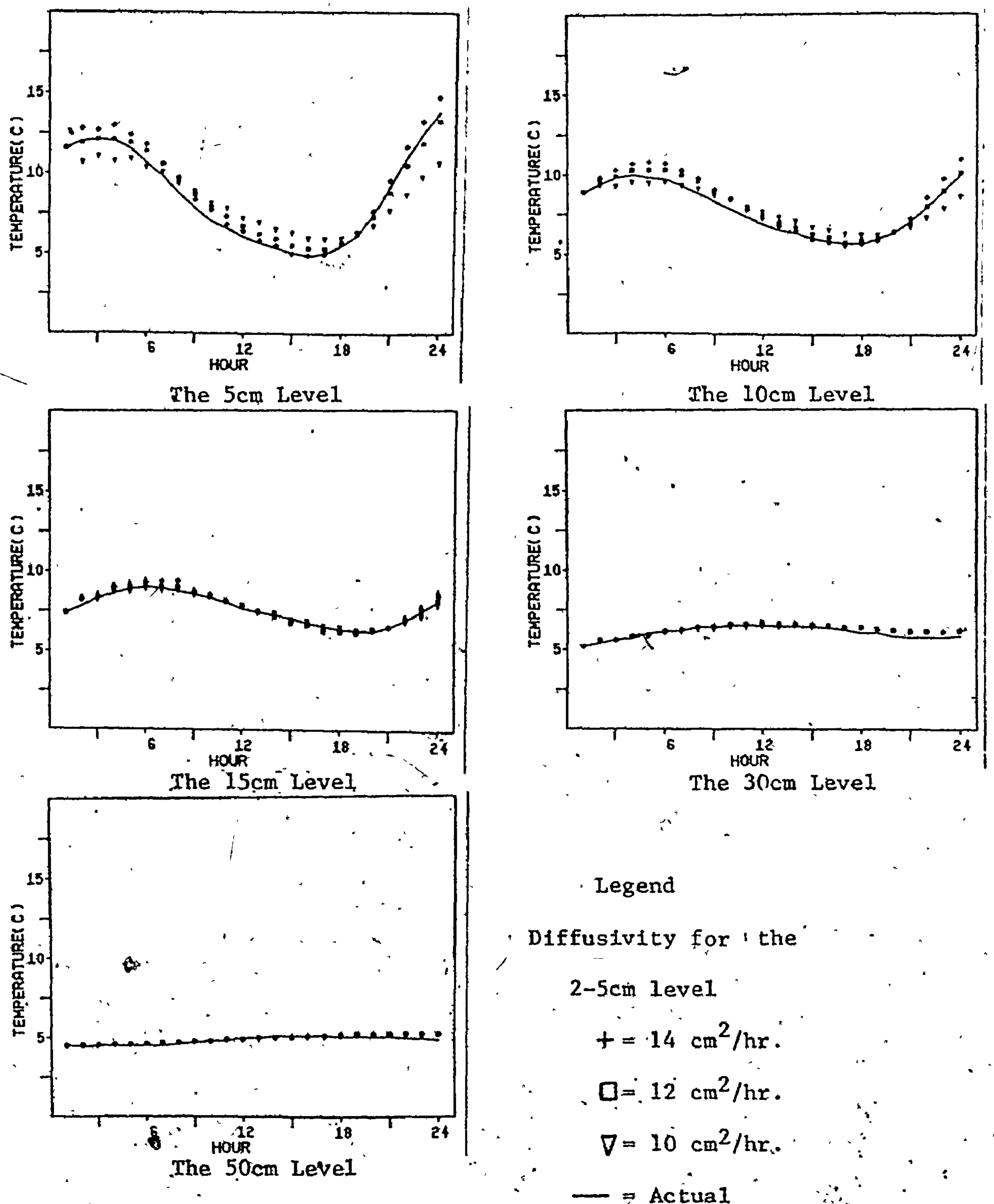


Figure 9. Prediction of the Model using Different Diffusivities for the Upper Layers over a Diurnal Period

8. cm^2/hr was accurate in the prediction of the 5 cm level but slightly over predictive for the 10 to 50 cm levels. This is in contrast to Day 10 in which a diffusivity of 4. cm^2/hr was the most accurate in the prediction of the 5-15 cm levels but slightly under predictive for the lower layers. These results are similar for the back ridge recorders as well so that there is some deviation in the 2-5 cm diffusivity from day to day.

Error under other associations was also increased by as much as .6°C, although some fits of the Dryas integrifolia and Cladina alpestris dominated associations were quite accurate with a maximum error of .6°C.

There was a considerable improvement in the fit of the calculated diffusivities on Day 38. All diffusivities from Day 10 proved most accurate for the upper levels however there was some increase in the under prediction of the phase angle in the lower levels (30-50 cm) of all sites although the absolute deviation in temperature was quite small.

On Day 40 there was some increase in the accuracy of fit using the optimized diffusivities except that, for all the Rhododendron lapponicum associations tested, there was some over prediction of the average temperature by as much as .7°C at the 15 cm level. There was a consistent over prediction of the 15 cm level temperature for the Dryas integrifolia dominated association of the front and middle ridges for each of the days tested including Day 10.

From these results it can be seen that there is some differences between sunny and cloudy days under the Rhododendron associations of the middle and back ridges. This is interpreted as a difference in the vapour transfer of heat due to the high near-surface temperature under some of the Rhododendron plants. In the previous chapter it was postulated that there was some difference in the radiation interception surface which was responsible for temperature differences at the 2 cm level. Under Rhododendron, some of the incoming radiation is absorbed directly at the soil surface causing high temperatures during sunny periods. The high temperature gradient in the humus layer enhances mass transfer of water vapour from the soil surface and is responsible for the change in apparent thermal diffusivity. Under cloudy skies, the interception of radiation is less, so that the temperature gradient is not as large, reducing mass transfer. This accounts for the observed difference in the response of this association under cloudy and sunny conditions (Section 4.4 1, ii).

The lag of the predicted phase angle behind the actual appears to increase with sunny conditions and decrease under cloudy.

4) Testing the Fit over Several Days

For each recorder and site the diffusivities determined for Day 10 were used to predict temperature fluctuation over several days starting at Day 8 or 9 and running to Day 11. This was a period of sunny weather where the diurnal temperature fluctuation was most accurately described by a sine function (Table 6, Appendix B).

The most accurate simulation over the three day period occurred at the front site where maximum error of the 5 cm level was .4°C. There was some increase in error at the 15 cm level of A1 (Fig. 11) but not in any other profile. There was also some accumulation of heat in the 30-50 cm levels in the predicted temperatures which was not evidenced in the actual measurements. Accumulation was as great as .7°C after 3 days.

Fit of the upper levels (5-15) of the middle ridge and back ridge were accurate to a maximum deviation of .5°C with no appreciable heat accumulation after three or four days, however, predicted accumulation of the 30-50 cm levels was as great as 1.3°C. In some rods this heat accumulation had raised the predicted average at the 15 cm level after three days.

Site 3a showed the least accumulation of heat with a temperature difference after 3 days of .4^{o}C while all other sites were 1.^{0}C out at the 50 cm level.

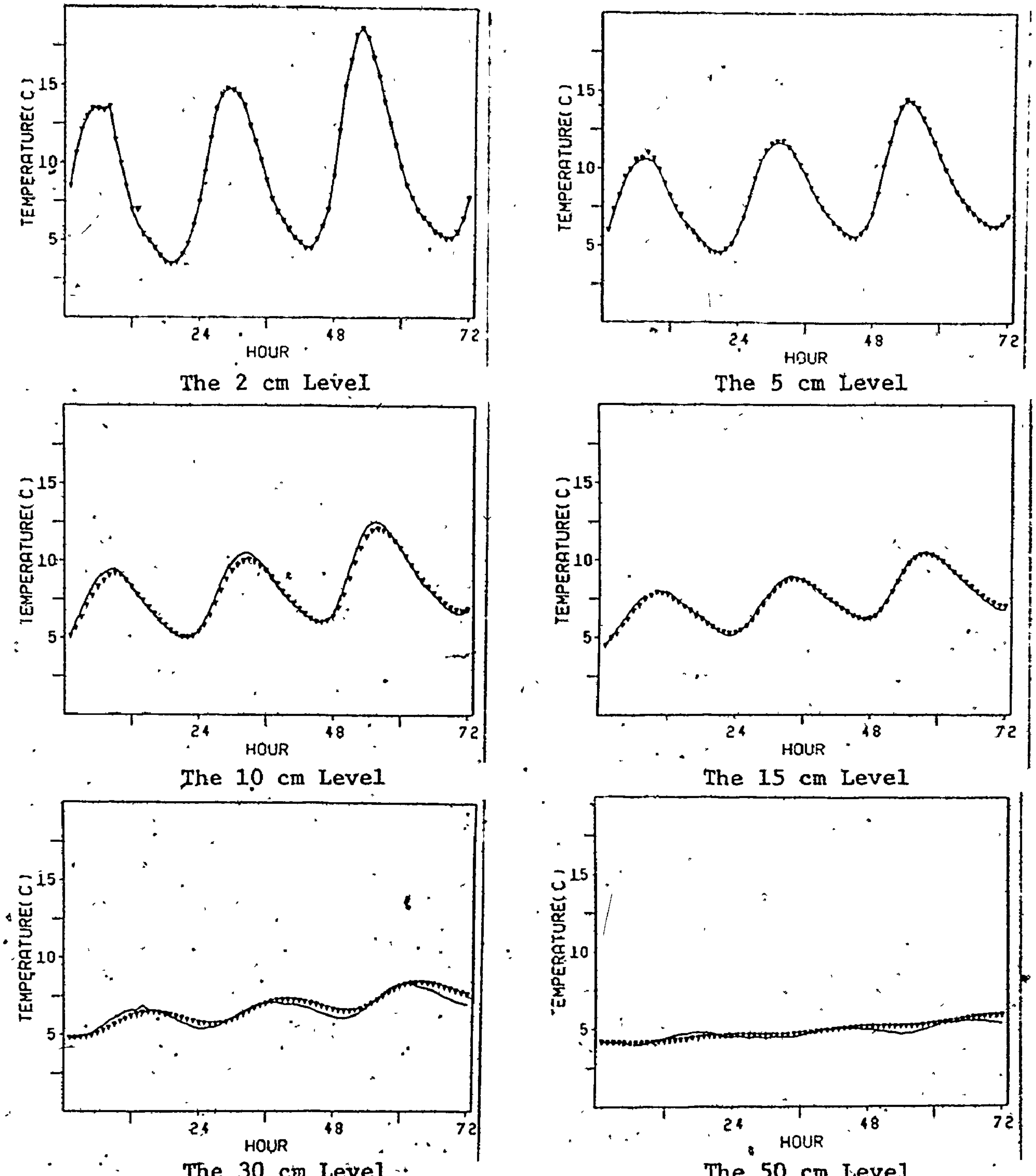
In some rods of 2a and 3b it was also noted that there was some accumulation at the 10-15 cm levels even after 24 hours and comparable with that observed in A1 of the front site; however, this is not restricted to any particular association but appears to be some difference in the thermal properties of the soil at this level or some error in the probe placement.

A visual representation of the extremes in the goodness of fit for the front site is given in Figs. 10 and 11 for the two rods under the Arctostaphylos rubra association. In A2 (Fig. 10), accuracy of prediction is good to the 15 cm level below which there is some alteration of the phase angle and, at the 50 cm level, some heat accumulation as well (.5^{o}C after a three day simulation).

In A1 (Fig. 11), the accumulation of heat and over prediction of the wave crest is evident at the 15 cm level and below, although the over prediction is not as pronounced in the lower layers. This type of accumulation was also present in some of the profiles from the middle and back sites and suggested a diurnal fluctuation in diffusivity or a diffusivity change down the profile.

5) Qualitative Tests for Changes in Diffusivity Down the Profile and Diurnally

Since there were no measurements of which would indicate a change of diffusivity down the profile or a diurnal fluctuation in diffusivity the changes in the model to accommodate either occurrence are arbitrary and are meant only to illustrate the influence each mechanism would have on the soil



Legend

▼ = Predicted

—— = Actual

Figure 10. The Prediction of Soil Temperature over Several Days

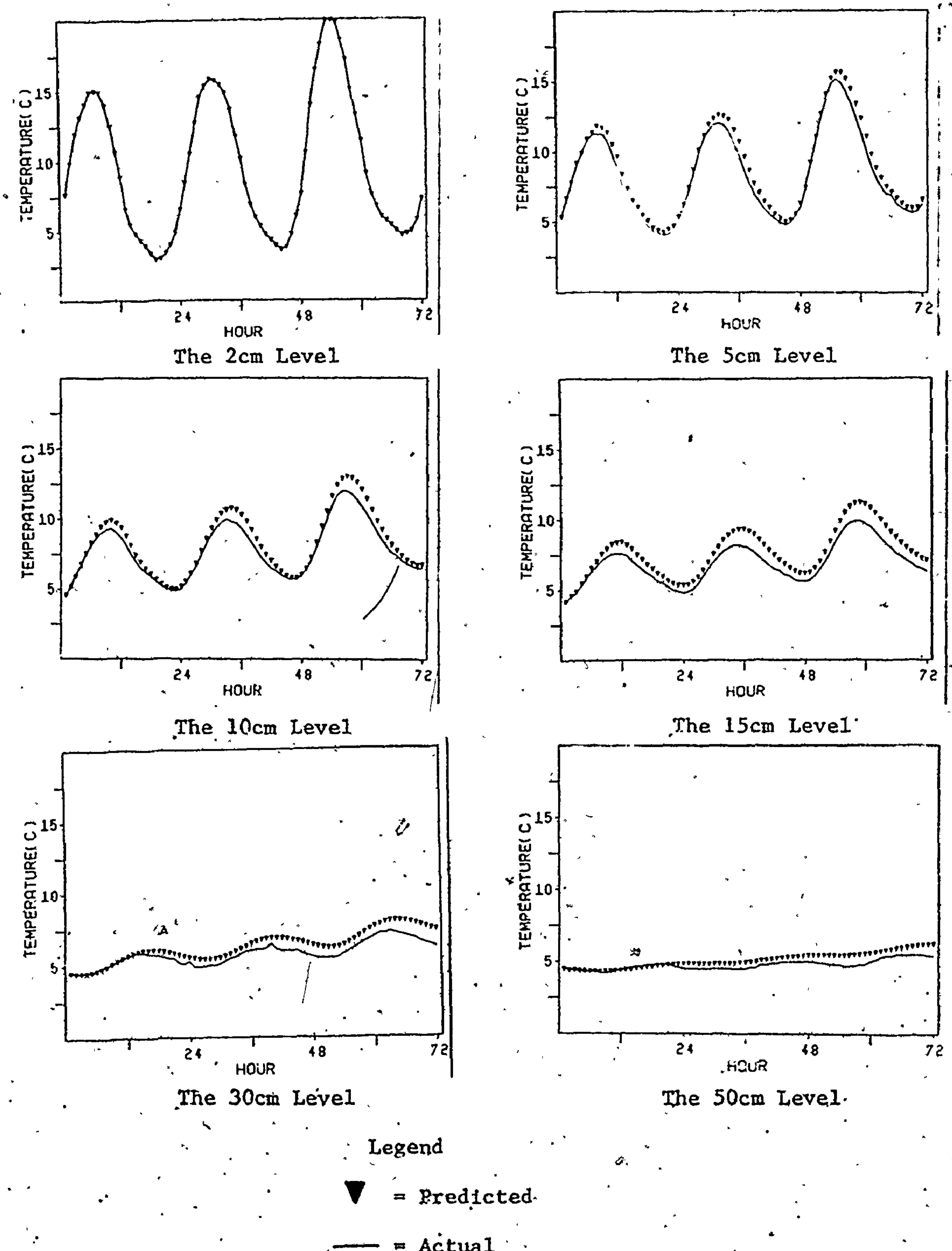


Figure 11. The Prediction of Soil Temperature over Several Days

temperature prediction.

i) Change of the Diffusivity Down the Profile; the 5-50 cm level.

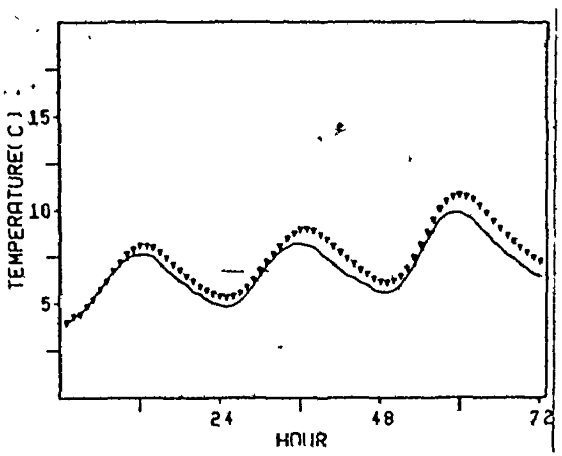
An increase of diffusivities to 30 and 40 cm^2/hr (Table 2, Appendix B) increased the heat accumulation in the lower levels of the predicted profile compared to actual although the daily temperature fluctuation as measured by the Fourier amplitude, were comparable.

By decreasing diffusivities to 10 and 16 cm^2 (Table 2, Appendix B) heat accumulation was reduced but underestimated the temperature fluctuation at the 50 cm level by 60% although in actual degrees centigrade the fluctuation was reduced by only .2°C.

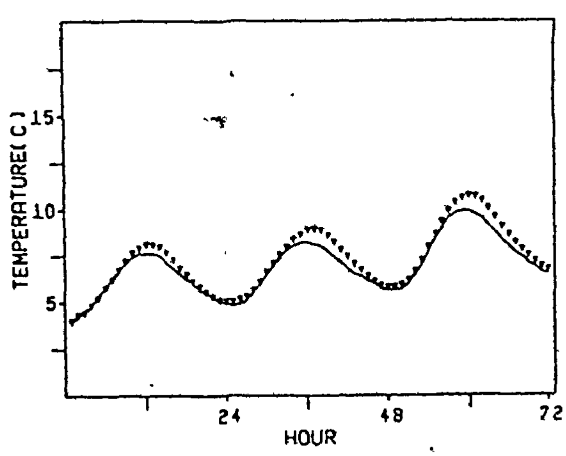
Increases in the diffusivity below the 15 cm level increased the accuracy of fit at the 15 cm level but dramatically increased heat accumulation by .4°C in a 24 hour period. From this it was concluded that a constant diffusivity at all levels could not account for the deviation of predicted temperature from actual.

ii) Diurnal Changes in Diffusivity

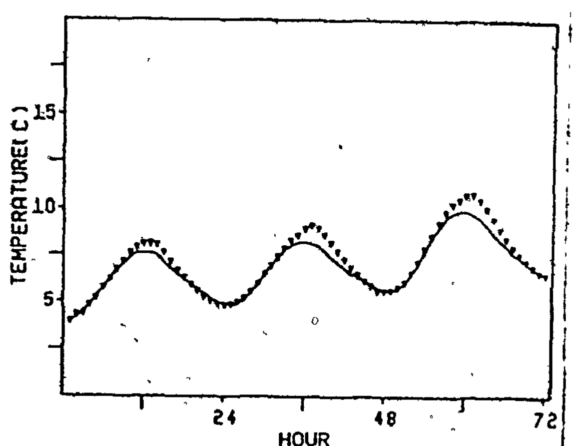
From the observations of daily and seasonal differences there appears to be a change in the energy flow whether the temperature is increasing or decreasing so that, for the first test, the diffusivity was doubled during periods of decreasing temperature at the 2 cm level in a step wise fashion for the 2-5 cm, 2-10 cm, and 2-15 cm levels. In Fig. 12a (15 cm level) it can be seen that, as the diffusivity is adjusted further into the soil the prediction of the wave trough becomes more accurate. However there is still a consistent over prediction of the wave crest. By inspection of the 50 cm level (Fig. 12b) over prediction is decreased but



Diurnal Diffusivity Fluctuation to the 5cm Level

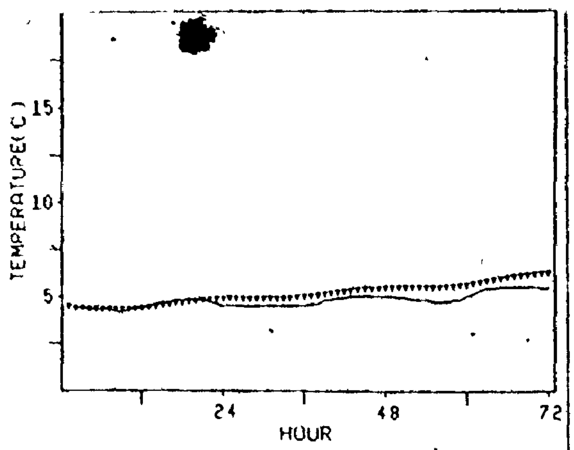


Diurnal Diffusivity Fluctuation to the 10cm Level

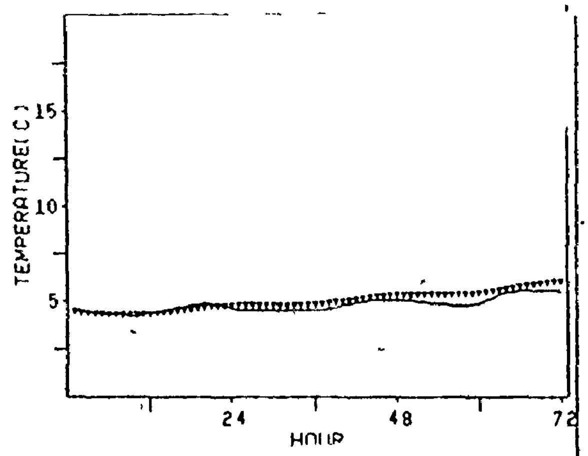


Diurnal Diffusivity Fluctuation to the 15cm Level

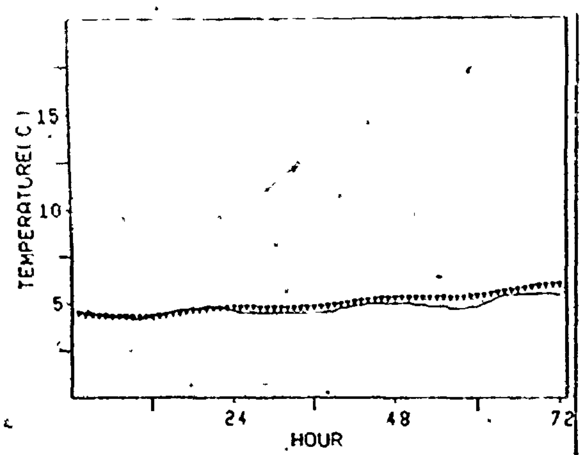
Figure 12a. Sensitivity of the Prediction of the 15cm Level to an Arbitrary Diurnal Diffusivity Fluctuation to Different Levels in the Soil



Diurnal Diffusivity Fluctuation
to the 5cm Level



Diurnal Diffusivity Fluctuation
to the 10cm Level



Diurnal Diffusivity Fluctuation
to the 15cm Level

Figure 12b. Sensitivity of the Prediction of the 50cm Level to an Arbitrary Diurnal Diffusivity Fluctuation to Different Levels in the Soil there is consistent under prediction of the temperature fluctuation at this level which while not significant as an absolute temperature variation, implies that there is some diurnal fluctuation of the diffusivity even at the 50 cm level.

By assuming that mass transfer occurs only in the organic layer as has previously been suggested (Nakano and Brown, 1972) and that it is controlled by temperature alone, (Westcott and Wieranga, 1974) the diffusivity was decreased like the upper half of a sine wave during the high temperature periods of the day at the 2 cm level so that minimum diffusivity occurred at maximum temperature and then increased to the original value of 12cm^2/hr for the night. The minimum diffusivity over the diurnal period ranged from 6-10 cm^2/hr in 2 cm^2/hr increments. Graphs of the prediction for all three diurnal changes in diffusivity are given in Fig. 13.

Predictive accuracy was greatly increased for the 15 cm level although there was some over prediction during times of decreasing temperature. Amplitude fluctuation at the 50 cm level was still under estimated, and at the 5 cm the maximum decrease in the diffusivity (to 6 cm^2/hr at 12 noon) greatly underestimated the temperature variation of this level.

From this test it is evident that there are two processes in operation which cannot be quantitatively specified. There is a diurnal fluctuation in the thermal diffusivity even to the 50 cm level and there is also some change in diffusivity with depth which is not consistent for all sites and profiles. Since there was not sufficient resolution in the particle size analysis to determine the diffusivity fluctuation down the

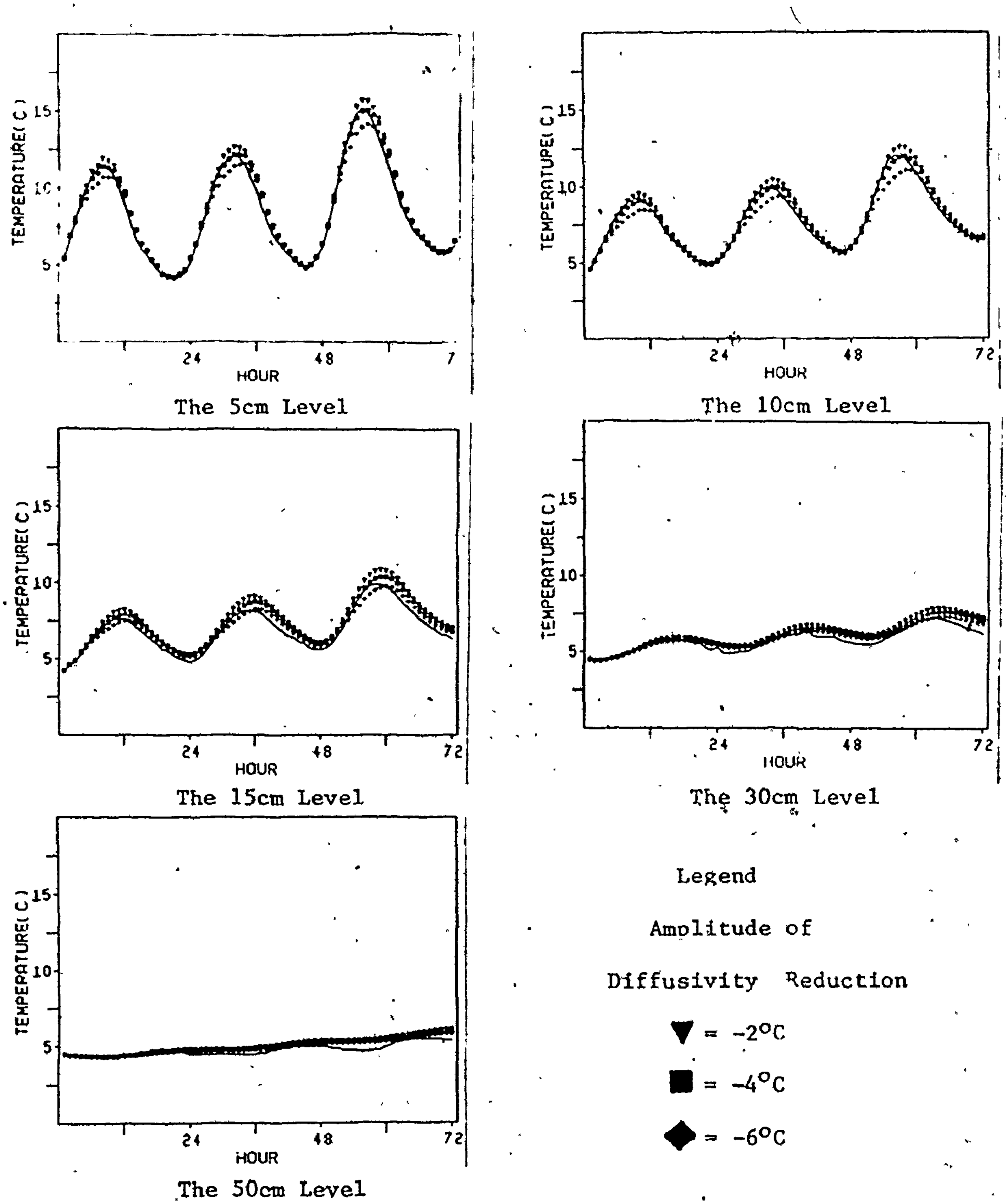


Figure 13. Sensitivity of the Model to a Sine-like Diurnal Change in the Diffusivity of the 2-5cm Level

profile and it was not possible to measure vapour flux changes in the soil, the separation of these two processes which affect the thermal diffusivity could not be made, effectively determining the end of the analysis.

From these qualitative tests of diurnal fluctuation of diffusivity, it has been established that the diurnal fluctuation in diffusivity does exist and that it occurs even to the 50 cm level. The heat accumulation observed over several days simulation is therefore interpreted as the result of the constant thermal conductivity used in the model.

(5.6) Discussion and Summary

There is some variation in the thermal diffusivity depending on the incoming energy conditions, and site and association differences which must be discussed before a summary of the results can be given.

There is a difference in diffusivity of the 2-5 cm level between the Dryas integrifolia-Alectoria ochroleuca association of the front ridge and all of the other sites and associations; however it was noted in the optimization procedure that the Dryas integrifolia association was the least sensitive to changes in diffusivity. The diffusivity under the Arctostaphylos rubra association of the front ridge was comparable to all other associations including the Dryas integrifolia-A. ochroleuca association of the middle ridge. This is in spite of the fact that there is an increase in humus depth of 2-4 cm between the front and the back two ridges, and implies that the depth of the humus layer below the 2 cm level has little effect on the distribution of energy and the subsequent soil temperature distribution during the field season.

This is supported by the observation of the actual Fourier amplitudes of the 50 cm level throughout all comparisons (Appendix B). In the middle and back sites temperature fluctuation at 50 cm is greater by .1 - .4°C than the front site, under sunny conditions. This is the opposite of the expected result if the organic layer was attenuating the temperature fluctuation as indicated by the assumption of literature values.

There was also a change in diffusivity under the Rhododendron lapponicum association depending on whether the day was cloudy or sunny and was demonstrated for the entire field season by the 2 cm analysis of daily increasing and decreasing temperatures (Section 4.4 (4), ii). These were the only instances of diffusivity changes on a daily basis and can be interpreted as a plant density difference over the soil surface. The open branching pattern of Rhododendron lapponicum allowed radiation to be absorbed by the soil surface directly. In the thick organic layer of the middle and back sites the direct absorption of radiation established a large temperature gradient in the first 5 cm of soil induced a mass transfer of water vapour out of the layer. The energy required for evaporation under this high thermal gradient was responsible for the decrease in diffusivity observed under sunny day conditions. It should be noted that under low incoming energy the diffusivity under Rhododendron is comparable to that of the rest of the associations.

Although it appears that the difference in humus depth has little effect on the heat distribution during the field season there are differences in temperatures throughout the rooting zone and in permafrost levels between sites. Differences in snow depth may explain part of the difference in the permafrost depth between sites especially between the middle and the back sites where the humus layer is of approximately the same depth but the permafrost is 20 cm closer to the soil surface at the back site. Since the back site has a much shallower topography and is more distant from the coast, snow may tend to remain on it longer during the spring melt. However, it is unlikely that the snow depths of the middle and front site are sufficiently different to account for the large difference in permafrost depth and the consequent increase in soil temperature of the rooting depth zone of the front site.

It has been demonstrated (Nakano and Brown, 1972) that thaw of the organic soils is much slower than that of mineral soils because of the large latent heat function in the organic layer during the thaw. It is this difference between the front and the back two sites which I postulate as the main cause of the permafrost difference.

In conclusion the assumption of heat conduction as the mechanism of energy transfer made in Section IV is not entirely valid in the Pen Island soils. A quantitative relationship between transfer of energy out the soil by mass transfer of water vapour and soil temperature could not be made but it was established that some vapour transfer occurred to the 50 cm level, the base of the rooting zone as defined in this thesis. However, by a combination of the interpretation of the differences at the 2 cm level under Rhododendron and vapour transfer it was possible to explain the differences in thermal diffusivity for sunny and cloudy conditions as a vapour transfer induced by high thermal gradients in the humus layer.

Since there is no effective difference in thermal properties between sites during the field season except under the Rhododendron association, it is postulated that the differential thaw of the thicker organic layer of the middle site when compared to the sand of the front site is the determining factor in the difference observed in temperatures of the rooting zone and in the permafrost depth.

Section VI

SUMMARY OF FINDINGS

There are two different aspects of the relationship of plant association to physical soil environment which have been considered in this study: 1) the influence of the plant association over the soil temperature in the upper levels of the soil and 2) the potential influence of physical differences, which are related to the time sequence established from the Hudson Bay coast to the treeline, over plant development.

1) Plant Association Control over Soil Temperature.

Coupling the findings of the quantitative description of the 2 cm level with the results of the model prediction it has been demonstrated that there are fluctuations in the amount of energy transferred to the soil under different plant covers but that this is most likely a result of plant density differences in vertical projection rather than discrete changes in albedo from plant association to plant association. The plant density difference in turn, sets up different temperature gradients in the upper layers of the soil which differentially alter the exchange of water vapour with the atmosphere, so that there are two factors which are essentially inseparable that control energy flow to the rooting zone during the summer season: plant density and mass transfer of water vapour in the humus layer.

This points to an over-simplification of the energy balance (Equation 1) in the determination of the microenvironment of the plant.

The assumption of a plant surface as the energy exchange boundary, is only possible to a limited extent in the research area. When measurements are made at the 1 m level (Rouse and Stewart, 1973) the surface of energy exchange is homogeneous as evidenced by the accuracy of their results, however, at the individual plant level there is a measureable difference in the surfaces of energy absorpiton and dissipation as evidenced by the combination of the 2 cm description under different associations and the model prediction of daily and diurnal fluctuation in the thermal diffusivity.

The implications of this slight difference in energy regime is not readily apparent since studies of growth of the vascular flora of the coastal tundra are few. It is unlikely that this small energy difference found in ridges close to the tree line has any effect on the germination on subsequent establishment of the seedlings of Picea mariana (the only ridge crest species) since this is a wide ranging species which must germinate over a wide range of environmental conditions (Rowe, 1959).

2) Physical Differences and Their Potential Influence over Plant Development

From the modelling of soil temperature (Section V) it was demonstrated that humus differences between sites had little influence over the distribution of energy in the rooting depth zone for the field season. However, it was noted that there were differences in soil temperature and permafrost depths between sites and it was postulated that these differences were initiated in the spring thaw and were not related to the physical or vegetation differences found between sites during the field season.

The argument is based on the large latent heat function of the organic layer which has been demonstrated in tundra soils (Nakano and Brown, 1972). The thicker the humus layer the more insulation it provides during spring thaw but once it and the sand layer adjacent to it are thawed the humus layer has much less importance in the distribution of energy in the soil.

Since this directly affects the permafrost level and the consequent availability of soil moisture, the middle and back ridges will have a higher atmospheric temperature for metabolism when soil moisture is readily available than the front site, where the fast thaw of the thin humus layer and the underlying sand quickly induces drought conditions.

The increase in available soil moisture during warm periods of the year from the coast to the tree line is of obvious significance in the formation of the tree line. The similarity in the moisture characteristic of the ridge coupled with their predictable above surface and below surface energy exchange and consequent levels of permafrost and soil moisture demonstrates the importance of the coastal tundra zone as a study area for the phenomena of the tree line.

APPENDIX A

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Table I

LINEAR REGRESSION OF AVERAGED DATA
THE 2 CM LEVEL
TOTAL DATA

Site	Variable Ind	Variable Dep	Regression Coefficient	Intercept	Range (Independent Variable)
1	A1	A2	1.1 ± .0*	-.9 ± .4**	4.6-15.9
		D1	1.1 ± .0	-.2 ± .4	
		D2	1.1 ± .0	-.9 ± .4	
	A2	D1	1.0 ± .0	.8 ± .3	4.1-15.5
		D2	1.0 ± .0	.2 ± .3	
	D1	D2	1.0 ± .0	-.5 ± .5	4.7-15.8
2a	D1	D2	1.0 ± .1	.1 ± .4	4.1-13.1
		R1	1.1 ± .1	-.3 ± .7	
		R2	.9 ± .2	1.5 ± 1.4	
	D2	R1	1.1 ± .1	-.5 ± .5	3.9-13.8
		R2	1.0 ± .2	.3 ± 1.5	
	R1	R2	.9 ± .1	1.1 ± 1.7	4.1-13.4
2b	D1	D2	1.1 ± .0	-.4 ± .2	4.0-13.4
		R1	1.1 ± .0	-1.1 ± .4	
		R2	1.1 ± .0	-.6 ± .2	
	D2	R1	1.1 ± .0	-.7 ± .3	3.5-13.8
		R2	1.0 ± .0	-.2 ± .2	
	R1	R2	1.0 ± .0	.6 ± .3	3.8-13.9
3a	C1	C2	1.1 ± .0	-.03 ± .2	3.5-14.2
		R1	1.1 ± .1	-.3 ± .4	
		R2	.8 ± .1	.4 ± .9	
	C2	R1	1.1 ± .0	-.3 ± .4	3.0-13.2
		R2	.8 ± .1	.5 ± .9	
	R1	R2	.7 ± .1	.9 ± 1.1	3.3-13.8
3b	C1	C2	1.0 ± .1	-.5 ± .8	4.1-13.0
		R1	1.3 ± .2	-1.6 ± 1.3	
		R2	1.2 ± .1	-1.7 ± 1.0	
	C2	R1	1.3 ± .2	-.4 ± 1.4	3.2-12.7
		R2	1.2 ± .1	-1.1 ± .6	
	R1	R2	.8 ± .1	.1 ± .9	4.3-15.6

* calculated as the standard deviation of the regression coefficient (Wang Lab. Ref. Manual, 1972).

** calculated as the standard deviation of the intercept (Wang Lab. Ref. Manual, 1972).

LINEAR REGRESSION OF AVERAGED DATA
THE 2 CM LEVEL
DAYS OF INCREASING TEMPERATURE

Site	Variable Ind	Variable Dep	Regression Coefficient	Intercept
1	A1	A2	1.1 ± .0	-1.4 ±.3
		D1	1.1 ± .0	-.7 ±.3
		D2	1.1 ± .0	-1.2 ±.3
	A2	D1	1.0 ± .0	.8 ±.2
		D2	1.0 ± .0	.2 ±.2
	D1	D2	1.0 ± .0	-.4 ±.4
2a	D1	D2	1.0 ± .0	.4 ± .3
		R1	1.0 ± .1	.3 ± .4
		R2	.8 ± .1	3.0 ± .7
	D2	R1	1.0 ± .0	-.2 ± .3
		R2	.9 ± .1	1.9 ±1.3
	R1	R2	.8 ± .1	2.9 ± .7
2b	D1	D2	1.1 ± .0	-.6 ± .1
		R1	1.1 ± .0	-.7 ± .2
		R2	1.1 ± .0	-.6 ± .2
	D2	R1	1.1 ± .0	-.8 ± .2
		R2	1.0 ± .0	-.2 ± .1
	R1	R2	1.0 ± .0	.6 ± .1
3a	C1	C2	1.0 ± .0	.1 ± .1
		R1	1.1 ± .0	-.2 ± .2
		R2	.8 ± .1	.4 ± .4
	C2	R1	1.1 ± .0	-.2 ± .2
		R2	.8 ± .1	.3 ± .5
	R1	R2	.7 ± .1	.6 ± .6
3b	C1	C2	1.1 ± .1	-1.6 ± .8
		R1	1.3 ± .1	-.8 ± .7
		R2	1.3 ± .1	-2.5 ± .8
	C2	R1	1.5 ± .1	1.3 ± .5
		R2	1.2 ± .0	-.6 ± .3
	R1	R2	1.0 ± .0	-1.6 ± .5

Table 3

LINEAR REGRESSION OF AVERAGED DATA
THE 2 CM LEVEL
DAYS OF DECREASING TEMPERATURE

Site	Variable Ind	Variable Dep	Regression Coefficient	Intercept
1	A1	A2	1.1 ± .0	-1.0 ± .4
		D1	1.1 ± .0	-.2 ± .3
		D2	1.1 ± .1	-.7 ± .5
	A2	D1	1.0 ± .0	.9 ± .2
		D2	1.0 ± .0	.4 ± .4
	D1	D2	1.0 ± .0	-.4 ± .4
2a	D1	D2	1.0 ± .0	-.2 ± .3
		R1	1.1 ± .0	-.9 ± .3
		R2	1.1 ± .1	-.5 ± .9
	D2	R1	1.1 ± .0	-.7 ± .3
		R2	1.1 ± .7	-.7 ± .6
	R1	R2	1.0 ± .1	.3 ± .6
2b	D1	D2	1.1 ± .0	-.6 ± .1
		R1	1.1 ± .0	-.7 ± .2
		R2	1.1 ± .0	-.6 ± .2
	D2	R1	1.0 ± .0	-.2 ± .2
		R2	1.0 ± .0	-.1 ± .1
	R1	R2	1.0 ± .0	.2 ± .2
3a	C1	C2	1.1 ± .0	-.2 ± .2
		R2	1.0 ± .0	.4 ± .[illegible]
		R2	.9 ± .1	1.0 ± .7
	C2	R1	.9 ± .1	.6 ± .4
		R2	1.0 ± .1	.8 ± .7
	R1	R2	1.1 ± .1	-.2 ± 1.0
3b	C1	C2	.9 ± .0	.1 ± .2
		R1	1.1 ± .2	-.6 ± 1.2
		R2	1.0 ± .1	-.1 ± .5
	C2	R1	1.2 ± .2	-.6 ± 1.4
		R2	1.0 ± .1	-.2 ± .4
	R1	R2	.7 ± .1	1.5 ± .8

LINEAR REGRESSION OF AVERAGED DATA
THE 50 CM LEVEL
THE TOTAL DATA

Site	Variable Ind	Variable Dep	Regression Coefficient	Intercept
1	A1	A2	1.1 ± .1	-.3 ± .5
		D1	1.0 ± .1	-.1 ± .5
		D2	1.1 ± .1	- 3 ± .5
	A2	D1	1.0 ± .1	-.1 ± .4
		D2	1.1 ± .1	-.0 ± .5
	D1	D2	1.1 ± .0	-.1 ± .2
2a	D1	D2	.9 ± .1	.2 ± .3
		R1	1.0 ± .1	.0 ± .2
		R2	1.0 ± .1	.1 ± .3
	D2	R1	1.1 ± .1	-.2 ± .3
		R2	1.1 ± .0	-.1 ± .2
	R1	R2	1.0 ± .1	.1 ± .3
2b	D1	D2	1.0 ± .0	-.3 ± .1
		R1	1.0 ± .1	.1 ± .3
		R2	1.0 ± .1	.0 ± .3
	D2	R1	1.0 ± .1	.2 ± .3
		R2	.9 ± .1	.2 ± .2
	R1	R2	1.0 ± .0	.0 ± .1
3a	C1	C2	1.0 ± .1	.3 ± .2
		R1	1.0 ± .0	.0 ± .1
		R2	1.0 ± .1	.0 ± .3
	C2	R1	1.0 ± .1	-.3 ± .2
		R2	1.0 ± .1	-.3 ± .2
	R1	R2	.9 ± .1	.0 ± .2
3b	C1	C2		
		R1		
		R2		
	C2	R1	1.1 ± .1	.3 ± .2
		R2	1.0 ± .0	-.1 ± .0
	R1	R2	.9 ± .1	-.4 ± .2

Table 5

LINEAR REGRESSION OF FOURIER COEFFICIENTS
THE 2 CM LEVEL
TOTAL DATA

Site	Variable Ind	Variable Dep	Regression Coefficient	Intercept	Range (Independent Variable)
1	A1	A2	.9 ± .0	.0 ± .1	1.3-7.3
		D1	.9 ± .0	.0 ± .1	
		D2	.9 ± .0	.4 ± .1	
	A2	D2	1.0 ± .0	.1 ± .1	1.2-6.1
		D2	1.0 ± .0	.5 ± .1	
	D1	D2	.9 ± .0	.4 ± .1	1.2-6.6
2a	D1	D2	1.0 ± .1	.2 ± .3	.6-3.9
		R1	1.1 ± .1	.2 ± .4	
		R2	1.4 ± .5	.6 ±1.4	
	D2	R1	1.3 ± .1	-.5 ± .4	.8-4.3
		R2	2.5 ± .1	1.1 ± .4	
	R1	R2	1.1 ± .4	.7 ±1.4	.7-4.9
2b	D1	D2	.9 ± .0	.0 ± .1	.7-4.4
		R1	1.1 ± .1	.0 ± .2	
		R2	.9 ± .1	.2 ± .2	
	D2	R1	1.3 ± .0	-.1 ± .1	.7-4.7
		R2	1.0 ± .1	.1 ± .1	
	R1	R2	.7 ± .0	.24 ± .9	.7-3.7
3a	C1	C2	.9 ± .1	.4 ± .3	.9-5.0
		R1	1.3 ± .3	.0 ±1.3	
		R2	.6 ± .1	-.1 ± .4	
	C2	R1	1.4 ± .1	-.3 ± .2	1.2-4.7
		R2	.9 ± .1	-1.2 ± .3	
	R1	R2	.6 ± .1	.8 ± .5	1.6-6.3
3b	C1	C2	.4 ± .1	1.5 ± .2	1.1-7.2
		R1	.9 ± .1	2.4 ± .4	
		R2	.5 ± .1	2.0 ± .3	
	C1	R1	2.0 ± .2	.1 ± .6	1.0-4.4
		R2	1.0 ± .1	.9 ± .3	
	R1	R2	.5 ± .1	.6 ± .3	2.1-8.6

Table 6

LINEAR REGRESSION OF FOURIER COEFFICIENTS
THE 5 CM LEVEL
TOTAL DATA

1	A1	A2	.8 ± .0	.2 ± .1	.8-4.2
		D1	1.1 ± .0	.1 ± .1	
		D2	1.2 ± .0	.6 ± .1	
	A2	D1	1.3 ± .0	-.1 ± .1	.8-3.8
		D2	1.4 ± .1	.5 ± .1	
	D1	D2	1.1 ± .0	.5 ± .1	.9-4.7
2a	D1	D2	1.0 ± .1	.1 ± .2	.5-2.7
		R1	1.0 ± .1	.0 ± .3	
		R2	.9 ± .2	.3 ± .4	
	D2	R1	1.1 ± .1	-.2 ± .2	.5-3.1
		R2	1.3 ± .1	-.3 ± .3	
	R1	R2	1.0 ± .1	.1 ± .2	.5-3.0
2b	D1	D2	1.0 ± .0	.0 ± .1	1.0-2.4
		R1	.8 ± .1	.0 ± .2	
		R2	.7 ± .1	.2 ± .1	
	D2	R1	.8 ± .1	.1 ± .1	1.2-2.7
		R2	.8 ± .1	.1 ± .1	
	R1	R2	.9 ± .1	.2 ± .1	.9-2.8
3a	C1	C2	.8 ± .1	.2 ± .2	.5-3.2
		R1	.9 ± .1	-.2 ± .2	
		R2	.6 ± .1	.2 ± .1	
	C2	R1	1.0 ± .1	.2 ± .1	.5-2.5
		R2	.8 ± .1	-.2 ± .2	
	R1	R2	.8 ± .1	-.1 ± .1	.4-2.4
3b	C1	C2	.9 ± .1	.1 ± .1	.5-2.7
		R1	.9 ± .1	.4 ± .2	
		R2	.6 ± .1	.2 ± .1	
	C2	R1	.9 ± .1	.4 ± .2	.4-2.8
		R2	.7 ± .1	.1 ± .1	
	R1	R2	.6 ± .1	.1 ± .2	.4-2.2

Table 7

LINEAR REGRESSION OF AVERAGED DATA
2 CM LEVEL

Site		Regression Coefficient	Intercept
1	2a	.8 ± .1	.5 ± .6
	2b	.8 ± .1	-.2 ± .5
	3a	.9 ± .1	-1.5 ± .6
	3b	.9 ± .1	.8 ± .8
2a	2b	1.1 ± .0	-.8 ± .3
	3a	1.2 ± .1	-2.9 ± .4
	3b	1.1 ± .1	-1.8 ± .7
2b	3a	1.0 ± .0	-1.0 ± .3
	3b	1.0 ± .1	-.2 ± .6
3a	3b	1.0 ± .0	.7 ± .4

Table 8

LINEAR REGRESSION OF AVERAGED DATA
50 CM LEVEL

Site		Regression Coefficient	Intercept
1	2a	.7 ± .1	-.6 ± .5
	2b	.9 ± .1	-2.0 ± .7
	3a	.9 ± .1	-2.3 ± .7
	3b	.9 ± .2	-2.8 ±1.1
2a	2b	1.1 ± .1	-.5 ± .3
	3a	1.1 ± .1	-1.3 ± .4
	3b	1.3 ± .1	-1.8 ± .4
2b	3a	.8 ± .1	-.1 ± .2
	3b	1.0 ± .1	.3 ± .4
3a	3b	1.1 ± .1	-.1 ± .2

Table 9

LINEAR REGRESSION OF FOURIER SERIES COEFFICIENTS
THE 2 CM LEVEL

Site		Regression Coefficient	Intercept
1	2a	.8 ± .1	-.2 ± .3
	2b	.6 ± .1	.4 ± .3
	3a	.5 ± .3	.7 ±1.5
	3b	.9 ± .1	-.2 ± .3
2a	2b	.8 ± .1	.4 ± .3
	3a	.6 ± .1	1.5 ± .4
	3b	1.2 ± .2	-.1 ± .6
2b	3a	1.0 ± .1	.4 ± .4
	3b	1.4 ± .2	-.3 ± .5
3a	3b	1.1 ± .2	.0 ± .9

Table 10

LINEAR REGRESSION OF FOURIER SERIES COEFFICIENTS
THE 5 CM LEVEL

Site		Regression Coefficient	Intercept
1	2a	.6 ± .1	.0 ± .3
	2b	.5 ± .0	.2 ± .1
	3a	.5 ± .1	.1 ± .4
	3b	.5 ± .1	-.1 ± .2
2a	2b	.9 ± .1	.1 ± .1
	3a	.8 ± .4	-.1 ± .9
	3b	.8 ± .2	.2 ± .5
2b	3a	.9 ± .1	.0 ± .3
	3b	1.0 ± .1	-.2 ± .2
3a	3b	.9 ± .2	.3 ± .3

APPENDIX B

LIST OF TABLES

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Table 1, Appendix B

Prediction with Literature Values
Organic diffusivity=3.16cm^2/hr
Sand diffusivity=41.25cm^2/hr
(from Kersten, 1949)

Site 1, Association A1
Humus Depth = 0.0 cm

Level	Amplitude		Phase		Average	
	P-A*(°C)	Actual(°C)	P-A*(hr)	Actual(r)	P-A*(°C)	Actual(°C)
5 cm	1.6	3.9	.4	.9	.8	8.6
10 cm	1.5	2.1	1.2	.5	.6	7.9
15 cm	1.1	1.2	1.6	.1	.8	6.9
30 cm	.4	.4	2.0	4.9	.4	5.8
50 cm	.2	.3	1.6	3.5	.1	4.8

Site 2b, Association D1
Humus Depth = 3.8 cm

5 cm	-1.1	2.3	-.4	.1	-1.3	6.1
10 cm	-.8	1.4	.0	5.8	-1.0	5.2
15 cm	-.6	1.0	.8	5.3	-.9	4.9
30 cm	-.5	.8	.0	4.0	-.1	3.2
50 cm	-.4	.7	-1.6	3.6	-.1	2.3

Site 3b, Association C1
Humus Depth = 2.6 cm

5 cm	-.8	2.5	-.4		-1.0	6.2
10 cm	-.4	1.5	.0		-.3	5.0
15 cm						
30 cm	-.4	1.0	.0		-.1	3.0
50 cm	-.2	.7	-.8		.1	1.6

* Predicted-Actual (°C)

Table 2

Sensitivity of the Prediction to changes in the Diffusivity Down the Profile

Site 1, Association A1

Levels	Amplitude** 1	2	3	4	5	6	7*	Act.	Phase 1	2	3	4.	5	7*	Act.	Average 1	2	3	4	5	6	7*	Act.
5 cm	-.6	.0	-.2	.0	.0	-.3	.4	3.9	-.7	-.3	-.4	-.3	-.2	-.4	.9	.0	.3	.1	.2	.2	.3	.5	8.6
10 cm	.0	.4	.4	.4	.3	.1	.4	2.1	-.4	-.1	.0	.0	.1	-.4	.5	.2	.4	.3	.2	.1	.3	.5	7.9
15 cm	.2	.4	.4	.3	.2	.1	.3	1.2	-.3	.0	.4	.1	.1	-.4	.1	.6	.7	.6	.5	.3	.6	.7	6.9
30 cm	.1	.2	.2	.2	.2	.1	.1	.4	-.7	-.3	.7	.5	1.0	-2.0	4.9	.4	.5	.5	.5	.4	.3	.4	5.8
50 cm	.1	.1	.2	.1	.1	.0	.0	.3	-.3	-.2	.6	.5	1.0	-1.2	3.5	.3	.3	.4	.4	.4	.1	.1	4.8

Legend*

Diffusivity (cm^2/hr)

Level	1	2	3	4	5	6	7
2- 5 cm	8	12	12	12	12	8	12
5-10 cm	30	30	40	30	30	20	20
10-15 cm	30	30	40	30	30	20	20
15-30 cm	30	30	40	40	50	20	20
30-50 cm	30	30	40	40	50	20	20
50-2000 cm	30	30	40	40	50	20	20

* Predicted - Actual
** Legend

Site 1, Association DI

Level	Amplitude** (°C) 1	2	3	4	5	6*	Phase (hr) 1	2	3	4	5	6*	Average (°C) 1	2	3	4	5	6*
5 cm	-.3	-.2	-.1	-.4	-.3	-.4	.2	+.2	.4	.0	.3	.2	.1	.1	.1	.0	.1	.0
10 cm	-.2	.0	.1	.0	-.1	-.1	-.4	-.2	.0	-.2	-.4	-.2	.5	.5	.5	.5	.4	.3
15 cm	-.2	.0	.1	.0	-.1	-.1	-1.2	-.8	-.4	-.6	-.8	-.6	.4	.4	.4	.3	.2	.2
30 cm	-.1	-.1	.0	.0	-.1	-.1	-3.6	-2.8	-1.6	-2.0	-2.4	-1.4	.2	.3	.3	.3	.2	.2
50 cm	.1	+.2	+.3	.3	.2	.3	-3.2	-2.8	-2.0	-2.4	-2.0	-1.2	.3	.4	.5	.5	.5	.5

Legend*

Diffusivity (cm²/hr)

Level	1	2	3	4	5	6
2-5 cm	16	20	24	18	18	18
5-10 cm	16	20	24	24	20	22
10-15 cm	16	20	24	24	22	26
15-30 cm	16	20	24	24	24	30
30-50 cm	16	20	24	24	26	34
50-2000 cm	16	20	24	24	28	39

* Predicted - Actual
** Legend

TABLE 3

PREDICTION USING DIFFERENT 2-5 CM DIFFUSIVITIES

Day 10

<u>SITE 1</u>

Assoc.	Level	Amplitude** (°C) 4	8	12	16	20	24*	Actual (°C)	Phase** (hr) 4	8	12	16	20	24*	Actual (r)	Average** (°C) 4	8	12	16	20	24*	Actual (°C)
A1	5 cm	-1.3	-.3	.4	.8	1.1		3.9	-1.6		-.4	.0	.4			.1	.3	.5	.6	.8		8.6
	10 cm	-.5	.1	.4	.6	.8		2.1	-1.2		-.4	.0	.0			.1	.3	.5	.5	.6		7.9
	15 cm	-.2	.1	.3	.4	.5		1.2	-1.6		-.4	-.4	.0			.5	.6	.7	.7	.8		6.9
	30 cm	.0	.1	.1	.1	.1		.4	-2.7		-2.0	-1.6	-1.6			.3	.3	.4	.4	.4		5.8
	50 cm	.0	.0	.0	.0	.0		.3	-1.6		-1.2	-1.2	-1.2			.1	.1	.1	.1	.2		4.8
A2	5 cm	-.9	-.6	-.4	.7	1.0		3.2	-1.2		.0	.4	.4			-.3	.0	.2	.3	.4		8.8
	10 cm	-.7	-.4	-.3	.1	.3		2.2	-1.2		-.4	.0	.0			-.3	-.1	.0	.0	.1		8.3
	15 cm	-.3	-.1	-.2	.2	.3		1.2	-.8		.0	.4	.4			-.1	.0	.1	.1	.1		7.6
	30 cm	-.1	-.1	.0	.0	.0		.5	-2.0		-1.2	-1.2	-1.2			.1	.2	.2	.2	.2		6.0
	50 cm	.0	.0	.0	.0	.0		.3	-1.6		-1.6	-1.6	-1.6			.1	.1	.1	.1	.1		4.8
D1	5 cm	-1.8	-.9	-.4	.1	.2		4.3	-1.6		-.4	-.4	.0			-.4	-.2	.0	.1	.1		9.6
	10 cm	-.8	-.3	.0	.2	.3		2.5	-1.6		-.8	-.8	-.4			.3	.4	.4	.5	.5		8.5
	15 cm	-.5	-.3	.0	.1	.2		1.6	-2.0		-1.2	-1.2	-.8			.2	.3	.4	.4	.4		8.1
	30 cm	-.1	.0	.0	.0	.0		.5	-3.2		-2.4	-2.0	-2.0			.2	.2	.2	.2	.2		6.6
	50 cm	.0	.0	.1	.1	.1		.3	-1.2		-1.2	-1.2	-1.2			.3	.3	.3	.3	.3		4.9
D2	5 cm	-2.5	-1.7	-1.3	-.9	-.7	-.6	5.3	-2.0		-1.2	-.8	-.8	-.8		-.6	-.5	-.4	-.3	-.3	-.3	10.0
	10 cm	-1.9	-1.4	-1.2	-1.0	-.9	-.8	3.9	-2.4		-1.6	-1.6	-1.6	-1.2		-.4	-.4	-.3	-.3	-.3	-.3	9.4
	15 cm	-.4	-.1	.0	-.1	-.2	.2	1.7	-1.6		-1.2	-1.2	-.8	-.8		.4	.4	.4	.4	.4	.4	8.0
	30 cm	-.1	-.1	.0	.0	.0	.0	.6	-3.6		-2.4	-2.0	-2.0	-2.0		.3	.3	.3	.3	.3	.3	6.5
	50 cm	.0	.0	.0	.0	.0	.0	.4	-2.0		-1.6	-1.6	-1.6	-1.6		.2	.2	.2	.2	.2	.2	5.0

* Diffusivity of the 2-5 cm Level (cm^2/hr)
** Quoted as Predicted-Actual

SITE 2A

Assoc.	Level	Amplitude**(°C) 3	4	5	8	12	16*	Actual (°C)	Phase **(hr) 3	4	5	8	12	16*	Actual(r)	Average**(°C) 3	4	5	8	12	16*	Actual (°C)
D1	5 cm	-1.0		-.7	-.2	.1	.1	1.81	-1.2		-.8	-.4	.0	.4	.07	-.9		-.5	-.4	-.1	.2	6.06
	10 cm	-.7		-.5	-.1	.1	-.1	1.17	-1.6		-1.2	-.8	-.4	.0	5.85	-.7		-.3	-.3	-.2	.2	5.4
	15 cm	-.6		-.4	-.1	.1	-.1	.89	-1.6		-1.2	-.8	-.4	.0	5.24	-.5		-.3	-.3	-.2	.1	4.9
	30 cm	-.4		-.4	-.2	-.1	-.2	.70	-2.8		-2.9	-2.4	-2.0	.0	4.11	-.4		-.3	-.3	-.3	-.1	3.7
	50 cm	-.4		-.4	-.2	-.2	-.3	.6	-3.2		-3.2	-3.2	-3.2	-3.2	3.71	-.2		-.	-.	-.2	-.2	2.6
D2	5 cm	-1.0		-.7	-.3	.1	.3	2.2	-.8		-.8	-.4	.0	.4	.36	-1.1		-.3	-.3	-.3	-.2	6.8
	10 cm	-.5		-.2	.0	.2	.3	1.2	.0		.0	.4	.8	.8	5.99	-.2		.0	.2	1.3	.4	5.5
	15 cm	-.5		-.3	-.2	-.1	.0	1.0	.0		.0	.4	.4	.8	5.57	-.9		-.8	-.6	-.5	-.5	5.8
	30 cm	-.4		-.3	-.3	-.3	-.2	.7	2.0		1.6	1.2	1.2	1.2	4.23	-.2		-.1	-.1	.0	.0	3.9
	50 cm	-.2		-.2	-.1	-.1	-.1	.4	-2.8		-2.8	-2.8	-2.8	-2.8	3.79	-.2		-.2	-.2	-.1	-.1	2.6
R1	5 cm	-1.2		-.8	-.4	.1	.3	2.6	-1.6		-1.2	-.8	-.4	.0	.51	-.8		-.5	-.1	.1	.3	6.9
	10 cm	-.7		-.4	-.2	.1	.2	1.5	-.8		-.4	.0	.4	.4	6.15	-.5		-.2	.0	.2	.3	6.1
	15 cm	-.6		-.4	-.3	-.1	.0	1.1	-.4		-.4	-.0	.4	.8	5.59	-.4		-.2	.0	.2	.2	5.5
	30 cm	-.3		-.3	-.2	-.2	-.1	.7	-2.4		-2.0	-2.0	-1.6	-1.6	4.25	-.2		-.1	.0	.1	.1	4.0
	50 cm	-.3		-.2	-.2	-.2	-.2	.5	-3.2		-3.2	-3.2	-3.2	-3.2	3.82	-.1		-.1	-.1	-.1	.0	2.7
R2	5 cm	-.4	.0	.4	1.2	2.0	2.5	2.5	-.8		.0	.4	.8	.8	.62	-.1	.2	.5	.9	1.3	1.6	6.7
	10 cm	-.3	-.1	.1	.6	1.0	1.3	1.5	-.8		-.4	.0	.8	.8	.20	.0	.2	.3	.6	.9	1.0	6.0
	15 cm	-.2	-.1	.1	.3	.5	.6	.9	-.8		-.4	.0	.8	.8	5.89	.3	.4	.5	.7	.8	1.0	5.2
	30 cm	-.2	-.1	-.1	-.1	-.1	.0	.6	-2.0		-1.6	-1.2	-.8	-.8	4.36	.0	.0	.1	.2	.3	.3	4.0
	50 cm	-.2	-.2	-.2	-.2	-.1	-.1	.5	-3.2		-3.2	-3.2	-3.2	-3.2	3.84	.0	.0	.1	.1	.1	.1	2.9

* Diffusivity of the 2-5 cm Level (cm^2/hr)
** Quoted as Predicted-Actual

SITE 2B

Assoc.	Level	Amplitude** (°C) 4	8	12	16*	Actual (°C)	Phase** (hr) 4	8	12	16*	Actual (r)	Average** (°C) 4	8	12	16*	Actual (°C)
D1	5 cm	-1.0	-.4	-.1	.2							-.8	-.4	-.1	.0	
	10 cm	-.5	-.1	.1	.3							-.3	.0	.1	.2	
	15 cm	-.5	-.2	-.1	.0							-.5	-.2	-.1	.0	
	30 cm	-.4	-.3	-.3	-.3							-.1	-.1	-.1	.0	
	50 cm	-.4	-.4	-.4	-.4							-.3	-.3	-.2	-.2	
D2	5 cm	-1.4	-.8	-.5	-.3	2.4	-1.2	-.8	-.4		6.2	-1.1	-.6	-.3	-.2	6.6
	10 cm	-.8	-.2	-.2	-.1	1.4	-.8	-.4	-.4		5.6	-.6	-.2	.0	.1	5.6
	15 cm	-.6	-.4	-.2	-.2	1.1	-1.2	-.8	-.4		5.0	-.2	.1	.3	.4	4.6
	30 cm	-.4	-.3	-.2	-.2	.8	-2.4	-2.0	-2.0		4.0	-.3	-.1	.0	.0	3.3
	50 cm	-.4	-.4	-.3	-.3	.6	-2.4	-2.4	-2.4		3.6	-.1	-.1	-.1	.0	1.9
R1	5 cm	-.6	.1	.5	.8	2.0	-.4	.4	.8	.8	.12	-.3	-.2	.4	.8	5.6
	10 cm	-.2	.2	.5	.6	1.0	.4	1.2	1.2	1.6	5.65	-.1	.3	.5	.6	4.8
	15 cm	.3	.0	.2	.3	.8	-.4	1.2	1.6	2.0	4.99	-.1	.2	.3	.4	4.4
	30 cm	-.4	-.3	-.2	-.2	.8	-1.2	-.8	-.4	-.4	3.90	-.2	-.1	.0	.1	3.2
	50 cm	-.4	-.4	-.4	-.3	.6	-2.4	-2.4	-2.4	-2.4	3.58	-.3	-.3	-.3	-.3	2.3
R2	5 cm	-.7	-.2	.1	.3	1.8	-.4	.0	.4	.8	.01	-1.1	-.6	-.3	-.2	6.1
	10 cm	-.5	-.2	.0	.1	1.1	.4	.8	1.2	1.6	5.57	-.6	-.2	.0	.1	5.4
	15 cm	-.5	-.3	-.2	-.2	.9	-.4	.0	.4	.8	5.10	-.2	.1	.3	.4	4.8
	30 cm	-.4	-.3	-.3	-.2	.8	-1.6	-1.6	-1.2	-1.2	3.96	-.3	-.1	.0	.0	3.4
	50 cm	-.4	-.4	-.3	-.3	.6	-2.4	-2.4	-2.4	-2.4	3.62	-.1	-.1	-.1	.0	2.2

* Diffusivity of the 2-5 cm Level (cm^2/hr)
** Quoted as Predicted-Actual

SITE 3A

Assoc.	Level	Amplitude** (°C) 3	5	8	12*	Actual (°C)	Phase** (hr) 3	5	8	12*	Actual (r)	Average** (°C) 3	5	8	12*	Actual (°C)
C1	5 cm	-1.2	-.7	-.3	.1	2.2	-.8	-.8	-.4	.0	6.1	-1.7	-1.3	-1.0	-.8	6.0
	10 cm	-.6	-.3	.0	.2	1.3	-1.2	-.8	-.4	.0	5.6	-.3	.0	.2	.4	4.2
	15 cm	-.3	-.1	.1	.2	.8	-2.4	-2.0	-1.6	-1.3	5.3	.1	.3	.5	.7	3.4
	30 cm	-.1	.0	.1	.1	.4	-2.4	-2.0	-2.0	-1.6	4.0	-.2	.0	.1	.1	2.5
	50 cm	-.1	-.1	.0	.0	.3	-2.0	-2.0	-2.0	-2.0	3.4	.0	.0	.0	.1	1.4
C2	5 cm	-1.0	-.5	.0	.4	2.1	-1.2	-.4	.0	.4	5.9	-.7	-.2	.1	.4	5.2
	10 cm	-.5	-.2	.1	.3	1.3	-1.2	-.8	.0	.4	5.4	-.3	.0	.3	.5	4.4
	15 cm	-.4	-.2	.0	.2	.9	-1.6	-1.2	-.8	-.4	5.0	-.3	.0	.2	.3	3.9
	30 cm	-.2	-.1	.0	.1	.5	-2.4	-2.4	-2.0	-1.6	4.0	-.3	-.1	.0	.1	2.9
	50 cm	-.2	-.1	-.1	-.1	.3	-1.2	-1.2	-1.2	-1.2	3.2	-.1	.0	.0	.0	1.7
R1	5 cm	-.4	.3	1.0	1.6	1.9	-1.2	-.8	.0	.4	5.9	-.1	.5	1.0	2.2	4.8
	10 cm	.1	.4	.8	1.2	1.1	-.4	.0	.4	1.2	5.2	.2	.7	1.0	1.3	4.0
	15 cm	.0	.2	.5	.7	.8	-1.2	-.4	.4	.8	4.8	.2	.6	.9	1.0	3.5
	30 cm	.1	.1	.2	.3	.5	-2.0	-1.6	-1.2	-.8	3.8	-.1	.1	.3	.4	2.6
	50 cm	.1	.1	.1	.1	.3	-1.6	-1.6	-1.6	-1.2	3.2	.0	.1	.1	.1	1.5
R2	5 cm	-.9	-.6	-.3	-.1	1.4	-1.6	-1.2	-.8	-.4	5.7	-1.0	-.7	-.5	-.3	4.6
	10 cm	-.6	-.4	-.2	.0	1.0	-2.0	-2.0	-1.2	-.4	5.2	-.5	-.2	.0	.1	3.7
	15 cm	-.4	-.3	-.2	-.1	.7	-2.4	-2.0	-1.6	-1.2	4.8	-.4	-.3	-.1	.0	3.4
	30 cm	-.2	-.1	-.1	.0	.4	-2.4	-2.4	-2.0	-2.0	3.8	-.3	-.2	-.2	-.1	2.4
	50 cm	-.1	-.1	-.1	-.1	.2	-2.0	-2.0	-2.0	-2.0	3.4	-.1	-.1	-.1	-.1	1.3

* Diffusivity of the 2-5 cm Level (cm^2/hr)

** Quoted as Predicted-Actual

SITE 3B

Assoc.	Level	Amplitude ** (°C)					Actual (°C)	Phase** (hr)					Actual (r)	Average** (°C)					Actual (°C)
		3	4	8	12	16*		3	4	8	12	16*		3	4	8	12	16*	
C1																			
R1	5 cm		-.7	-.2	.2	.4	1.8		-1.2	-.4	.0	.0	6.1		-.6	-.1	.1	.3	5.0
	10 cm		-.3	.1	.3	.5	1.0		.4	.8	1.2	1.6	5.2		-.2	.2	.4	.5	4.0
	15 cm		-.2	.0	.1	.2	.8		-1.2	-.4	.0	.4	4.9		-.1	.2	.4	.5	3.4
	30 cm		-.5	-.4	-.3	-.3	.9		-1.6	-1.2	-.8	-.8	3.8		-.3	-.1	.0	.0	2.4
	50 cm		-.5	-.5	-.4	-.4	.7		-2.8	-2.8	-2.8	-2.8	3.5		-.3	-.2	-.2	-.2	1.4
R1	5 cm	-.1	.3	1.6	2.5	3.0	2.3		-.4	.0	.8	.8	.0	.3	.8	1.5	2.0	2.2	5.4
	10 cm	.1	.5	1.5	1.7	2.0	1.2		.8	1.6	2.0	2.4	5.4	.6	.8	1.5	1.8	1.9	4.5
	15 cm	.1	.1	.6	.9	1.1	1.0		.8	1.6	2.0	2.4	4.9	.6	.7	1.2	1.4	1.6	3.9
	30 cm	-.3	-.2	.0	.1	+.1	.9		-1.6	-.8	-.8	-.4	4.0	.1	.2	.4	.6	.6	2.7
	50 cm	-.5	-.4	-.3	-.3	-.3	.8		-2.8	-2.8	-2.8	-2.8	3.6	-.3	-.3	-.2	-.2	-.2	1.8
R2	5 cm	-.3	.0	.9	1.3	1.6	1.4		.4	.8	1.2	1.2	5.9	-.2	+.3	.9	1.2	1.4	4.0
	10 cm	-.1	.1	.6	.9	1.0	.9		2.0	2.8	3.2	3.6	4.7	.1	.4	.9	1.1	1.3	3.2
	15 cm	-.2	-.1	.2	.4	.5	.8		1.2	2.0	2.8	3.2	4.3	.1	.2	.7	.9	1.0	2.9
	30 cm	-.4	-.4	-.2	-.2	-.1	.8		-1.2	-.8	-.4	-.4	3.7	-.2	-.1	.1	.2	.2	2.1
	50 cm	-.5	-.5	-.5	-.4	-.4	.7		-2.8	-2.8	-2.8	-2.8	3.5	-.3	-.3	-.3	-.3	-.2	1.3

* Diffusivity of the 2-5 cm Level (cm^2/hr)
** Quoted as Predicted-Actual

TABLE 4

Sensitivity of the Model to changes in the Diffusivity

Initial Conditions Set at 6 am
Day 9-11 **

Assoc.	Level	Amplitude (P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
9	5 cm	.2	3.7	-.8	5.4	.5	7.3
	10 cm	.4	2.2	-1.2	5.0	.6	6.8
	15 cm	.7	1.6	-.8	4.5	1.0	6.0
	30 cm	.5	.7	-1.2	3.6	.5	5.2
	50 cm	.1	.3	-.8	2.6	.1	4.5
10	5 cm	-.3	3.6	-.8	5.4	.7	8.8
	10 cm	.3	2.2	-1.2	5.0	.9	7.5
	15 cm	.7	1.5	-.8	4.5	1.5	6.7
	30 cm	.3	.7	-.8	3.5	1.3	5.6
	50 cm	.1	.3	.0	2.6	1.0	4.7
11	5 cm	-.2	4.6	-.8	5.5	.8	9.8
	10 cm	.5	2.8	-.8	5.0	1.3	9.0
	15 cm	.9	1.9	-.8	4.6	2.0	7.9
	30 cm	.4	.9	-1.2	3.6	2.0	6.4
	50 cm	.1	.4	-.4	2.7	1.5	5.1

* Predicted-Actual

** Diffusivity 2-5 cm = 8. cm^2/hr
5-2000 cm = 20 cm^2/hr

Initial Conditions Set at 6 am
Day 9-11**

Assoc.	Level	Amplitude P-A*(^oC)	Amplitude Actual(^oC)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(^oC)	Average Actual(^oC)
9	5 cm	.1	3.7	-.4	5.4	.3	7.3
	10 cm	.3	2.2	-.4	5.0	.3	6.8
	15 cm	.3	1.6	-.4	4.5	.4	6.1
	30 cm	.2	.7	-1.2	3.6	.1	5.2
	50 cm	-.1	.3	-1.2	2.6	.0	4.5
10	5 cm	.1	3.6	-.4	5.4	.4	8.1
	10 cm	.3	2.2	-.4	5.0	.5	7.5
	15 cm	.3	1.5	-.4	4.5	.8	6.7
	30 cm	.1	.7	-1.2	3.5	.5	5.7
	50 cm	.0	.3	.0	2.6	.3	5.0
11	5 cm	.2	4.6	-.4	5.4	.5	9.8
	10 cm	.4	2.8	.0	5.0	.6	9.0
	15 cm	.3	1.9	-.4	4.6	1.0	7.9
	30 cm	.1	.9	-1.2	3.6	.8	6.4
	50 cm	-.1	.4	.0	2.7	.6	5.7

* Predicted-Actual
** Diffusivity 2-5 cm = 8. cm^2/hr
5-2000 cm = 20 cm^2/hr

Initial Conditions Set at 6 am
Day 9-11 **

Assoc.	Level	Amplitude P-A* (^oC)	Amplitude Actual (^oC)	Phase P-A* (hr)	Phase Actual (r)	Average P-A (^oC)	Average Actual (^oC)
9	5 cm	.4	3.7	.0	5.4	.5	7.3
	10 cm	.5	2.2	.0	5.0	.4	6.8
	15 cm	.4	1.6	-.4	4.5	.6	6.1
	30 cm	.2	.7	-.8	3.6	.2	5.4
	50 cm	-.1	.3	-.8	2.6	.0	4.5
10	5 cm	.4	3.6	.0	5.4	.5	8.1
	10 cm	.5	2.2	-.4	5.0	.5	7.5
	15 cm	.4	1.5	.0	4.5	.9	6.7
	30 cm	.1	.7	-.8	3.5	.6	5.7
	50 cm	.0	.3	.0	2.6	.4	4.7
11	5 cm	.6	4.6	.0	5.5	.7	9.8
	10 cm	.7	2.8	.0	5.0	.8	9.0
	15 cm	.4	1.9	.0	4.6	1.1	7.9
	30 cm	.1	.9	-.8	3.6	.9	6.4
	50 cm	.1	.4	.0	2.7	.7	5.1

* Predicted-Actual

** Diffusivity 2-5 cm = 10 cm^2/hr

5- 2000 cm = 20 cm^2/hr

Initial Conditions Set at 12 pm
Day 8-11 **

Assoc.	Level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
8	5 cm	.2	2.9	.0	1.0	.2	5.9
	10 cm	.2	1.7	.0	.6	.1	5.7
	15 cm	.1	1.1	.0	.2	.3	5.5
	30 cm	-.1	.5	-2.0	5.5	.1	5.1
	50 cm	-.1	.2	-7.2	5.1	.0	4.6
9	5 cm	.3	3.7	.0	.8	.5	7.5
	10 cm	.5	2.1	.0	.4	.5	7.0
	15 cm	.3	1.3	.0	6.2	.8	6.2
	30 cm	.0	.5	-2.0	5.0	.5	5.3
	50 cm	.0	.3	-4.0	4.1	.4	4.5
10	5 cm	.4	3.9	-.4	.9	.6	8.6
	10 cm	.5	2.1	-.4	.5	.7	7.9
	15 cm	.4	1.2	-.4	.1	1.0	6.9
	30 cm	.1	.4	-2.0	4.9	.8	5.8
	50 cm	.0	.3	-1.2	3.5	.6	4.8
11	5 cm	.6	4.4	.0	.7	.7	9.5
	10 cm	.7	2.7	.0	.3	.9	8.9
	15 cm	.4	1.8	.0	6.2	1.2	8.0
	30 cm	.1	.6	-1.6	5.1	1.1	6.6
	50 cm	.0	.4	-2.4	3.7	.9	5.2

* Predicted-Actual
** Diffusivity 2-5 cm = 12 cm^2/hr
5-2000 cm = 20 cm^2/hr

Initial Conditions Set at 12 pm
Day 8-11**

Assoc.	Level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(°C)	Average P-A*(°C)	Average Actual(°C)
8	5 cm	-.2	2.9	-.4	1.0	.2	5.9
	10 cm	.0	1.7	-.4	.6	.1	5.7
	15 cm	-.1	1.1	-.4	.2	.3	5.2
	30 cm	-.2	.5	-2.4	5.5	.2	4.9
	50 cm	-.1	.2	-7.6	5.1	.0	4.6
9	5 cm	-.3	3.7	-.4	.8	.3	7.5
	10 cm	.0	2.1	-.4	.4	.3	7.0
	15 cm	.0	1.3	-.8	6.2	.6	6.2
	30 cm	.0	.5	-2.4	5.0	.4	5.3
	50 cm	.0	.3	-4.0	4.1	.3	4.5
10	5 cm	-.4	3.9	-.8	.9	.3	8.6
	10 cm	.0	2.1	-.8	.5	.3	7.9
	15 cm	.1	1.2	-.8	.1	.8	6.9
	30 cm	.0	.5	-2.0	4.9	.7	5.8
	50 cm	.0	.3	-1.6	3.5	.6	4.8
11	5 cm	-.2	4.4	-.4	.6	.5	9.5
	10 cm	.1	2.7	-.4	.3	.6	8.9
	15 cm	.1	1.8	-.4	6.2	1.0	8.0
	30 cm	.0	.6	-2.4	5.1	.9	6.6
	50 cm	.0	.4	-2.4	3.7	.8	5.2

* Predicted-Actual
** Diffusivity 2-5 cm = 8. cm^2/hr
5-2000 cm = 20 cm^2/hr

Initial Conditions Set at 6 am
Day 9-11 **

Assoc.	Level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
9	5 cm	-.2	3.7	-.4	5.4	.2	7.3
	10 cm	.3	2.2	.0	5.0	.2	6.8
	15 cm	.3	1.6	.0	4.5	.5	6.1
	30 cm	.3	.7	.0	3.6	.3	5.2
	50 cm	.1	.3	.0	2.6	.1	4.5
10	5 cm	-.2	3.6	-.4	5.4	.3	8.1
	10 cm	.2	2.2	-.4	5.0	.4	7.5
	15 cm	.4	1.5	.0	4.5	.7	7.5
	30 cm	.7	.7	.0	3.5	.8	5.7
	50 cm	.1	.3	.8	2.6	.6	4.7
11	5 cm	-.2	4.6	-.4	5.5	.3	9.8
	10 cm	.4	2.8	.0	5.0	.6	9.0
	15 cm	.5	1.9	.0	4.6	1.1	7.9
	30 cm	.3	.9	.0	3.6	1.2	6.4
	50 cm	.1	1.4	.4	2.7	1.1	5.1

* Predicted-Actual

** Diffusivity 2-5 cm = 10 cm^2/hr
5-2000 cm = 30 cm^2/hr

Initial Conditions Set at 12 pm
Day 8-11**

Assoc.	level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A(hr)	Phase Actual(r)	Average P-A(°C)	Average Actual(°C)
8	5 cm	.0	2.9	-.1	1.0	.2	5.8
	10 cm	.2	1.7	.3	.6	.0	5.7
	15 cm	.2	1.1	.4	.2	.3	5.2
	30 cm	.0	.5	-.3	5.5	.2	4.9
	50 cm	.1	.2	-4.4	5.1	.1	4.6
9	5 cm	.0	3.7	-.3	.8	.4	7.5
	10 cm	.5	2.1	.1	.4	.5	7.0
	15 cm	.4	1.3	.4	6.2	.8	6.2
	30 cm	.1	.5	-.1	5.0	.7	5.3
	50 cm	.1	.3	-2.3	4.1	.6	4.5
10	5 cm	.0	3.9	-.3	.9	.5	8.6
	10 cm	.5	2.1	-.1	.5	.6	7.9
	15 cm	.5	1.2	.1	.1	1.1	6.9
	30 cm	.2	.4	.3	4.9	1.1	5.8
	50 cm	.1	.3	.1	3.5	1.0	4.8
11	5 cm	.2	4.4	-.1	.7	.7	9.5
	10 cm	.6	2.7	.2	.3	.8	8.9
	15 cm	.6	1.8	.3	6.2	1.3	8.0
	30 cm	.2	.6	.1	5.1	1.5	6.6
	50 cm	.1	.4	-.9	3.7	1.5	5.2

* Predicted-Actual
** Diffusivity 2-5 cm = 12 cm^2/hr
5-2000 cm = 30 cm^2/hr

Initial Conditions Set at 12 pm
Day 8-11**

Assoc.	Level	Amplitude P-A(^{o}C)*	Amplitude Actual(^{o}C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A(^{o}C)	Average Actual(^{o}C)
8	5 cm	-.2	2.9	-.2	1.0	.1	5.8
	10 cm	.2	1.7	.3	.6	.0	5.7
	15 cm	.2	1.1	.7	.2	.3	5.2
	30 cm	.0	.5	.5	5.5	.2	4.9
	50 cm	.0	.2	-2.9	5.1	.1	4.6
9	5 cm	-.2	3.7	-.3	.8	.3	7.5
	10 cm	.4	2.1	.2	.4	.5	7.0
	15 cm	.5	1.3	.7	6.2	.8	6.2
	30 cm	.2	.5	1.0	5.0	.8	5.3
	50 cm	.2	.3	-1.3	4.1	.7	4.5
10	5 cm	-.2	3.9	-.4	.9	.3	8.6
	10 cm	.4	2.1	.0	.5	.6	7.9
	15 cm	.6	1.2	.4	.1	1.1	6.9
	30 cm	.2	.4	1.4	4.9	1.2	5.8
	50 cm	.1	.3	1.0	3.5	1.3	4.8
11	5 cm	.0	4.4	-.2	.7	.6	9.5
	10 cm	.6	2.7	.2	.3	.8	8.9
	15 cm	.7	1.8	.6	6.2	1.4	8.0
	30 cm	.3	.6	1.1	5.1	1.7	6.6
	50 cm	.2	.4	.2	3.7	1.9	5.2

* Predicted-Actual
** Diffusivity 2-5 cm = 12 cm^2/hr
5-2000 cm = 40 cm^2/hr

Table 5

Prediction using Optimized Diffusivities for Several Different Days

Day 17

Site 2a

Assoc.	Level	Amplitude(°C)*		Act.(°C)	Phase*(hr)		Act.(r)	Average(°C)*		Act.(°C)
		8	10**		8	10**		8	10**	
D1	5cm	-.6	-.4	3.2	-.4	-.2	.0	.2	.2	9.8
	10cm	-.4	-.3	2.3	-.4	-.2	6.1	.3	.3	9.4
	15cm	-.5	-.4	1.7	.0	-.3	5.9	.2	.2	9.1
	30cm	-.1	-.1	.5	-2.8	-3.0	5.0	.6	.6	6.9
	50cm	.1	.1	.3	-2.4	-2.7	3.9	.3	.3	5.1
		5	8		5	8		5	8	
R2	5cm	-1.0	-.5	2.9	-.1	.0	6.2	-.1	.0	10.2
	10cm	.7	-.2	2.1	.1	.0	6.0	.1	.2	9.6
	15cm	-.7	-.5	1.6	-.1	.0	5.8	.1	.2	9.2
	30cm	-.2	-.1	.5	-3.4	-2.4	4.9	.2	.3	7.2
	50cm	.1	.1	.4	-2.3	-2.4	3.8	.3	.3	5.1

Site 2b

		8	14**		8	14**		8	14**	
D1	5cm	-.6	-.2	3.2	-.4	-.1	.0	.1	.1	9.8
	10cm	-.4	-.1	2.3	-.4	-.1	6.1	.3	.3	9.4
	15cm	-.4	-.3	1.7	-.4	-.3	5.9	.2	.2	9.1
	30cm	-.1	-.1	.5	-3.2	-2.7	5.0	.6	.6	6.9
		8	10**		8	10**		8	10**	
R2	5cm	-.4	-.2	2.8	.0	.0	6.2	.1	.1	10.1
	10cm	-.3	-.2	2.0	.4	.0	6.0	.2	.3	9.6
	15cm	-.4	-.3	1.6	-.4	-.2	5.8	.2	.3	9.2
	30cm	-.1	-.1	.5	-2.8	-3.0	4.9	.3	.3	7.2
	50cm	-.1	.1	.4	-2.4	-2.4	3.9	.3	.3	5.1

Site 3a

		3**		3**		3**	
R1	5cm	-.4	2.6	-.3	.1	.3	8.5
	10cm	-.2	1.8	-.2	6.1	.4	8.1
	15cm	-.2	1.3	-.3	5.9	.4	7.6
	30cm	-.2	.5	-4.0	5.4	.3	6.1
	50cm	.2	.2	-2.3	3.9	.6	3.8
		8**		8**		8**	
C2	5cm	-.1	3.0	-.1	.0	.1	9.0
	10cm	.1	2.0	-.2	6.1	.4	8.5
	15cm	.0	1.4	-.4	5.9	.5	8.0
	30cm	-.2	.5	-4.0	5.5	.5	6.5
	50cm	.3	.1	-2.1	3.8	.8	4.1

Day 17 Continued

Site 3b

Assoc.	Level	Amplitude*(°C)	Act.(°C)	Phase*(hr)	Act.(r)	Average*(°C)	Act.(°C)
		10 **		10 **		10**	
C1	5cm	-.2	2.8	-.1	.0	-.2	9.7
	10cm	-.2	2.1	-.2	6.1	.3	9.0
	15cm	-.2	1.5	-.2	5.9	.2	8.8
	30cm	-.3	.6	-2.2	5.3	.4	7.1
	50cm						
		3 **		3**		3**	
R1	5cm	-.7	3.5	-.4	.2	.3	9.3
	10cm	-.3	2.3	-.1	6.1	.4	9.0
	15cm	-.3	1.7	-.3	6.0	.5	8.5
	30cm	-.4	.8	-4.0	5.5	.4	6.9
	50cm	.1	.4	-2.4	3.9	.3	5.0

* Quoted as Predicted-Actual

** Diffusivity of the 2-5 cm Level (cm^2/hr)

5-2000 cm Level is 20 cm^2/hr

Day 38

Site 1

Assoc.	Level	Amplitude*(°C) 10	18 **	Act.(°C)	Phase*(hr) 10	18 **	Act.(r)	Average*(°C) 10	18**	Act.(°C)
A1	5cm	.1	.5	2.5	-.1	.4	.3	.2	+.2	7.5
	10cm	.1	.4	1.7	-.1	.2	6.2	.0	-.1	7.8
	15cm	.0	.2	1.3	-.1	.1	5.9	.2	+.2	7.5
	30cm	-.2	.1	.5	-1.7	-1.2	5.2	.1	+.1	7.3
	50cm	.0	.0	.1	-4.6	-4.4	4.3	.1	+.1	6.8
		12	18		12	18		12	18	
D1	5cm	.1	.4	2.8	.0	.4	.2	.0	-.1	8.0
	10cm	.0	.2	2.0	.0	.1	6.2	.2	.1	8.0
	15cm	-.2	.0	1.6	-.2	.0	5.9	.0	.0	8.0
	30cm	-.3	-.3	.7	-1.3	-.8	5.2	.0	.0	7.5
	50cm	.1	.1	.1	-5.9	-4.4	4.8	.3	.3	6.7

Site 2b

Assoc.	Level	Amplitude*(°C) 8	10	14**	Act.*(°C)	Phase*(hr) 8	10	14**	Act.(r)	Average(°C) 8	10	14**	Act.(°C)
D1	5cm	-.5	-.3	-.1	2.1	-.4	-.3	-.1	6.0	.1	.1	.1	6.7
	10cm	-.3	-.2	.0	1.4	-.2	-.1	.0	5.7	.2	.2	.2	6.5
	15cm	-.3	-.3	-.2	1.1	-.4	-.4	-.3	5.5	.0	.0	.0	6.6
	30cm	-.1	-.1	-.1	.3	-2.4	-2.1	-1.9	4.6	.3	.4	.4	5.6
	50cm	.0	.0	.0	.2	-3.6	-3.6	-3.6	4.0	.2	.3	.3	4.9
		8	10	12**		8	10	12**		8	10	12**	
R2	5cm	-.2	.0	.1	1.9	.0	.1	.2	6.0	.1	.1	.1	6.9
	10cm	-.1	.0	.1	1.3	.2	.3	.4	5.6	.2	.2	.2	6.7
	15cm	-.3	-.2	-.1	1.0	.0	.0	.1	5.4	.2	.2	.2	6.5
	30cm	-.2	-.1	-.1	.4	-2.2	-1.9	-1.8	4.7	.3	.3	.3	5.8
	50cm	.0	.0	.0	.2	-1.5	-1.5	-1.5	3.5	.5	.5	.5	4.8

Site 3b

Assoc.	Level	Amplitude*(°C) 3	10**	Act.(°C)	Phase*(hr) 3	10**	Act.(r)	Average*(°C) 3	10**	Act.(°C)
C1	5cm	-.7	-.1	1.7	-.4	.2	.1	-.1	-.2	6.7
	10cm	-.6	-.1	1.4	.0	.3	6.1	.3	.2	6.2
	15cm	-.5	-.2	1.1	.2	.2	5.9	.2	.2	6.2
	30cm	-.5	-.4	.6	-.8	-.7	5.3	.2	.2	5.6
	50cm									

Site 3b Continued

Assoc.	Level	Amplitude*(°C)		Act.(°C)	Phase*(hr)		Act.(r)	Average*(°C)		Act.(°C)
		3	8		3	8		3	8	
R1	5cm	-.4	.6	2.2	-.6	.3	.3	.3	.2	6.2
	10cm	-.2	.5	1.4	.1	.7	6.1	.3	.2	6.2
	15cm	-.2	.3	1.1	.0	.4	5.8	.4	.3	6.0
	30cm	-.4	-.2	.6	-2.1	-1.2	5.2	.4	.4	5.4
	50cm	-.2	-.2	.3	-6.6	-6.3	4.9	.4	.4	4.7

* quoted as Predicted-Actual

** Diffusivity of the 2-5 cm Level(cm^2/hr)
5- 2000 cm Level is 20 cm^2/hr)

Day 40

Site 1

Assoc.	Level	Amplitude*(°C) 10	Amplitude*(°C) 18**	Act.(°C)	Phase*(hr) 10	Phase*(hr) 18**	Act.(r)	Average*(°C) 10	Average*(°C) 18**	Act.(°C)
A1	5cm	.0	+.5	2.2	-.2	+.4	.1	.3	.7	9.9
	10cm	.0	+.3	1.3	-.3	+.3	5.9	.2	.4	9.4
	15cm	.0	+.2	.9	-.9	-.6	5.4	.3	.5	8.6
	30cm	.0	+.1	.5	-2.1	-2.2	4.2	.1	.2	7.5
	50cm	.0	+.1	.2	-1.5	-1.5	3.2	.1	.2	6.4
D1	5cm		.1	2.4		.3	.0		.1	10.8
	10cm		.0	1.5		.1	5.8		.2	9.9
	15cm		-.1	1.1		-.4	5.4		-.1	9.5
	30cm		-.1	.7		-1.8	4.2		-.2	8.0
	50cm		.1	.2		.4	2.8		.3	6.1

Site 2a

Assoc.	Level	Amplitude 8	Amplitude 10**	Act.	Phase 8	Phase 10**	Act.	Average 8	Average 10**	Act.
D1	5cm	-.3	-.1	1.4	-.8	-.4	6.2	.0	.1	7.9
	10cm	-.1	.0	.9	-1.4	-1.0	5.7	.1	.2	7.2
	15cm	.0	.0	.6	-1.6	-1.3	5.1	.1	.2	6.6
	30cm	.1	.1	.4	-1.6	-1.5	3.8	.1	.1	5.4
	50cm	.1	.1	.1	-1.6	-1.2	3.2	.2	.2	4.1
		4	8**		4	8**		4	8**	
R2	5cm	-.1	.8	1.8	-.7	.0	.4	.4	1.2	8.3
	10cm	.0	.5	1.0	-1.0	.3	6.2	.5	1.1	7.5
	15cm	.0	.3	.6	-1.8	-1.0	5.7	.7	1.2	6.6
	30cm	.1	.3	.3	-2.2	-2.0	4.2	.3	.5	5.5
	50cm	.1	.1	.2	-1.6	-1.6	3.4	.2	.3	4.2

Site 2b

Assoc.	Level	Amplitude 14**	Act.	Phase 14**	Act.	Average 14**	Act.
D1	5cm	-.1	1.5	-.4	5.8	.0	7.9
	10cm	.0	1.0	-.5	5.1	.2	7.0
	15cm	.0	.8	-1.1	4.7	-.1	6.8
	30cm	.0	.5	-.8	3.6	.3	5.1
	50cm	-.2	.4	-1.2	3.1	.1	4.2

Site 2b Continued

Assoc.	Level	Amplitude*(°C)	Act.(°C)	Phase*(hr)	Act.(r)	Average*(°C)	Act.(°C)
		10**		10**		10**	
R2	5cm	-.1	1.1	.1	5.5	-.1	7.8
	10cm	-.1	.9	.2	4.9	.0	7.1
	15cm	-.1	.8	-.6	4.5	.0	6.6
	30cm	-.1	.5	-.9	3.5	.1	5.2
	50cm	-.2	.3	-.7	3.0	.3	4.0

Site 3a

Assoc.	Level	Amplitude*(°C)	Act.(°C)	Phase*(hr)	Act.(hr)	Average*(°C)	Act.(°C)
		3**		3**		3**	
R1	5cm	-.1	.9	-1.1	.2	.0	6.8
	10cm	.1	.4	.0	5.4	.2	6.0
	15cm	.0	.3	-.4	4.8	.2	5.6
	30cm	.0	.3	-1.4	3.8	.0	4.6
	50cm	.0	.1	-1.3	3.3	.2	3.4
		8**		8**		8**	
C2	5cm	.1	1.2	-.1	6.1	.4	7.3
	10cm	.2	.7	-.2	5.5	.6	6.5
	15cm	.1	.5	-.9	4.9	.5	5.9
	30cm	.2	.3	-1.6	3.8	.2	4.8
	50cm	.1	.1	-.9	3.1	.3	3.5

Site 3b

Assoc.	Level	Amplitude*(°C)	Act.(°C)	Phase*(hr)	Act.(hr)	Average*(°C)	Act.(°C)
		10 **		10 **		10 **	
C1	5cm	-.1	1.0	.0	.1	-.4	7.9
	10cm	-.2	.7	.0	5.7	.0	6.9
	15cm	-.1	.5	-.8	5.1	-.1	6.4
	30cm	-.1	.5	-2.2	4.0	-.2	5.2
	50cm						

Assoc.	Level	Amplitude* 5	Amplitude* 8**	Act.(°C)	Phase* 5	Phase* 8**	Act.(hr)	Average* 5	Average* 8**	Act.(°C)
R1	5cm	-.2	.6	1.0	-.9	-.6	.6	-.1	1.0	7.7
	10cm	.0	.4	.4	.5	.8	5.7	.2	1.0	6.7
	15cm	-.1	.1	.4	-.6	-.9	4.9	.2	.8	6.1
	30cm	.0	.1	.4	-2.3	-2.2	4.1	.0	.3	4.9
	50cm	-.2	-.1	.4	-2.9	-2.6	3.7	-.1	.0	4.0

* Quoted as Predicted-Actual

** Diffusivity of the 2-5 cm Level (cm^2/hr)
5-2000 cm Level (cm^2/hr)

Table 6

Prediction of the Finite Difference Model over Several Days

Site 1, Association A2**
Modelled for Day 9-11

		P-A*(^{o}C)	Actual(^{o}C)	P-A*(hr)	Actual(r)	P-A*(^{o}C)	Actual(^{o}C)
9	5 cm	.4	3.1	.0	.7	.2	7.5
	10 cm	.0	2.2	.4	.4	.0	7.2
	15 cm	.0	1.4	.0	6.1	.1	6.6
	30 cm	-.1	.6	-1.6	4.8	.1	5.4
	50 cm	-.1	.3	-3.2	3.9	.0	4.5
10	5 cm	.4	3.2	.0	.8	.2	8.8
	10 cm	-.1	2.2	-.4	.5	.0	8.3
	15 cm	.1	1.2	.0	6.2	.1	7.6
	30 cm	-.0	.5	-1.2	4.7	.2	6.0
	50 cm	-.0	.3	-1.6	3.5	.2	4.8
11	5 cm	.4	3.8	.4	.5	.1	9.7
	10 cm	.0	2.9	.0	.2	.1	9.3
	15 cm	.0	1.8	.0	6.1	.2	8.6
	30 cm	-.1	.7	-1.2	4.9	.4	6.8
	50 cm	-.0	.4	-2.4	3.7	.4	5.3

* Predicted-Actual
** Diffusivity 2-5 cm = 12 cm^2/hr
5-2000 cm = 20 cm^2/hr

Site 1, Association D1**
Modelled for Day 9-11

Assoc.	Level	Amplitude P-A*(^oC)	Amplitude Actual(^oC)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(^oC)	Average Actual(^oC)
9	5 cm	.0	4.1	.1	.8	.0	8.5
	10 cm	.1	2.6	-.4	.4	.4	7.6
	15 cm	.0	1.7	-.7	.1	.3	7.2
	30 cm	.1	.6	-1.0	5.1	.1	6.0
	50 cm	.1	.3	-2.8	3.9	.2	4.5
10	5 cm	.2	4.3	.4	.8	.0	9.6
	10 cm	.2	2.5	.1	.5	.4	8.5
	15 cm	.0	1.6	-.5	.2	.2	8.1
	30 cm	.0	.5	-2.0	5.1	.2	6.6
	50 cm	.0	.3	-1.6	3.5	.5	4.9
11	5 cm	.1	4.8	-.2	.6	-.1	10.7
	10 cm	.1	3.1	-.4	.3	.3	9.8
	15 cm	.1	2.1	-.7	.0	.3	9.2
	30 cm	-.1	.8	-2.4	5.2	.3	7.5
	50 cm	.0	.4	-2.1	3.7	.7	5.4

* Predicted-Actual
** Diffusivity 2-5 cm= 18 cm^2/hr
5-2000 cm= 20 cm^2/hr

Site 2a, Association D1**
Modelled for Day 8-11

Day	Level	Amplitude P-A* (°C)	Amplitude Actual (°C)	Phase P-A* (hr)	Phase Actual (hr)	Average P-A* (°C)	Average Actual (°C)
8	5 cm	-.2	1.3	.4	6.1	.1	4.1
	10 cm	-.3	1.0	.4	5.7	.0	3.9
	15 cm	-.3	.8	.0	5.3	.0	3.7
	30 cm	-.3	.5	-2.8	4.5	-.1	3.2
	50 cm	-.3	.3	-5.0	4.1	-.1	2.6
9	5 cm	-.1	1.8	.0	6.0	.2	5.4
	10 cm	-.1	1.2	.0	5.5	.4	5.0
	15 cm	-.2	.9	.0	5.0	.4	4.6
	30 cm	-.3	.7	-1.6	4.0	.4	3.6
	50 cm	-.3	.4	-3.2	3.6	.4	2.8
10	5 cm	.1	1.8	.0	.1	.2	6.1
	10 cm	.1	1.2	.0	5.9	.3	5.4
	15 cm	.2	.9	.0	5.2	.4	4.9
	30 cm	.3	.7	-1.6	4.1	.5	3.7
	50 cm	.4	.6	-3.2	3.7	.6	2.6
11	5 cm	-.1	2.4	.0	.1	.2	7.2
	10 cm	.0	1.5	.0	5.9	.4	6.4
	15 cm	-.1	1.0	.0	5.4	.5	5.8
	30 cm	-.3	.8	-1.2	4.1	.6	4.4
	50 cm	-.3	.6	-2.8	3.7	.8	3.0

* Predicted-Actual
** Diffusivity 2-5 cm = 8. cm^2/sec
5-2000 cm = 20. cm^2/sec

Site 2a, Association R1**
Modelled for Day 8-11

Day	Level	Amplitude		Phase		Average	
		P-A*(°C)	Actual(°C)	P-A*(hr)	Actual(r)	P-A*(°C)	Actual(°C)
8	5 cm	-.1	1.6	.4	.3	.0	4.6
	10 cm	.1	1.0	.8	5.9	.0	4.3
	15 cm	-.3	.9	.8	5.5	-.1	4.1
	30 cm	-.3	.6	-2.0	4.5	-.1	3.4
	50 cm	-.2	.3	-5.2	4.2	-.1	2.7
9	5 cm	.0	2.1	.4	.2	.0	5.9
	10 cm	-.1	1.4	.6	5.9	.2	5.2
	15 cm	-.3	1.1	.8	5.3	.2	4.7
	30 cm	-.3	.7	-1.2	4.1	.5	3.4
	50 cm	-.3	.5	-3.2	3.6	.5	2.5
10	5 cm	.1	2.6	-.2	.5	.3	6.9
	10 cm	+.1	1.5	.4	6.2	.5	6.1
	15 cm	.0	1.1	.4	5.6	.5	5.5
	30 cm	-.2	.7	-1.2	4.3	.8	3.9
	50 cm	-.3	.5	-3.2	3.8	.8	2.7
11	5 cm	.0	3.0	.0	.3	.0	7.8
	10 cm	.1	2.0	.0	6.2	.4	7.0
	15 cm	-.1	1.3	.4	5.7	.5	6.4
	30 cm	-.3	.8	-.4	4.3	.9	4.6
	50 cm	-.3	.6	-2.8	3.7	1.0	3.1

* Predicted-Actual
** Diffusivity 2-5 cm =12. cm^2/sec
5-2000 cm =20. cm^2/sec

Site 2a, Association R2**
Modelled for Day 8-10

Day	Level	Amplitude		Phase		Average	
		P-A*(C^o)	Actual(^oC)	P-A*(hr)	Actual(r)	P-A*(^oC)	Actual(^oC)
8	5 cm	-.2	1.3	-.4	.5	.1	4.6
	10 cm	-.1	1.2	-.3	.0	.0	4.4
	15 cm	-.1	.7	.0	5.7	.2	3.9
	30 cm	-.3	.5	-2.0	4.7	-.1	3.5
	50 cm	-.2	.3	-5.0	4.3	-.1	2.8
9	5 cm	-.3	2.3	-.4	.4	.2	5.7
	10 cm	-.1	1.4	-.8	6.2	.3	5.2
	15 cm	.0	.9	-.4	5.6	.6	4.4
	30 cm	-.2	.6	-1.2	4.2	.4	3.5
	50 cm	-.4	2.5	-.8	.6	.2	2.5
10	5 cm	-.4	2.5	-.8	.6	.2	6.7
	10 cm	-.3	1.5	-1.0	.2	.3	6.0
	15 cm	-.2	.9	-.8	5.9	.6	5.2
	30 cm	-.3	.6	-1.6	4.3	.6	4.0
	50 cm	-.3	.5	-3.6	3.8	.7	2.8

* Predicted-Actual
** Diffusivity 2-5 cm = 3.0 cm^2/sec
5-2000 cm = 2.0 cm^2/sec

Site 2b, Association D1**
Modelled for Day 8-11

Day	Level	Amplitude		Phase		Average	
		P-A*(°C)	Actual(°C)	P-A*(hr)	Actual(r)	P-A*(°C)	Actual(°C)
8	5 cm	-.2	1.6	.0	.0	.0	4.2
	10 cm	-.1	1.0	.4	5.8	.1	3.8
	15 cm	-.3	.8	.0	5.3	-.1	3.7
	30 cm	-.3	.6	-2.0	3.8	.1	2.8
	50 cm	-.3	.5	-5.0	2.8	-.2	2.4
9	5 cm	-.2	2.6	-.4	.1	.1	5.3
	10 cm	.0	1.4	.0	5.8	.5	4.5
	15 cm	-.1	1.0	.0	5.3	.3	4.2
	30 cm	-.4	.8	-1.2	4.1	.8	2.7
	50 cm	-.4	.6	-3.4	3.7	.6	2.0
10	5 cm	-.2	2.3	-.4	.1	.1	6.1
	10 cm	.0	1.4	.0	5.8	.5	5.2
	15 cm	-.1	1.0	-.2	5.3	.6	4.9
	30 cm	-.4	.8	-.3	4.0	.9	3.2
	50 cm	-.5	.7	-2.8	3.6	.7	2.3
11	5 cm	-.3	3.1	-.4	.1	.1	7.5
	10 cm	.0	1.8	-.4	5.9	.6	6.4
	15 cm	-.1	1.3	-.7	5.5	.6	6.0
	30 cm	-.3	.8	-1.2	4.1	1.1	3.8
	50 cm	-.4	.7	-2.6	3.6	.9	2.7

* Predicted-Actual
** Diffusivity 2-5 cm = 12.0 cm^2/sec
5-2000 cm = 20.0 cm^2/sec

Site 2b, Association D2**
Modelled for Day 8-11

Day	Level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
8	5 cm	-.3	1.5	-.4	6.2	-.2	4.3
	10 cm	-.3	1.0	.0	5.5	-.1	3.9
	15 cm	-.3	.9	-.4	5.1	+.1	3.4
	30 cm	-.3	.6	-2.8	4.3	-.2	2.9
	50 cm	-.3	.5	-4.8	4.1	-.1	2.0
9	5 cm	-.5	2.3	-.6	6.2	-.1	5.6
	10 cm	-.2	1.4	-.0	5.6	.2	4.7
	15 cm	-.3	1.1	-.0	5.0	.6	3.9
	30 cm	-.2	.8	-1.6	4.0	.6	2.8
	50 cm	-.4	.6	-3.2	3.7	.7	1.6
10	5 cm	-.5	2.4	-.6	6.2	-.2	6.6
	10 cm	-.2	1.4	-.2	5.6	.3	5.6
	15 cm	-.2	1.1	-.2	5.0	.8	4.6
	30 cm	-.3	.8	-1.6	4.0	.8	3.3
	50 cm	-.4	.6	-2.8	3.6	1.0	1.9
11	5 cm	-.5	3.2	-.6	6.2	-.2	7.8
	10 cm	-.2	1.9	-.2	5.7	.4	6.6
	15 cm	-.2	1.3	-.2	5.2	.9	5.6
	30 cm	-.3	.9	-1.4	4.0	1.0	3.9
	50 cm	-.4	.7	-2.8	3.6	1.3	2.2

* Predicted-Actual
** Diffusivity 2-5 cm = 12.0 cm^2/sec
5-2000 cm = 20.0 cm^2/sec

Site 2b, Association R1**
Modelled for Day 8-11

Day	Level	Amplitude		Phase		Average	
		P-A* (°C)	Actual (°C)	P-A* (hr)	Actual (r)	P-A* (°C)	Actual (°C)
8	5 cm	.1	1.2	.4	.1	.1	3.7
	10 cm	.1	.7	1.6	5.6	.1	3.5
	15 cm	-.1	.7	1.4	5.1	.0	3.3
	30 cm	-.4	.5	-1.2	4.3	-.1	2.9
	50 cm	-.3	.4	-5.0	4.1	-.1	2.4
9	5 cm	.3	1.8	.2	.1	.4	4.6
	10 cm	.4	.9	1.2	5.7	.6	4.0
	15 cm	.1	.8	2.0	5.0	.6	3.6
	30 cm	-.4	.7	-.2	4.0	.6	2.7
	50 cm	-.4	.5	-2.8	3.7	.6	2.0
10	5 cm	.2	2.0	.2	.1	.5	5.6
	10 cm	.4	1.0	1.2	5.7	.8	4.8
	15 cm	.1	.8	1.6	5.0	.7	4.4
	30 cm	-.4	.8	.2	3.9	.8	3.2
	50 cm	-.4	.6	-2.6	3.6	.7	2.3
11	5 cm	.3	2.5	.0	.1	.5	6.5
	10 cm	.5	1.3	1.0	5.7	.9	5.7
	15 cm	.2	1.0	1.6	5.2	1.0	5.2
	30 cm	-.3	.8	.0	3.9	1.0	3.8
	50 cm	-.4	.7	-2.4	3.6	.9	2.7

* Predicted-Actual
** Diffusivity 2-5 cm = 8.0 cm^2/sec
5-2000 cm = 20.0 cm^2/sec

Site 2b, Association R2**
Modelled for Day 8-11

Day	Level	Amplitude P-A* (°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
8	5 cm	-.2	1.2	.4	.1	-.1	4.2
	10 cm	-.2	.9	1.2	5.6	-.1	3.9
	15 cm	-.4	.8	.8	5.2	-.1	3.7
	30 cm	-.4	.6	-2.4	4.3	-.1	3.0
	50 cm	-.3	.4	-4.8	4.1	-.1	2.4
9	5 cm	-.2	1.7	.4	.0	.0	5.2
	10 cm	-.1	1.1	1.2	5.6	.2	4.5
	15 cm	-.3	.9	.8	5.1	.3	4.1
	30 cm	-.4	.8	-1.2	4.0	.5	2.9
	50 cm	-.4	.5	-3.2	3.7	.6	1.9
10	5 cm	-.1	1.8	-.2	.0	.0	6.1
	10 cm	-.2	1.1	-.8	5.6	.2	5.3
	15 cm	-.3	.9	-.4	5.1	.3	4.8
	30 cm	-.4	.6	-2.8	4.0	.6	3.4
	50 cm	-.4	.6	-2.8	3.6	.8	2.2
11	5 cm	-.2	2.5	.0	6.2	.0	7.2
	10 cm	-.1	1.6	.4	5.7	.3	6.4
	15 cm	-.2	1.2	.3	5.3	.4	5.8
	30 cm	-.4	.9	-.8	4.0	.7	4.1
	50 cm	-.4	.7	-2.4	3.5	1.3	2.6

* Predicted-Actual
** Diffusivity 2-5 cm = 8.0 cm^2/sec
5-2000 cm = 20.0 cm^2/sec

Site 3a, Association C1**
Modelled for Day 9-11

Assoc.	Level	Amplitude P-A* (°C)	Amplitude Actual (°C)	Phase P-A* (hr)	Phase Actual (r)	Average P-A* (°C)	Average Actual (°C)
9	5 cm	.2	1.8	.0	6.0	-.1	3.9
	10 cm	.0	1.1	.0	5.4	.1	3.3
	15 cm	.0	.8	-.2	4.8	.2	2.7
	30 cm	-.1	.5	-1.4	3.9	-.1	2.0
	50 cm	-.1	.3	-2.4	3.3	-.1	1.2
10	5 cm	-.3	2.2	-.4	6.1	.0	5.0
	10 cm	.0	1.3	.6	5.6	.3	4.2
	15 cm	.1	.8	-1.0	5.2	.5	3.4
	30 cm	.0	.4	-1.6	4.0	.2	2.5
	50 cm	.0	.3	-2.0	3.4	.2	1.4
11	5 cm	-.3	2.7	-.4	6.1	.0	4.0
	10 cm	.0	1.5	-.4	5.7	.4	5.1
	15 cm	-.1	1.0	-.4	5.2	.8	4.2
	30 cm	.0	.5	-1.4	4.0	.5	3.1
	50 cm	-.1	.3	-1.6	3.2	.5	1.8

* Quoted as Predicted-Actual
** Diffusivity 2-5 cm = 8. cm^2/sec
5-2000 cm = 20. cm^2/sec

Site 3a, Association C2**
Modelled for Day 9-11

Assoc.	Level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
9	5 cm	-.1	1.8	.0	5.8	.1	4.1
	10 cm	.0	1.1	.0	5.2	.2	3.5
	15 cm	-.0	.9	.8	4.8	.0	3.2
	30 cm	-.1	.6	-1.6	3.9	-.2	2.3
	50 cm	-.1	.3	-2.4	3.3	-.1	1.4
10	5 cm	.1	2.1	.2	5.9	.2	5.2
	10 cm	.1	1.3	.3	5.4	.4	4.4
	15 cm	.1	.9	-.3	5.0	.4	4.0
	30 cm	.0	.5	-1.8	4.0	.1	2.9
	50 cm	-.1	.3	-1.6	3.2	.1	1.7
11	5 cm	.0	2.4	.0	6.1	.2	6.1
	10 cm	.1	1.5	.0	5.7	.4	5.3
	15 cm	.0	1.1	-.4	5.3	.4	4.8
	30 cm	-.1	.6	-2.4	4.3	.3	3.5
	50 cm	-.1	.3	-2.0	3.4	.3	2.1

* Predicted-Actual
** Diffusivity 2-5 cm = 8.0 cm^2/sec
5-2000 cm = 20.0 cm^2/sec

Site 3a, Association R1**
Modelled for Day 9-11

Assoc.	Level	Amplitude		Phase		Average	
		P-A*(°C)	Actual(°C)	P-A*(hr)	Actual(r)	P-A*(°C)	Actual(°C)
9	5 cm	-.2	1.7	-.9	5.8	.0	3.8
	10 cm	.1	.9	.0	5.1	.1	3.2
	15 cm	.0	.7	-.4	4.6	.1	2.8
	30 cm	-.1	.5	-1.2	3.7	-.1	2.1
	50 cm	-.1	.3	-1.4	3.1	-.1	1.2
10	5 cm	-.4	1.9	-1.1	5.9	-.1	4.8
	10 cm	.0	1.1	-.6	5.2	.2	4.0
	15 cm	-.1	.8	-1.2	4.8	.2	3.5
	30 cm	-.1	.5	-1.9	3.8	.0	2.6
	50 cm	-.1	.3	-1.7	3.2	.1	1.5
11	5 cm	-.4	2.2	-.8	6.1	.1	5.5
	10 cm	.0	1.1	-.2	5.5	.3	4.8
	15 cm	.0	.8	-.4	6.0	.4	4.2
	30 cm	-.1	.5	-1.6	4.0	.2	3.1
	50 cm	-.1	.3	-1.7	3.3	.3	1.8

* Predicted-Actual
** Diffusivity 2-5 cm = 3.0 cm^2/sec
5-2000 cm= 20.0 cm^2/sec

Site 3a, Association R2**
Modelled for Day 9-11

Assoc.	Level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
9	5 cm	.1	1.3	-.4	5.7	-.3	3.9
	10 cm	.0	.9	-.2	5.1	.1	3.1
	15 cm	-.1	.7	-.8	4.7	.0	2.7
	30 cm	-.1	.5	-1.6	3.7	-.2	1.9
	50 cm	-.1	.3	-2.4	3.3	-.1	1.1
10	5 cm	-.1	1.4	-1.2	5.7	-.3	4.6
	10 cm	.0	1.0	-.8	5.2	.2	3.7
	15 cm	-.1	.7	-.8	4.8	.1	3.4
	30 cm	.0	.4	-1.6	3.8	.1	.
	50 cm	-.1	.2	-2.0	3.4	.1	1.3
11	5 cm	-.1	1.7	-.6	5.8	-.2	5.4
	10 cm	.0	1.1	-.3	5.3	.3	4.4
	15 cm	-.1	.8	-.8	4.9	.2	4.1
	30 cm	-.1	.5	-1.6	3.8	.1	2.9
	50 cm	-.1	.3	-2.0	3.3	.2	1.6

* Predicted-Actual

** Diffusivity 2-5 cm = 8. cm^2/sec
5-2000 cm= 20. cm^2/sec

Site 3b, Association C2
Modelled for Day 9-11

Assoc.	Level	Amplitude P-A(°C)*	Amplitude Actual(°C)	Phase P-A(hr)*	Phase Actual(r)	Average P-A(°C)*	Average Actual(°C)
9	5 cm	.0	1.6	-.2	6.1	.0	4.1
	10 cm	.1	.9	1.2	5.2	.3	3.2
	15 cm	-.1	.9	.8	4.6	.1	2.8
	30 cm	-.3	.8	-1.3	3.9	-.2	2.0
	50 cm	-.5	.7	-3.3	3.6	-.3	1.2
10	5 cm	.3	1.8	-.5	6.1	.3	5.0
	10 cm	.4	1.0	1.0	5.2	.6	4.0
	15 cm	.0	.9	1.2	4.6	.6	3.5
	30 cm	-.4	.9	-.9	3.8	.3	2.4
	50 cm	-.4	.7	-2.6	3.5	.0	1.4
11	5 cm	.1	2.3	-.3	.2	.2	5.9
	10 cm	.4	1.2	.8	5.4	.7	4.8
	15 cm	.1	.9	1.2	4.8	.6	4.3
	30 cm	-.4	.8	-.4	3.8	.6	2.9
	50 cm	-.4	.7	-2.1	3.5	.4	2.7

* Predicted-Actual
** Diffusivity 2-5 cm = 10. cm^2/hr
5-2000 cm = 20. cm^2/hr

Site 3b, Association R1**
Modelled for Day 9-11

Assoc.	Level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
9	5 cm	-.1	2.0	-1.5	.3	.0	4.7
	10 cm	.1	1.1	.6	5.5	.3	3.7
	15 cm	-.1	.9	.4	4.9	.3	3.2
	30 cm	-.3	.9	-1.6	4.0	-.1	2.2
	50 cm	-.5	.7	-3.2	3.6	-.4	1.5
10	5 cm	-.1	2.3	-.9	.0	.5	5.4
	10 cm	.2	1.2	.5	5.4	.7	4.5
	15 cm	-.1	1.0	.5	4.9	.7	3.9
	30 cm	-.4	.9	-1.4	4.0	.4	2.7
	50 cm	-.5	.8	-2.7	3.6	.0	1.8
11	5 cm	-.2	2.8	-.7	.0	.7	6.2
	10 cm	.2	1.5	.3	5.6	1.0	5.3
	15 cm	.0	1.1	.5	5.0	1.0	4.7
	30 cm	-.4	.9	-1.1	4.0	.8	3.3
	50 cm	-.5	.8	-2.3	3.5	.3	2.2

* Predicted-Actual
** Diffusivity 2-5 cm = 3.0 cm^2/hr
5-2000 cm = 20. cm^2/hr

Site 3b, Association R2**
Modelled for Day 9-11

Assoc.	Level	Amplitude P-A*(°C)	Amplitude Actual(°C)	Phase P-A*(hr)	Phase Actual(r)	Average P-A*(°C)	Average Actual(°C)
9	5 cm	.0	1.3	-.1	5.8	.2	3.1
	10 cm	.0	.8	2.0	4.7	.3	2.5
	15 cm	-.2	.9	1.0	4.3	.2	2.2
	30 cm	-.4	.8	-1.5	3.8	-.2	1.7
	50 cm	-.5	.7	-3.8	3.7	-.4	1.1
10	5 cm	.1	1.5	-.8	6.0	.3	4.1
	10 cm	.1	.9	2.3	4.7	.6	3.2
	15 cm	-.1	.8	1.6	4.3	.5	2.9
	30 cm	-.4	.8	-1.0	3.7	.1	2.1
	50 cm	-.5	.7	-2.7	3.5	-.2	1.3
11	5 cm	.1	1.8	-.4	6.0	.5	4.7
	10 cm	.3	.8	2.2	4.9	.9	3.9
	15 cm	.0	.8	1.9	4.4	.8	3.5
	30 cm	-.4	.8	-.6	3.7	.4	2.6
	50 cm	-.5	.7	-2.3	3.5	.1	1.6

* Predicted-Actual
** Diffusivity 2-5 cm = 4. cm^2/hr
5-2000 cm = 20. cm^2/hr

APPENDIX C

PROGRAMS

```
      PROGRAM SIM(INPUT,OUTPUT,PUNCH,AF,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1=
     1AF)
C
C THIS PROGRAM IS USED TO SOLVE THE FOURRIER HEAT CONDUCTION EQUATION FOR ONE
C DIMENSIONAL HEAT FLOW IN SOILS
C IT IS BASED ON THE CRANK AND NICHOLSON(1946) SCHEME  OF FINITE APPROXIMATION
C INPUT DATA IS READ FROM A PERMANENT FILE FROM HOURLY TEMPERATURE DATA
C
      DIMENSION AVET(6),AVEP(6),COEF(3,800),COEFF(800),SUM(6)
     1,RTEMP(24,6),OTEMP(24),CHIP(6)
      COMMON NORM(6),HEAD(2),TEMP(48,6,4),BOTEMP(50),UPTEMP(50),
     1INITEMP(800),IMP(10),PIMP(10),CON(10),A(800)
      COMMON/B/ PLEV(6)
      REAL INITEMP
C
C THE ARRAY PLEV IS USED TO STORE THE ACTUAL LEVELS OF TEMPERATURE
C MEASUREMENT
C
      DATA(PLEV(I),I=1,6)/0.,3.,8.,13.,28.,48./
C
C KL REPRESENTS THE FIRST ROD TO BE ANALYSED,KL THE LAST ROD AND PHE THE
C COEFFIENCIENT OF THE FINITE APPROXIMATION
C
      READ(5,531)KL,KM,KN,PHE
  531 FORMAT(3I2,F5.2)
C
C NF SPECIFIES THE NUMBER OF DIFFERENT INCREMENT SIZES TO BE USED IN THE
C PROGRAM
C DATA FOR THE DIFFERENT INCREMENT SIZES IS READ IN BY THE SUBROUTINE INCRE
C WHICH DOES THE ACTUAL CALCULATION AND DETERMINES THE LOCATION OF THE ACTUAL
C MEASUREMENT LEVELS IN THE FINITE DIFFERENCE ARRAY
C
      NF=4
      CALL INCRE(NF)
C
C RV SPECIFIES THE DISPLACEMENT OF THE UPPER BOUNDARY CONDITION
C
      RV=0.
C
C RTEMP IS THE LOWER BOUNDARY CONDITION
C
      RTEMP=-40.
C
C NJIB SPECIFIES THE NUMBER OF POINTS FOR THE FOURRIER ANALYSIS
C
      NJIB=24
C
C NRT SPECIFIES THE UPPER BOUNDARY CONDITION AS A MEASUREMENT LEVEL IN THE SOI
C
      NRT=1
      LPD=NRT+1
C
C REP IS USED TO DISPLACE THE INITIAL CONDITIONS
C
      REP=0
      MOD=0
C
C N SPECIFIES THE NUMBER OF HOURS IN THE ANALYSIS
C
```

```
      N=24
      PRINT 610,KL,KM,KN
  610 FORMAT(1H0,*ROD*,I3,*  TO*,I3,* WITH JUMP SIZE*,I3)
      DO 1001 K=KL,KM,KN
      NM=N-1
      MOD1=1
      REWIND 1
C
C DATA IS READ IN FROM THE PERMANENT FILE
C
   12 READ(1)(MHEAD(I),I=1,2),(((TEMP(I,J,KT),J=1,6),I=1,24),KT=1,4)
      IF(EOF(1)) 1001,13
   13 PRINT 600,(MHEAD(I),I=1,2)
  600 FORMAT(1H0,*RECORDER*,I2,*DAY*,I3)
      PRINT 601,(((TEMP(I,J,KT),I=1,24),J=1,6),KT=1,4)
  601 FORMAT(1H0,24F5.1/1H ,24F5.1/1H ,24F5.1/1H ,24F5.1/1H ,24F5.1/
     11H ,24F5.1)
C
C CALCULATE ACTUAL TEMPERATURE AVERAGE
C
      DO 63 JV=NRT,6
      SUMT=0.0
      DO 62 I=1,24
   62 SUMT=SUMT+TEMP(I,JV,K)
   63 AVET(JV)=SUMT/24
C
C THE FIRST ROW OF THE PREDICTED TEMPERATURE ARRAY IS SET EQUAL TO THE FIRST
C ACTUAL TEMPERATURE ROW DESIGNATED BY NRT
C
      DO 1 I=1,N
    1 PTEMP(I,NRT)=TEMP(I,NRT,K)-RV
C
C WHICH IN TURN SETS THE UPPER BOUNDARY CONDITION IN THE ARRAY UPTEMP
C
      DO 10 IQ=1,N
   10 UPTEMP(IQ)=PTEMP(IQ,NRT)
C
C DELT IS THE TIME INCREMENT
C
      DELT=1.
C
C WHEN MOD1=1 THIS IS THE RUN OF THE FIRST 24 HOUR SET OF DATA, WHEN
C MOD1IS 0 THE DATA IS FROM A SUBSEQUENT DATA SET
C
      IF(MOD1) 16,16,17
C
C DIFFU SPECIFIES THE DIFFUSIVITY VALUES AND SETS THEM INTO ARRAY A
C DATA IS READ INTO THE DIFFU SUBROUTINE AND THEN TRANSFERRED BY COMMON TO THE
C MAIN PROGRAM
C MIL IS USED IN SOME CASES TO SET THE DIFFUSIVITY VALUES FROM THE MAIN PROGR
C
   17 CALL DIFFU(NF,MOD,MIL)
      IF(MOD) 420,420,1001
C
C THE DIFFUSIVITY FUNCTION FOR ALL THE DIFFERENT INCREMENT SIZES IS SET IN TH
C SECTION TO STATEMENT 101
C
  420 NTE=1
```

```
      IT=IMP(NF)
      DO 101 JB=1,NF
      IV=IMP(JB)-1
      DO 102 KB=NTF,IV
  102 A(KB)=(DELT*A(KB))/CON(JB)**2
      NTF=IMP(JB)
  101 CONTINUE

 SUBROUTINE COND SETS THE INITIAL CONDITIONS
 NO DATA IS READ IN TO THE SUBROUTINE, RBG IS USED TO CHANGE THE
 INITIAL CONDITIONS ARBITRARILY

      CALL COND(N,NF,PTEMP,K,RFB)

 THE FIRST ROW OF THE PREDICTED TEMPERATURE ARRAY IS SET EQUAL TO THE INITIAL
 CONDITIONS
      DO 9 JQ=NRT,6
    9 PTEMP(1,JQ)=INITEMP(NORM(JQ))
   16 CONTINUE
      NIMP=IMP(NF)
      NIMPMM=NIMP-2
      NACK=NIMPMM-NORM(NRT)+1

 TO STATEMENT 303 THE COEFFICIENT OF THE THREE BANDED MATRIX OF THE CRANK AND
 NICHOLSON SCHEME ARE CALCULATED
 IP IS VARIED DEPENDING ON WHETHER THIS IS THE FIRST DATA SET OR SUBSEQUENT

      DO 59 I=1,NM
  212 IF(MOD1) 21,21,20
   20 IP=I+1
      GO TO 23
   21 IP=I
   23 DO 303 JVD=1,NACK
      J=JVD+NORM(NRT)-1
      JP=J+1
      JPP=J+2
      COFF(1,JVD)=-PHF*A(J)
      COFF(3,JVD)=-PHF*A(JP)
      COFF(2,JVD)=1+PHF*(A(J)+A(JP))
      COFFF(JVD)=(1-PHF)*(A(J)*(INITEMP(J)-INITEMP(JP))+A(JP)*
     1(INITEMP(JPP)-INITEMP(JP)))+INITEMP(JP)
  303 CONTINUE

 THIS SETS THE FIRST AND LAST OF THE CONSTANTS OF THE CRANK AND NICHOLSON SCEM

      COFFF(NACK)=COFFF(NACK)+PHF*(A(NIMPMM)*BOTEMP(IP))
      COFFF(1)=COFFF(1)+PHF*(A(NORM(NRT))*UPTEMP(IP))

 DIAG3 IS A GAUSSIAN ELIMINATION PROGRAM FOR A THREE BANDED MATRIX AVAILABLE
 FROM THE MCMASTER PROGRAM LIBRARY, IT IGNORES THE FIRST COEFFICIENT OF THE
 FIRST ROW AND THE THIRD COEFFICIENT OF THE LAST ROW

      CALL DIAG3(COFF,COFFF,NACK)
      NIFF=NRT+1
      DO 40 JT=NIFF,6
      NORT=NORM(JT)-NORM(NRT)
      PTEMP(IP,JT)=COFFF(NORT)
   40 CONTINUE
```

```
      DO 50 JVD=1,NACK
      J=JVD+NORM(NRT)-1
      JP=J+1
C
C SET THE PREDICTED TEMPERATURE EQUAL TO THE APPROPRIATE COEFFICIENT
C RESET INITIAL CONDITIONS AND UPPER AND LOWER BOUNDARY CONDITIONS TO THE I+1
C TIME ROW
C
   50 INITEMP(JP)=COEFF(JVD)
      INITEMP(NORM(NRT))=UPTEMP(IP)
      INITEMP(NIMP)=BOTEMP(IP)
   59 CONTINUE
C
C CALCUALTE THE PERCENTAGE DEVIATION AND THE PREDICTED AVERAGE TEMPERATURE
C
      DO 6 J=NRT,6
      CHIP(J)=0.0
      SUM(J)=0.0
      DO 2 I=1,24
      RLQ=(TEMP(I,J,K)-PTEMP(I,J))
      CHIP(J)=CHIP(J)+(ABS(RLQ)/TEMP(I,J,K))
    2 SUM(J)=SUM(J)+PTEMP(I,J)
      CHIP(J)=CHIP(J)/24.
    6 AVFP(J)=SUM(J)/24
C PRINT OUT
      PRINT 604
  604 FORMAT(1H0,*AVERAGES*/1H ,*ACTUAL VS.PRODICTED*,5X,*DEVIATIONS*)
C PLOT PRE4IQ+E4AND ACTUAL VALUES ON THE LINE PRINTER
C
      DO 85 J=NRT,6
      PRINT 605,AVFT(J),AVFP(J),CHIP(J)
  605 FORMAT(1H ,F10.6,4X,F10.6,4X,F10.6)
   85 CONTINUE
      DO 511 JLQ=2,6
      DO 67 IK=1,24
      CALL SCALF(0.,24.,0.,20.)
      RD=IK
      CALL PLOTPT(RD,TEMP(IK,JLQ,K),3)
   67 CALL PLOTPT(RD,PTEMP(IK,JLQ),44)
      CALL OUTPLT
  511 CONTINUE
C
C CALCULATE THE FOURRIER COEFFICIENTS FOR EACH LEVEL AND PRINT OUT
C
      PRINT 781
  781 FORMAT(1H0,30X,*PREDICTED*/1H ,20X,*AMPLITUDE*,5X,*PHASE*)
      DO 81 JLQ=NRT,6
      DO 68 IL=1,24
   68 QTEMP(IL)=PTEMP(IL,JLQ)
      CALL FOUREX(QTEMP,NJIB,PAMP,PPHI)
      PRINT 649,PAMP,PPHI
   81 CONTINUE
      PRINT 780
  780 FORMAT(1H0,30X,*ACTUAL*/1H ,20X,*AMPLITUDE*,5X,*PHASE*)
      DO 80 JLQ=NRT,6
      DO 69 IL=1,24
   69 QTEMP(IL)=TEMP(IL,JLQ,K)
      CALL FOUREX(QTEMP,NJIB,AAMP,APHI)
```

```
      PRINT 649,AAMP,APHI
  649 FORMAT(1H ,20X,2F14.10)
   80 CONTINUE
      DO 817 J=1,6
      PUNCH 820,(TEMP(I,J,K),I=1,12),(MHEAD(I),I=1,2),K,J
      PUNCH 820,(TEMP(I,J,K),I=13,24),(MHEAD(I),I=1,2),K,J
  820 FORMAT(12F5.2,10X,*R*,I1,*D*,I2,*S*,I1,*L*,I1,*A*)
      PUNCH 810,(PTEMP(I,J),I=1,12),(MHEAD(I),I=1,2),K,J
      PUNCH 810,(PTEMP(I,J),I=13,24),(MHEAD(I),I=1,2),K,J.
  810 FORMAT(12F5.2,10X,*P*,I1,*D*,I2,*S*,I1,*L*,I1)
  817 CONTINUE
      PRINT 601,((PTEMP(I,J),I=1,24),J=1,6)
      MODI=0
      NM=N
      GO TO 12
 1001 CONTINUE
      STOP
      END
      SUBROUTINE DIFFU(NF,MOD,MIL)
C
C SUBROUTINE DIFFU ALLOWS FOR VARIABLE THERMAL DIFFUSIVITIES IN THE SOIL COLUMN
C IT READS IN ITS OWN DATA AND THE FORMAT VARIES DEPENDING ON THE EXPERIMENT TO
C TO BE PERFORMED
C
      DIMENSION DIFF(5)
      COMMON NORM(6),MHEAD(2),TEMP(48,6,4),BOTEMP(50),UPTEMP(50),
     1INITEMP(800),IMP(10),PIMP(10),CON(10),A(800)
      READ(5,500) DIFF(1),DOT
  500 FORMAT(2F5.2)
      DO 16 IK=2,5
   16 DIFF(IK)=DOT
      DIP=DOT
   11 IV=0
      PRINT 600,(DIFF(IK),IK=1,5)
  600 FORMAT(1H0,20X,*ACTUAL DIFFUSIVITIES*/1H0,10X,5F10.6)
      ID=1
      DO 3 I=1,5
      IQ=NORM(I+1)-1
      DO 2 J=ID,IQ
      IV=IV+1
    2 A(IV)=DIFF(I)
    3 ID=IQ+1
      IT=IMP(NF)
      NO=NORM(6)
      DO 6 IG=NO,IT
      IV=IV+1
    6 A(IV)=DIP
    8 RETURN
      END
      SUBROUTINE COND(N,NF,RTEMP,K,REG)
C
C SUBROUTINE INCRE SETS THE DEPTH INCREMENT LEVELS AND CALCULATES THE LEVELS
C CORRESPONDING TO ACTUAL
C
      REAL INITEMP
      DIMENSION SLOPE(10)
      COMMON NORM(6),MHEAD(2),TEMP(48,6,4),BOTEMP(50),UPTEMP(50),
     1INITEMP(800),IMP(10),PIMP(10),CON(10)
```

```
      COMMON/B/ RLEV(6)
C
C SUBROUTINE COND SETS THE INITIAL CONDITIONS FOR THE FIRST TIME INCREMENT EQUA
C TO THE LINEAR INTERPOLATION BETWEEN ACTUAL MEASURED VALUES
C
C THIS SUBROUTINE CALCULATES THE INITIAL CONDITIONS FROM A POLYNOMIAL FIT
C AND A LINEAR APPROXIMATION TO BASE TEMPERATURE,RTEMP
C IT ALSO SETES THE LOWER BOUNDARY CONDITIONS AT RTEMP
C UPPER BOUNDARY CONDITIONS MUST BE SET BY ANOTHER ROUTINE
C FIT POLYNOMIAL TO INITIAL TEMPERATURE PROFILE
      DO 321 JK=1,6
      TEMP(1,JK,K)=TEMP(1,JK,K)-REG
  321 CONTINUE
      DO 500 JD=1,5
      JDP=JD+1
  500 SLOPE(JD)=(TEMP(1,JD,K)-TEMP(1,JDP,K))/(RLEV(JD)-RLEV(JDP))
      I=1
      DO 1 JD=1,5
      JDP=JD+1
      NORTP=NORM(JDP)-1
      NORT=NORM(JD)
      KIMP=IMP(I)
      IP=I+1
      IF(NORTP-IMP(I)) 2,2,4
    2 CONT=0.0
      DO 3 IG=NORT,NORTP
      INITEMP(IG)=TEMP(1,JD,K)+SLOPE(JD)*CONT
      CONT=CONT+CON(I)
    3 CONTINUE
      GO TO 1
    4 CONT=0.0
      DO 5 IG=NORT,KIMP
      INITEMP(IG)=TEMP(1,JD,K)+SLOPE(JD)*CONT
      CONT=CONT+CON(I)
    5 CONTINUE
      IT=IMP(I)+1
      CONT=CONT-CON(I)+CON(IP)
      DO 6 IG=IT,NORTP
      INITEMP(IG)=TEMP(1,JD,K)+SLOPE(JD)*CONT
      CONT=CONT+CON(IP)
    6 CONTINUE
      I=I+1
    1 CONTINUE
      INITEMP(NORM(6))=TEMP(1,6,K)
      N100=1
    9 N1=NORM(6)+1
      N2=IMP(N100)
      SL=(RTEMP-INITEMP(NORM(6)))/1952.
      CONT=0.0
   15 DO 12 IR=N1,N2
      CONT=CONT+CON(N100)
   12 INITEMP(IR)=INITEMP(NORM(6))+SL*CONT
      IF(N100-NE) 14,13,13
   14 N100=N100+1
      NP=N100-1
      N1=IMP(NP)+1
      N2=IMP(N100)
      GO TO 15
```

```
   13 DO 25 IQ=1,N
   25 BOTEMP(IQ)=INITEMP(IMP(NF))
      PRINT 601
  601 FORMAT(1H0,*INITIAL CONDITIONS*)
      RETURN
      END
      SUBROUTINE INCRE(NF)
      COMMON NORM(6),NHEAD(2),TEMP(48,6,4),BOTEMP(50),UPTEMP(50),
     1INITEMP(800),IMP(10),RIMP(10),CON(10)
      COMMON/B/ RLEV(6)
      READ(5,500) (CON(I),I=1,NF)
      READ(5,500) (RIMP(I),I=1,NF)
  500 FORMAT(10F10.6)
      JP=1
      ILT=0
      RILT=0.0
      DO 1 I=1,NF
      IMP(I)=((RIMP(I)-RILT)/CON(I))+ILT+.05
      ILT=IMP(I)
    1 RILT=RIMP(I)
      LIP=1
      RLET=0.0
      DO 6 I=1,6
      IF(RLEV(I)-RIMP(JP)) 4,3,3
    3 NORM(I)=((RIMP(JP)-RLET)/CON(JP))+((RLEV(I)-RIMP(JP))/CON(JP+1))
     1+LIP+.05
      RLET=RLEV(I)
      LIP=NORM(I)
      JP=JP+1
      GO TO 6
    4 NORM(I)=((RLEV(I)-RLET)/CON(JP))+LIP+.05
      RLET=RLEV(I)
      LIP=NORM(I)
    6 CONTINUE
      PRINT 601
  601 FORMAT(1H3,4X,*LOOP NO.*,4X,*LEVEL NO.*,7X,*INCREMENT*,4X,
     1*ACTUAL*)
      DO 7 I=1,NF
      PRINT 602, IMP(I),RIMP(I),CON(I),NORM(I)
  602 FORMAT(1H ,7X,I3,7X,F8.3,7X,F8.3,7X,I3)
    7 CONTINUE
      NT=NF+1
      DO 11 I=NT,6
      PRINT 603, NORM(I)
  603 FORMAT(1H ,47X,I3)
   11 CONTINUE
      RETURN
      END
      SUBROUTINE FOUREX(T,N,AMP,PHI)
C
C     FOURIER EXPANSION
C     T IS INPUT DATA FROM  N  EVENLY SPACED PERIODS, UP TO 50 PERIODS. (P/2)
C     TITLE IS DIMENSIONED (20A4)
C     THE PROGRAMME ASSUMES AN INTERVAL OF TWO PI TO BE UNIFORMLY DIVIDED INTO
C           N = 2*P WHERE PERIOD IS HERE CONSIDERED AS  P/2
C     COMPUTATION STOPS WHEN CALCULATED VARIANCE IS UNDER 59 OBSERVED VARIANCE,
C           UNLESS OVER-RIDDEN BY  L  BEING GIVEN A SPECIFIC VALUE EQUAL TO THE
C           HIGHEST HARMONIC DESIRED (MAX. ALLOWED IS 10)
```

```
C     PROGRAMME RETURNS  VALUES OF  2*P=N,  NO. OF HARMONICS (L), MEAN (AVE),
C            AMPLITUDES(AMP)  AND  PHASE ANGLES(PHI).
C
      DIMENSION  T(N),  TITLE(20), AMP(10), PHI(10),
     1             TEXP(50, 10), F(50), VARAMP(10), PVAR(10)
C     Z = PI / PERIOD
      Z = 6.2832 / (FLOAT(N))
      NHALF = N/2
C     FIND VARIANCE AND DEVIATIONS FROM MEAN
10    AVE = 0.0
      VAR = 0.0
      DO 20 I = 1, N
20    AVE = T(I) + AVE
      AVE = AVE / (FLOAT(N))
      DO 25 I = 1, N
      F(I) = T(I) - AVE
25    VAR = (VAR + F(I)*F(I))
      VAR = VAR / (FLOAT(N-1))
C
C     FIND COEFFICIENTS FOR VARIOUS HARMONICS
C     A = 1/P * SUM ( F(X) COS(KZX) ),    X = (1, N)
C     B = 1/P * SUM ( F(X) SIN(KZX) ),    X = (1, N)
      K = 1
26    S = K
      A = 0.0
      B = 0.0
      DO 30 I = 1, N
      R = I
      A = F(I) * COS(R*S*Z) + A
30    B = F(I) * SIN(R*S*Z) + B
      A = 2.0 * A / (FLOAT(N))
      B = 2.0 * B / (FLOAT(N))
C     AMPLITUDE AND PHASE ANGLE
      PHI(K) = ATAN(A/B)
      AMP(K) = SQRT(A*A + B*B)
C     FOR THE LAST HARMONIC, B AND THE SINE COMPONENT WOULD BE ZERO
      IF (K.EQ.NHALF) AMP(K) = ABS(A)
C     ENSURE CORRECT SIGN FOR PHASE ANGLE
      PHI(K) = ABS(PHI(K))
      IF (A.GE.0.0. AND .B.GE.0.0) GO TO 34
      IF (A.GE.0.0. AND .B.LT.0.0) GO TO 31
      IF (A.LT.0.0. AND .B.LT.0.0) GO TO 32
      IF (A.LT.0.0. AND .B.GE.0.0) GO TO 33
31    PHI(K) = 3.1416 - PHI(K)
      GO TO 34
32    PHI(K) = 3.1416 + PHI(K)
      GO TO 34
33    PHI(K) = 6.2832 - PHI(K)
   34 RETURN
      END
        6400 END OF RECORD
```

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