Cover

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 2108

Computer Analysis of Norman Wells Pipeline Thermal Data

D.W. Riseborough

1989

Energy, Mines and
Resources Canada

Énergie, Mines et
Ressources Canada

Canada

Inside Title Page

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 2108

Computer Analysis of Norman Wells Pipeline Thermal Data

Final Report to

Permafrost Research Section
Terrain Sciences Division
Geological Survey of Canada
Energy, Mines and Resources
1 Observatory Cres.
Ottawa, Ont.
K1A 0Y3

by

D.W. Riseborough

1989

Geotechnical Science Laboratories
Carleton University
Ottawa, Ont.
K1S 5B6

DSS File Number: 23233-8-1204/SZ

FOREWORD

This report documents work undertaken as part of the federal government's Permafrost and Terrain Research and Monitoring Program along the 868.6 km Norman Wells to Zama oil pipeline. The 324 mm diameter, shallow burial (1 m) pipeline, traverses the discontinuous permafrost zone of northwestern Canada and began operation in April 1985. A joint monitoring program with Interprovincial Pipe Lines (NW) Ltd. was established following the signing of an environmental agreement between the pipeline company and the Department of Indian and Northern Affairs (INAC) in 1983. INAC coordinates the government's monitoring program in which Energy, Mines and Resources' Geological Survey of Canada, the National Research Council's Institute for Research in Construction, and Agriculture Canada's Land Resource Research Institute participate.

A major component of this research and monitoring program involves the detailed quantification of changes in the ground thermal regime and geomorphic conditions at thirteen instrumented sites along the route. This project was developed in cooperation with the Permafrost Research Section of the Geological Survey in order to examine and quantify the effects of pipeline construction, operation and maintenance in thaw sensitive terrain. Many components of this research are contracted out.

The work undertaken in this contract report describes but one aspect of these site investigations. Interpretations contained herein are often limited to the specific data base under analysis and may thus not present an integrated or comprehensive analysis of all site observations. The opinions and views expressed by the authors are their own and do not necessarily reflect those of the Geological Survey of Canada or Indian and Northern Affairs.

Funding for the research and analyses reported herein was largely provided by INAC's Northern Affairs Program.

Margo Burgess
Scientific Authority
Permafrost Research Section
Geological Survey of Canada

Table of Contents

Acknowledgements

The long term ground thermal regime monitoring program of the Norman Wells Pipeline permafrost and terrain research and monitoring program has been undertaken by the Permafrost Research Section of the Geological Survey of Canada, in cooperation with the Department of Indian and Northern Affairs and Interprovincial Pipe Line Ltd. This report is based upon field measurments taken by many people from Energy Mines and Resources and the Department of Indian and Northern Affairs as part of that program. Funding for this contract has come from the Federal Panel on Energy Research and Development and the Department of Indian and Northern Affairs. The work described in this report was assisted and expedited with the help of M. Burgess of the Permafrost Research Section and K. MacInnes of Indian and Northern Affairs.

Computer Analysis of
Norman Wells Pipeline Thermal Data

D.W. Riseborough

Geotechnical Science Laboratories
Carleton University
Ottawa, Ontario
K1S 5B6

SECTION 1

Introduction

Ground temperature data have been collected along the Norman Wells - Zama pipeline route, at the monitoring sites established in 1984 and 1985 (Burgess et al. 1985). This report summarizes the results of several analyses performed using the data collected to the end of October 1988. Some emphasis is placed upon the analysis of data obtained since the last report (Riseborough et al. 1987), and on extended analyses of the entire record for selected sites.

The work undertaken for this part of the contract comprised the following:

1. Using geothermal simulation, examine changes in mean annual temperature with depth (over a period of 10 years) following a 1 degree rise in surface temperature for "warm", "cold", and "no" permafrost cases.

2. Extend calculation of running mean annual air temperatures with monthly Atmospheric Environment Service data from Norman Wells and Fort Simpson.

3. Obtain weekly estimates of pipe and ground temperatures by interpolating between approximately monthly temperature measurements, and use the interpolated values to obtain running mean annual temperatures.

4. Compare pipe temperatures to ground temperatures on the adjacent right-of-way and off right-of-way.

5. Compare right-of-way ground and off right-of-way temperature trends with depth for selected sites.

6. Interpret trends in light of available snow depth data, air temperature trends, and soil physical and thermal properties as established in Part II of this report; determine whether response varies according to major soil groupings or site characteristics.

In essence, the work of this contract is to examine variations in ground temperatures over distance and over time. The spatial variations include changes in temperature with depth, across the right-of way (by comparing pipe, T1, T3 and T4 sensors), and over the length of the pipeline from Norman Wells to Km 819.5. Temporal variations in temperature are examined primarily as changes in mean annual temperatures, though this requires interpretation of variations in the annual temperature waves.

1.1 Sensor Cable installations

Pipe and ground temperature sensors were usually installed in a standard configuration at the monitoring sites. At each site, a set of thermistor temperature sensor cables were installed, referred to collectively as a "fence". In the typical configuration :

- pipe temperatures are monitored with 5 sensors on the exterior surface of the pipe;

- sensor cables, labelled T1 and T2 are installed to a depth of 5 meters on either side of the pipeline (less than 2 meters from the pipe), typically with sensors at 50 cm intervals;

- a sensor cable labelled T3 is installed to a depth of 20 meters (with sensors at 1 and 2 meter intervals) at some distance from the pipe (typically 5 meters away) but still on the right of way;

- a sensor cable labelled T4 is installed to a depth of 20 meters (with sensors at 1 and 2 meter intervals), at some distance from the pipeline right-of-way.

The sensor fences permit an assessment of three different ground thermal regimes: adjacent to the pipe, on the right-of- way, and in the "undisturbed" ground away from the right-of-way. Interpolated temperature curves and running mean annual temperatures were obtained for all sensors: due to the volume of numbers they are not included in this report. A floppy disk copy of all measured, interpolated, and running mean temperatures, for all sensors on all cables has been supplied to the scientific authority. Additional sensor cables are installed at some sites, and one site (Redknife Hills) does not conform to the "fence" configuation. While estimates and running means have been supplied with the other data, no further analysis of results from these cables has been undertaken.

SECTION 2

Methods of Analysis

2.1 Interpolation of ground and pipe temperature data.

Smooth temperature curves were created from the original monitoring program data for plotting purposes as well as to permit mean annual temperature estimates. Intermediate soil and pipe temperatures were estimated between temperature measurements using cubic spline interpolation, as described in the previous report (Riseborough et al. 1987). As recommended in the addendum to the previous report (Riseborough 1988), the interpolation program was modified to give estimates at 5 day intervals rather than 1 week (as previous) in order to improve slightly the precision of the mean annual temperatures calculated with the estimates. Pipe temperatures in graphs in Appendix I are the average for the five pipe sensors (with the single exception noted below).

Table I comprises a list of those sites for which there are gaps of more than two months between measurements. Whether gaps of this length are significant to individual interpolated temperature curves depend upon the rate of temperature change of the individual sensors. With the exception of the Petitot River sites, there are no new gaps for the year ending October 1988.

Data files for many cables required some manipulation before satisfactory interpolations were obtained. As noted in the previous report, sharp transitions from rapid to slower temperature change can produce an interpolation curve which oscillates from datum to datum, rather than forming a smooth curve. Measurements taken within a short period (relative to the average measurement interval) can cause similar problems. The oscillation problems were dealt with only as required: interpolation was performed on the original data sets for each cable, and the resulting curve for the 1 meter sensor plotted. If the interpolated curve displayed the problems as described, "extra" data were removed. This was repeated until a satisfactory interpolated curve was produced. Modifications were usually either :

a) removal of measurements taken less than one week apart, or

b) removal of the first few measurements in the data set.

Removal of the early part of the data set was nessesary at a number of sites which experienced a rapid warming trend at the start of the measurement program (due to snow removal operations along the right-of-way in the winter of 1984-85). The sudden change in behavior lead to the oscillations described above.

Two further modifications to the data sets was perfomed at the request of the scientific authority: First, pipe temperature data collected in October 1987 were removed from the data sets for the MacKenzie highway south and Moraine south sites. These measurements corresponded to a period when oil

Table I Sites with gaps between measurements exceeding 60 days.

		Gaps		
Site	Cable	From	To	Duration (Days)
1	ALL	23-11-84	26-01-85	64
2A	T1	23-11-84	26-01-85	64
		19-02-85	22-05-85	92
	T2,T3	25-11-84	26-01-85	62
	T4	25-11-84	26-01-85	62
		06-03-85	22-05-85	77
		16-10-85	24-05-86	220
		28-10-86	08-02-87	103
		14-03-87	27-05-87	74
	HT137	16-06-87	11-09-87	87
2B	T1,T2	24-11-84	26-01-85	63
		08-02-87	16-04-87	67
	T3	24-11-84	26-01-85	63
		10-12-86	08-02-87	60
		14-03-87	27-05-87	74
	T4	10-12-86	08-02-87	60
2C	T1,T2	24-11-84	26-01-85	63
	T3,T4	21-09-84	24-11-84	64
		24-11-84	26-01-85	63
3A	ALL	20-09-84	24-11-84	65
		24-11-84	29-01-85	66
		16-06-87	15-08-87	60
3B	ALL	24-11-84	29-01-85	66
4A	ALL	27-11-84	22-02-85	87
4B	ALL	28-09-84	27-11-84	60
		04-03-86	28-05-86	85
5A	ALL	25-09-84	26-11-84	62
		26-11-84	21-02-85	87
		13-10-85	26-05-86	221
		23-10-86	05-02-87	105
		12-03-87	23-05-87	72
		20-08-87	06-03-88	154
		06-03-88	27-05-88	82

Table I (cont.'d) Sites with gaps between measurements exceeding 60 days.

Site	Cable	Gaps From	To	Duration (Days)
5B	ALL "OLD"	21-11-84	21-02-85	87
		13-10-85	26-05-86	225
	ALL"NEW"	05-02-87	23-05-87	107
		19-06-87	18-08-87	60
	T1"NEW"	20-08-87	07-06-88	276
		07-06-88	10-11-88	107
	T3"NEW"	04-10-87	18-01-88	106
6	ALL	25-09-84	26-11-84	62
		26-11-84	21-02-85	87
		13-10-85	26-05-86	221
		23-10-86	05-02-87	105
		12-03-87	23-05-87	72
		04-10-87	06-03-88	154
		06-03-88	27-05-88	82
		06-07-88	15-09-88	71
	T4	27-05-88	15-09-88	111
7A	T1,T2	25-05-86	26-10-86	154
		22-05-87	06-10-87	137
	T3,T4	22-05-87	06-10-87	137
7B	T1,T2,T3,T4	25-05-86	26-10-86	154
		22-05-87	06-10-87	137
	HA129,HA132	26-10-86	10-03-87	135
7C	T1,T2,T3,T4	12-10-85	03-03-86	142
		03-03-86	25-05-86	83
	HA109	19-11-86	16-01-87	78
13	ALL	13-10-85	26-05-86	221
		24-10-86	05-02-87	104

was not flowing in the pipe, so that temperatures obtained were not representative of normal conditions. Second, average pipe temperatures were determined for only four of the five pipe sensors at the Great Bear River B site. This permits inclusion of the majority of the record, during which the fifth pipe temperature sensor was not functioning.

2.2 Running mean annual temperature estimates

Running mean annual temperatures were calculated from the interpolated temperatures. For each sensor, the first mean annual temperature was obtained as the average of the first 73 five-day values (since 73 x 5 = 365): this mean was assigned to the midpoint of the first year of data. For each subsequent value, the mean annual temperature was re-calculated by dropping the first value and adding the next value to the year. This can be thought of as either a running mean of 73 five day values, or a mean annual temperature updated at five day intervals.

2.3 Preparation of Geotherm Plots

Geotherms are similar to contour lines on topographic maps, except that they are lines of equal temperature rather than equal elevation. A geotherm plot may be drawn showing a thermal cross section (with depth and distance for y- and x-axes), or showing depth along the y-axis and time on the x-axis. The second type of plot is presented in this report. In a geotherm plot, the spacing between lines indicates the rate of change of temperature over both time and depth. Unfortunately, the distance between sensors on the cables is too coarse to permit accurate plots to be prepared for the monitoring program temperatures, particularly in the upper 2 meters of the ground. Fortunately, however, the rate of change of the mean annual temperature is much more gradual, both over time and with depth, permitting "mean annual geotherms" to be plotted instead. Mean annual geotherms are similar to simple temperature geotherms except that they are lines of equal mean annual temperature.

Geotherm plots were prepared for Sites 1, 2A and B, and 7A, B, and C, using the running mean annual temperatures estimates generated from the interpolations. For each site, plots were prepared for the cable closest to the pipe (T1 or T2) as well as cables T3 and T4.

The data were supplied to a three dimensional plotting computer program to generate contour (i.e. geotherm) plots. Producing the plots was somewhat cumbersome, since the program was designed for height-contour plotting, and assumes that x and y co-ordinates are in the same units. The program generated a grid 25 divisions wide (the time axis), with the number of height divisions (the depth axis) determined by the ratio of the ranges of the y- and x-values supplied. This required that the units of time on the x axis be adjusted so that the plot produced a plot of reasonable proportions. For this reason, the time axis is unlabeled, since the units supplied to the program were for proportionality only. To help in interpretation, the vertical dashed lines are included at one year intervals. The rightmost dates for all of the plots presented is approximately April 10, 1988.

2.5 Geothermal simulation

Long term geothermal simulations were performed using a one-dimensional finite difference model, described in Smith and Riseborough (1985). Pertinent features of the model include :

- variable spacing of 200 ground temperature nodes;
- various types of ground surface temperature regime can be specified;
- temperature dependent soil thermal properties can be specified; latent heat of fusion is calculated from the freezing characteristic curve of the soil, and is included in the "apparent" thermal diffusivity.

For the simulations presented in Section 3, the time increment for calculation was one day, with a node spacing of 20 cm.

SECTION 3

Geothermal Simulation

The aim of the geothermal simulations presented here is to indicate the range of thermal responses which can be expected of earth materials due simply to differences in their initial thermal condition (temperature profile). Plotting the results of the simulations in the same form as for the monitoring site data (temperature-time and running mean-time plots for the 1 meter depth, and geotherm plots of running means versus time) will also assist in the interpretation of the field data presented in subsequent sections of this report. It must be stressed that the nature (step, gradual linear or non-linear) of the change in ground surface temperature will also determine the nature of the response of the ground thermal regime. In the present study, only a simple step temperature change is examined.

The response of ground temperatures to warming at the surface was examined by computer (numerical) simulation for three types of ground thermal regime (using the model described in section 2.5):

- a "cold" permafrost site (mean annual temperature of -2.),

- a "warm" permafrost site (mean annual temperature of -0.5), and

- a non-permafrost site (mean annual temperature of +0.5).

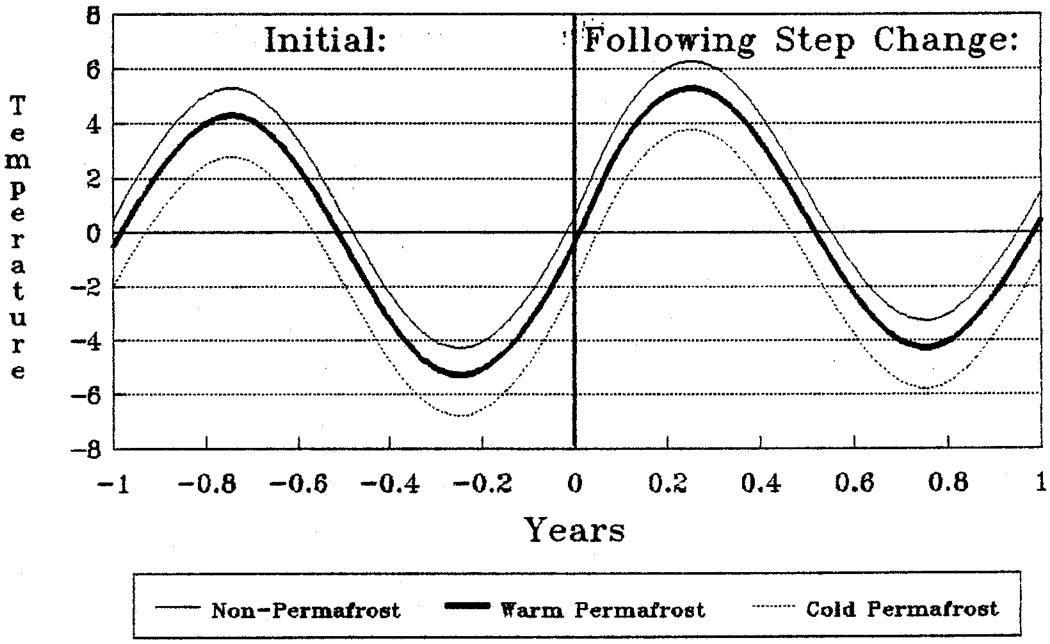


Figure 1 Surface temperatures specified in simulations

Table II Soil properties specified in simulations

Thermal Conductivity:
Frozen: 3.0 $Wm^{-1}K^{-1}$
Thawed: 1.5 $Wm^{-1}K^{-1}$

Heat Capacity:
Frozen: 2.200 E+06 $Jm^{3}K$
Thawed: 2.760 E+06 $Jm^{3}K$

Total Water Content: 41%

Unfrozen water content:
13.3 % below -0.5°C

Latent heat is released or
absorbed over the range
0.0 to -0.5°C

A sinusoidal temperature wave with a period of one year and an amplitude of 10 degrees was imposed at the ground surface (Figure 1). The sites differed only in temperature (initially uniform at the temperatures specified above); the temperature dependent soil thermal properties specified for each site were identical (see Table 1.1).Before imposing the surface temperature change, the simulations were run for 6 years, to establish initial equilibrium ground temperature profiles. Following this, the temperature waves imposed at the surface were warmed by 1 degree, and the new surface condition was sustained for 10 years.

The variation in temperature at 1 meter depth for the three thermal regimes is shown in Figure 2. In the year prior to the temperature increase (step change), the active layer does not reach 1 meter at the cold permafrost site, and the annual temperature range is about 5 degrees at this depth; the active layer does reach beyond 1 meter at the warm permafrost site, with an annual temperature range of about 3 degrees; the freezing front extends beyond 1 meter at the non-permafrost site, which experiences a 4 degree temperature range.

Following the step change in temperature, the different sites respond in different ways:

At the cold permafrost site, the active layer extends to 1 meter depth the first year, with the maximum summer temperature at this depth remaining fairly constant thereafter. The winter minimum temperature rises progressivly over several years, by about 2 degrees: the annual range at this site is reduced to about 3.5 degrees by the end of the simulation, as a greater part of the year is spent in the "warm" temperature range.

At the warm permafrost site, the winter minimum temperature rises by about 1 degree in the first year, and remains stable thereafter. The summer maximum temperature also rises by about 1 degree in the first year, but continues to climb very slowly year by year. The annual temperature range thus is initially unchanged, though it rises slowly over time, as temperatures within the summer active layer become less influenced over time by the receeding permafrost table. After 10 years, the temperature range at this depth is about 3.5 degrees. Since the ground will ultimately attain the same equilibrium temperature profile as that for the non-permafrost example prior to the step change, the long term trend for the temperature range at this depth is about 4 degrees.

At the non-permafrost site, the winter minimum temperature rises by about one half of one degree in the first year, remaining stable thereafter. Summer maximum temperatures climb over a few years to a difference from the initial maximum of about 1.5 degrees. By the end of the simulation, the annual range has increased to about 5 degrees.

Figure 3 shows the trends of mean annual temperature at the 1 meter depth for the three sites, while Figure 4 compares the changes to one another, by subtracting the initial temperature from each of the trends. Most of the temperature rise at the surface has penetrated to this depth within the first year following the change. The cold permafrost lags behind the non-permafrost briefly following the change, and then responds more rapidly thereafter: this change in behavior could be an artifact of the precise timing of the step change in the annual cycle. After 4 years the non-permafrost and cold permafrost sites have warmed by over 0.95 degrees at 1 meter, and have effectively attained a 1 degree warming after 10 years.

In contrast, the response is considerably slower for the warm-permafrost simulation, since it must thaw the permafrost in order to raise the ground temperature by one degree. A warming of 0.6 degrees is attained in the first year, rising after 10 years to only about 0.72 degrees. This slow response even at such a relatively shallow depth is due to the anchoring effect of the retreating permafrost table on temperatures within the active layer, effectivly maintaining a nearly linear temperature gradient between the surface and the base of the active layer.

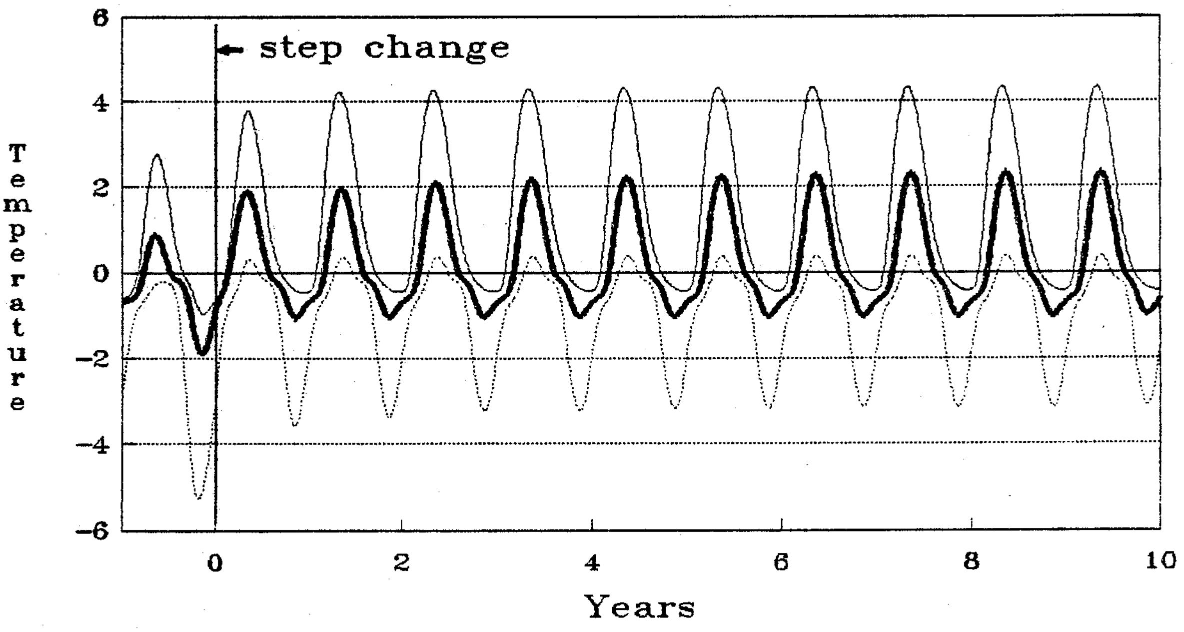


Figure 2 Temperatures at 1 meter depth prior to and following surface temperature rise.

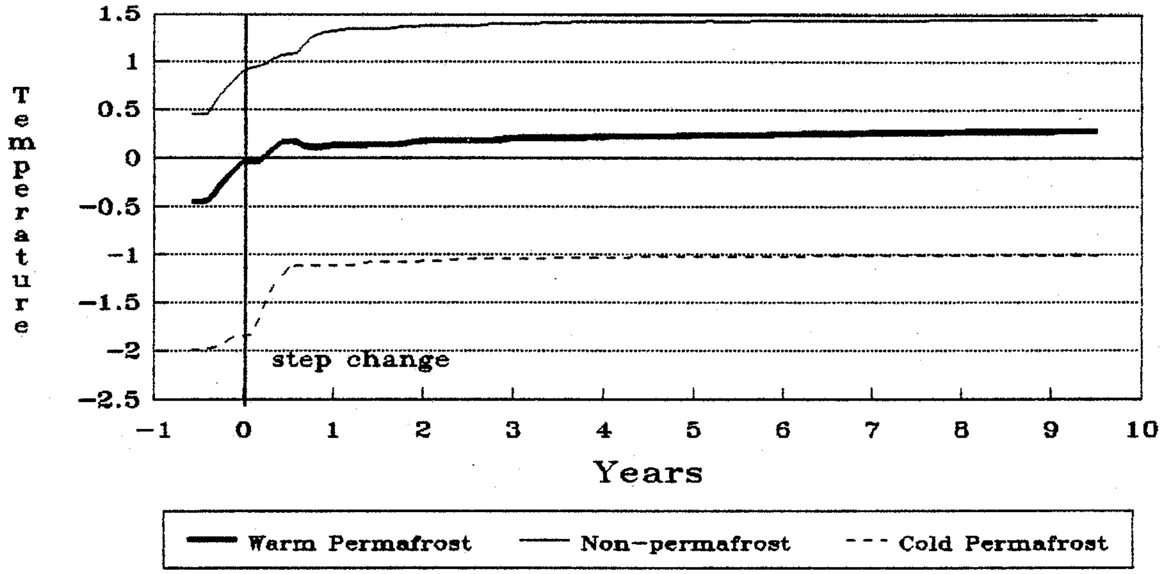


Figure 3 Simulated mean annual temperature trend at 1 meter depth

Figures 5 to 7 are geotherm plots which show the changes in mean annual ground temperature (down to 20 m) at each of the sites over the 10 year simulation, starting at the midpoint of the last year of equilibration before the change was imposed (dashed lines on these diagrams represent 1 year).

The results show the relative rates at which the temperature change at

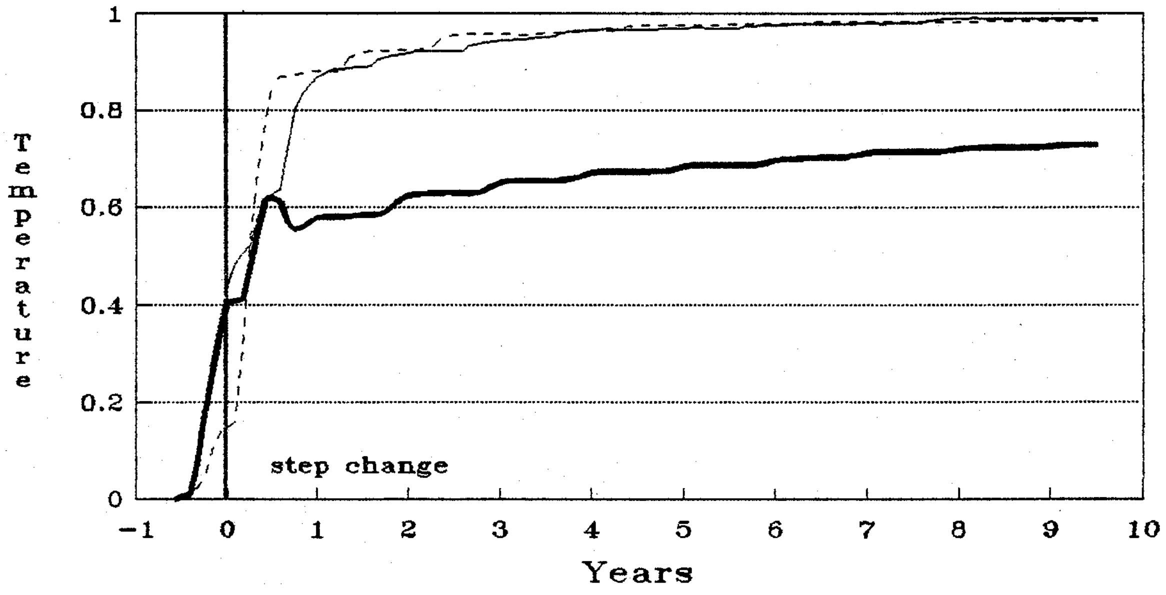


Figure 4 Rise in mean annual temperature at 1 m following step change

the surface is propagated into the soil. The effects of latent heat and thermal diffusivity are also apparent. Because the change at the surface was 1 degree in all cases, and because the geotherm interval is the same for all three plots (0.2 degrees) the distance between geotherms shows the effect of different thermal regimes on the penetration of the surface temperature change. Penetration is least at the warm permafrost site, since the change of 1 degree requires the absorbtion of the entire latent heat of fusion of the soil as it warms above zero. This results in a steep temperature gradient (i.e. closely spaced geotherms) between the surface and the degrading permafrost front. For the cold permafrost and non-permafrost sites, changes in the latent heat of the soil occurred only in a narrow range of depths at the base of the active layer: the differences in the rate of propagation of the surface disturbance into the soil at these two sites can be attributed to the relatively high thermal diffusivity of the cold permafrost (i.e. of the frozen soil relative to unfrozen soil).

For all sites, the change at the surface is attenuated significantly with depth : in warm permafrost, temperatures have increased by less than 0.1 degrees at six meters even after 10 years. In contrast the soil has warmed by 0.4 degrees at 20 m in the cold permafrost and by about .32 in the non-permafrost site, to only 0.45^0 at the non-permafrost site.

The temperature range over which latent heat is released or absorbed for a particular soil establishes the temperature range over which it behaves as "warm" permafrost: coarse grained soils containing no fine grained material may not begin to release latent heat until within one tenth of one degree below 0 celsius, while in fine grained soils latent heat effects can be observed over several degrees. As well, the amount of ice present in the frozen soil determines the penetration rate of a surface warming trend into warm permafrost, with icier sediments taking longer to thaw.

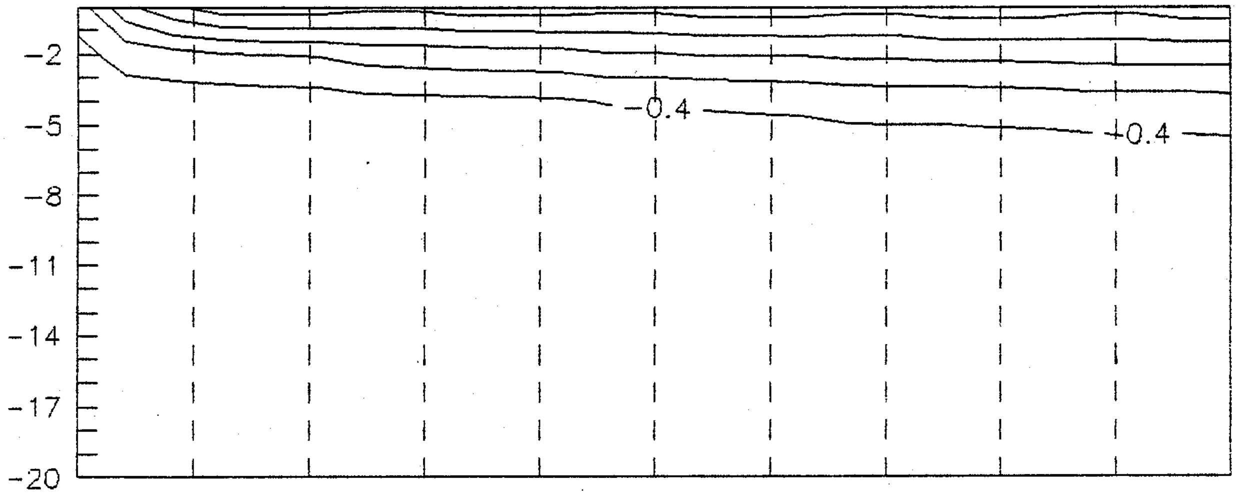


Figure 5 Response of mean annual temperatures within warm permafrost to a 1 degree increase in mean annual surface temperature.

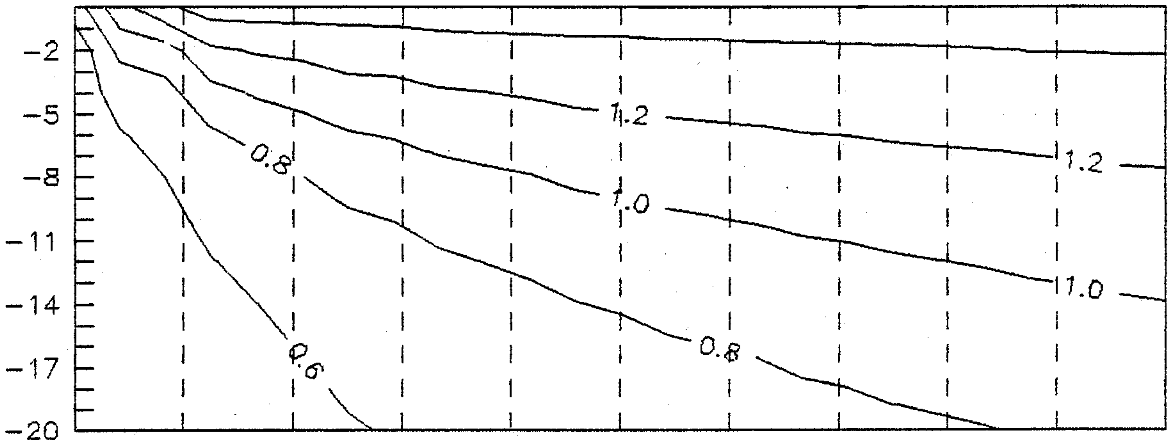


Figure 6 Response of mean annual temperatures within non-permafrost to a 1 degree rise in mean annual surface temperature.

Figure 2 demonstrates that a change in surface temperature reults in more than just a change in mean annual ground temperatures. The thermal regime is changed, altering the annual range: seasonal extremes adjust to the new mean in different ways, depending on whether the surface temperature is shifting toward or away from the range in which latent heat has a significant effect.

Smaller differences in diffusivity (due to differences in soil type as well as latent heat effects) than those presented here will have a similar effect on the thermal response of the soil. As a result, differences in long term temperature trends (between temperatures on and off of the pipeline right of way for example) cannot be an absolute measure of the magnitude of the change to the surface thermal regime.

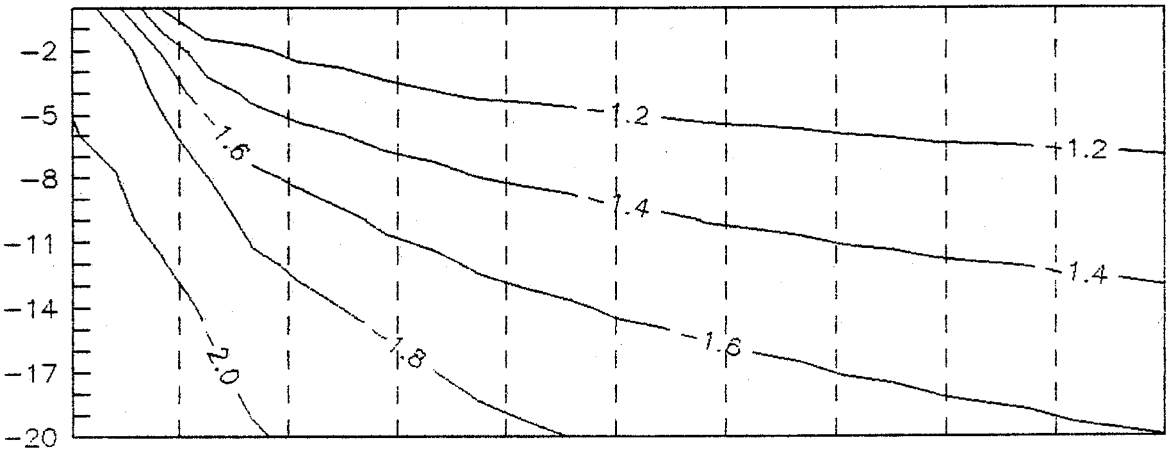


Figure 7 Response of mean annual temperatures within cold permafrost to a 1 degree rise in mean annual surface temperature.

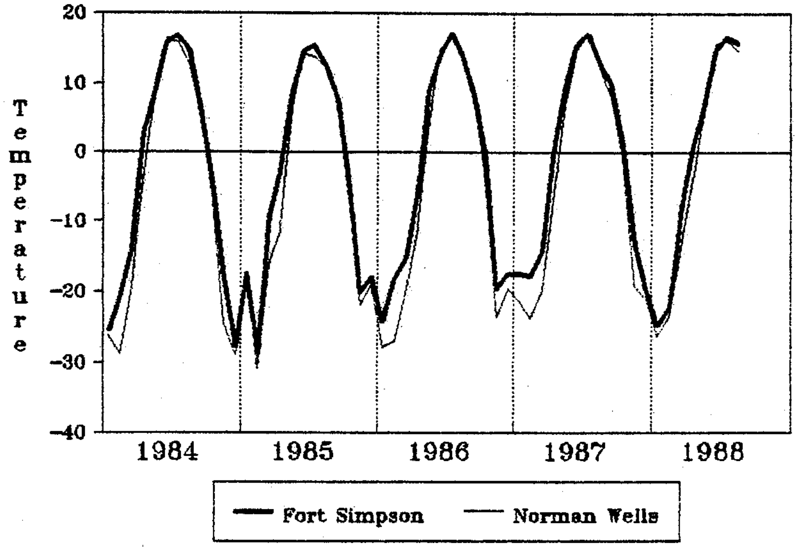
SECTION 4

The Meteorological Record at Norman Wells and Fort Simpson

Interpretation of a meteorological record of less than 5 years is somewhat hazardous, since the number of years available to examine the fluctuations of the important variables is too small to distinguish true "trends" from fluctuations around a longer term trend.In addition, apparent correlations between the meteorological record and the thermal behavior of the pipeline and right of way must be examined in physical terms, since they may be random coincidence.

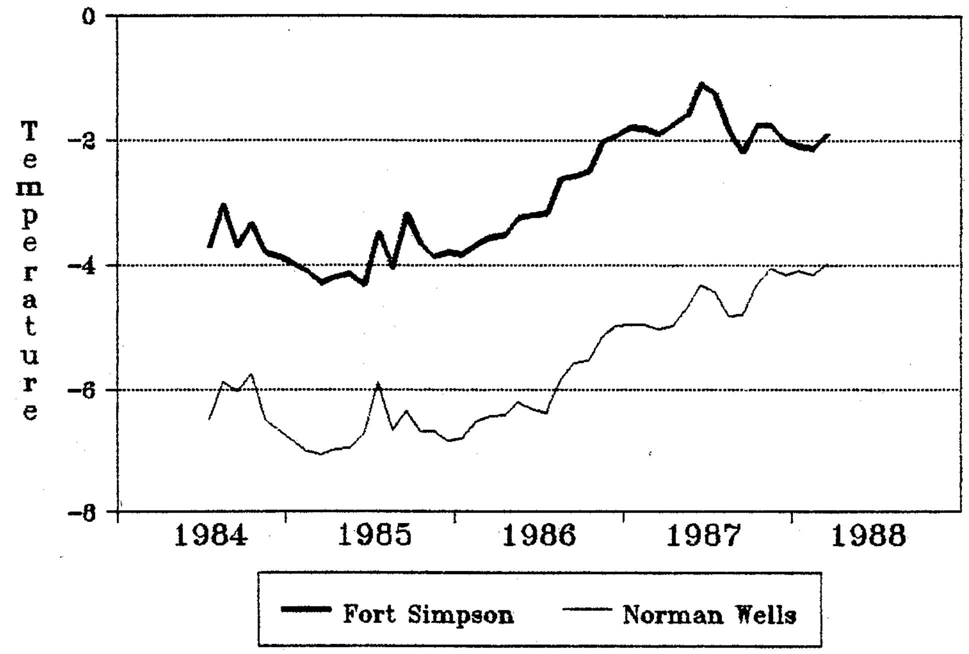
No analysis before the period of pipeline installation is undertaken here, since the most important relationships to be explored are those which have occured within the period of pipeline operation. Of the three weather stations close to the pipeline route, only those at Norman Wells and Fort Simpson have a continuous record for the period of pipeline construction and operation. The monthly mean temperatures for both stations are shown in Figure 8. These were used to obtain running mean annual temperatures (i.e. 12 month running means), shown in Figure 9.

Monthly average temperatures change smoothly throughout the spring, summer, and fall. In winter however, monthly average temperatures fluctuate significantly, reflecting variations in the position of the arctic front and the stalling of high pressure systems in February (see Burns 1973, p.57). These variations show up in the running means (Figure 9) in each calender year: the smooth trend is interupted in mid-year as exceptionally warm or cold winter months are added or dropped from the averaging interval.



Data: K. MacInnes

Figure 8 Monthly mean air temperatures, Fort Simpson and Norman Wells weather stations.

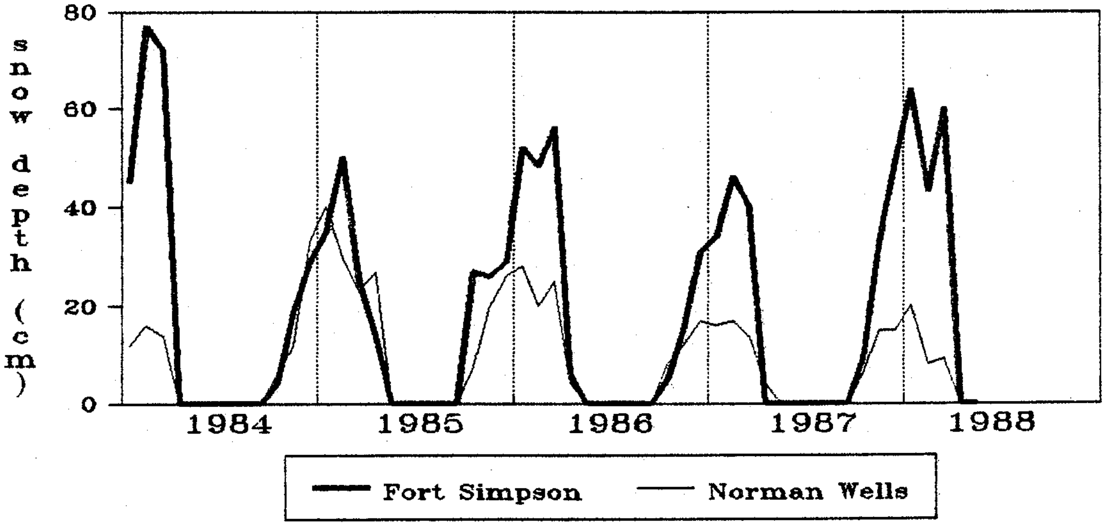


based on monthly means

Figure 9 Mean annual temperatures at Norman Wells and Fort Simpson weather stations.

Trends in the running means are roughly similar at the two stations: following a short, moderate cooling period (6 months at Norman Wells, 1 year at Fort Simpson), the mean annual temperature rises continuously to mid-1987. At Norman Wells, temperatures decline slightly following this, then recover to higher temperatures to the end of the record. The short cooling trend in mid-1987 is apparent at Fort Simpson as well, but without the recovery to a higher mean annual temperature. The overall change in mean annual temperature from the low point in mid 1985 to the end of the record (the high point) is approximately 3 degrees at Norman Wells; at Fort Simpson, the change from mid-1985 to the end of the record is approximately 2.4 degrees, with a total range in mean annual temperature over the period of consideration of 3.25 degrees. From Figure 8 it can be seen that the warming trend is primarily due to warmer winter temperatures.

Figure 10 shows snow accumuluation at the Norman Wells and Fort Simpson weather stations over the years of interest. In every year, snow is much deeper at Fort Simpson, in most years more than twice as deep. Of partcular interest is the trend in snow cover at Nornan Wells: mid-winter accummulation has been progressively less from 1985 to 1988. As a result, the full effect of the warming trend in the air may not be felt at the ground surface of sites which experience this trend: the effect of warmer winter temperatures would be offset by a thinner insulating snow layer. It must be stressed, however, that the extreme spatial heterogeneity of snow cover precludes detailed conclusions to be drawn from weather station data.



data: K. MacInnes

Figure 10 Snow on ground recorded at Norman Wells and Fort Simpson weather stations.

The precipitation record for the weather stations may not present a reliable picture of conditions along the pipeline route. Summer precipitation (Figure 11) shows a tendency to lower values from 1984 to 1987, with rainfall in 1988 far above the normal. However, fire observation towers near the southern end of the pipeline reported record rainfall events in the summer of 1986 which were not reported at Fort Simpson or High Level weather stations.

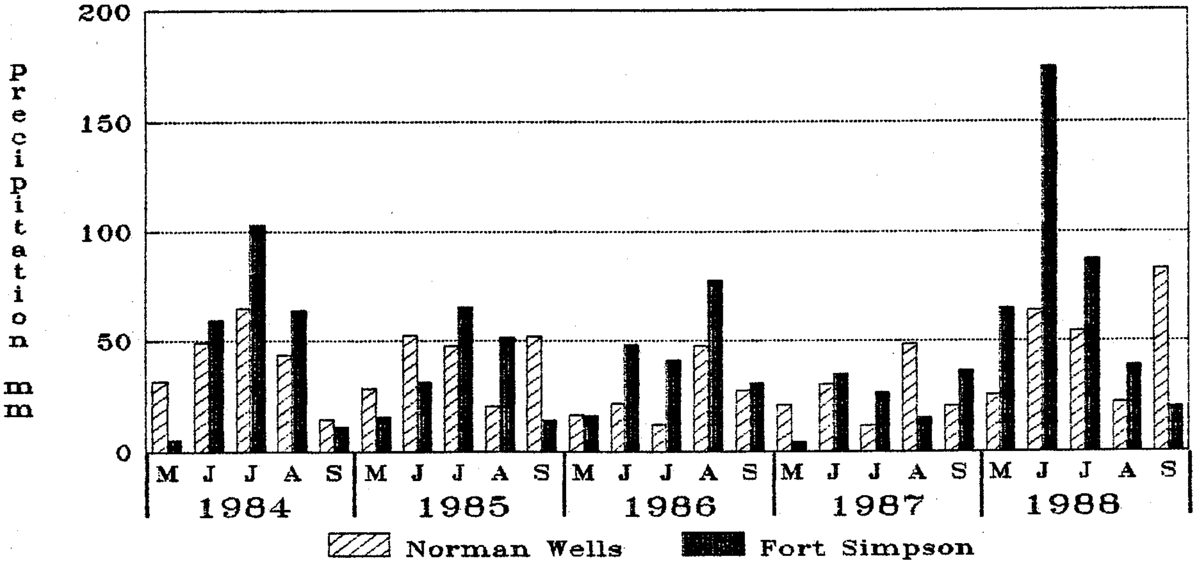


Figure 11 Summer precipitation, Norman Wells and Fort Simpson.

SECTION 5

Pipe and Ground Temperatures

5.1 Introduction

Interpolated and running mean annual temperatures for all sensors on all cables at all monitoring sites have been provided to the scientific authority on floppy disks. In this section, selected results are analysed in order to give a general picture of the evolving thermal regime.

Most analyses of ground temperatures have concentrated on the 1 meter sensors since this corresponds to the mean depth of pipe burial. Appendix I presents the most detailed summary of results for all standard "thermal fence" sites: graphs of interpolated temperature and running mean annual temperature curves for the pipe and for the 1 meter sensor on both the T3 and T4 cables are presented for each fence.

Appendix II presents geotherm plots of running means versus time for Norman Wells Pump Station, Canyon Creek sites A and B, and Table Mountain sites A,B and C. Geotherm plots are presented for the cable nearest the pipeline (T1 or T2), as well as the T3 and T4 cable: results are presented for the full depth of the cables. The graphs presented in these appendices are discussed in this section.

Perhaps the most useful indicator of changes in permafrost thermal regimes is a change in active layer depth. Unfortunately, the spacing of sensors on the cables used in the monitoring program does not permit accurate estimation of the freezing or thawing front. As a result, most extended analyses presented here have used running mean annual temperatures to examine trends. Comparison of sites with markedly different thermal regimes is simplified with running means, since differences in the amplitude of the annual temperature wave (due to differences in depth or soil thermal properties) are eliminated.

5.2 Trends in pipe temperatures

Figure 12 shows the running mean temperature curves for all pipe temperature monitoring sites combined. A significant increase in mean annual temperature is apparent for most sites: Since November of 1985,(at which time pipe temperature sensors were available for all sites presented in the figure), mean pipe temperatures have risen by an average of 1.5 degrees. Many sites experienced exceptionally high summer temperatures in 1986 (causing the "hump" in the running means for that year), a phenomenon discussed in Section 5.5 below. Reference to the individual running mean plots in Appendix I identifies Norman Wells, which has oil temperature artificially controlled, as the only site experiencing a prolonged cooling trend. Canyon Creek, the next site down stream from Norman Wells, shows little change. Norman Wells is also the only site at which the average mean annual pipe temperature is still below 0 C. The interpolated pipe temperature curves show that most of the increases in mean annual temperatures have been due to summer warming.

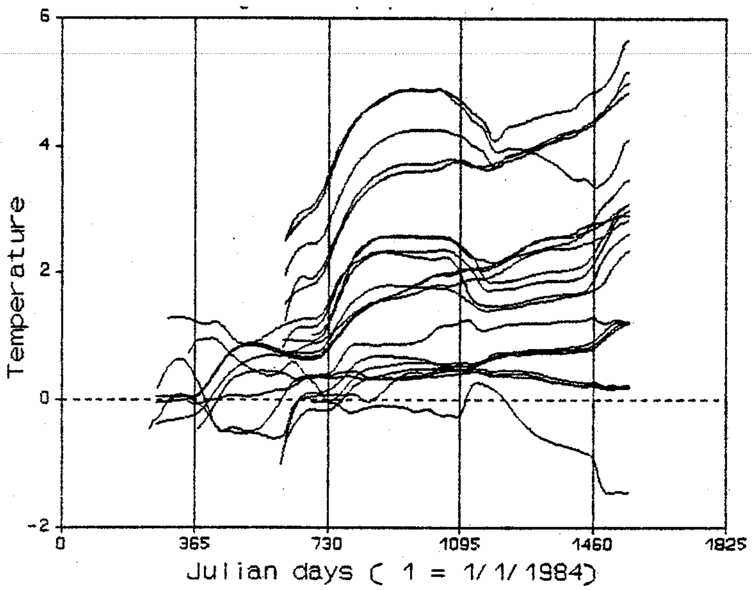


Figure 12 Mean annual pipe temperatures for all monitoring sites.

Thermal behavior of the pipe in the 12 month period at the end of the temperature record has for the most part been similar to its long term behavior. With the exception of the Norman Wells and Canyon Creek sites, temperatures have increased steadily, on average by 0.6 degrees.

5.3 Trends in right-of-way temperatures at 1 m depth

Figure 13 shows the running mean 1 meter ground temperature curves for

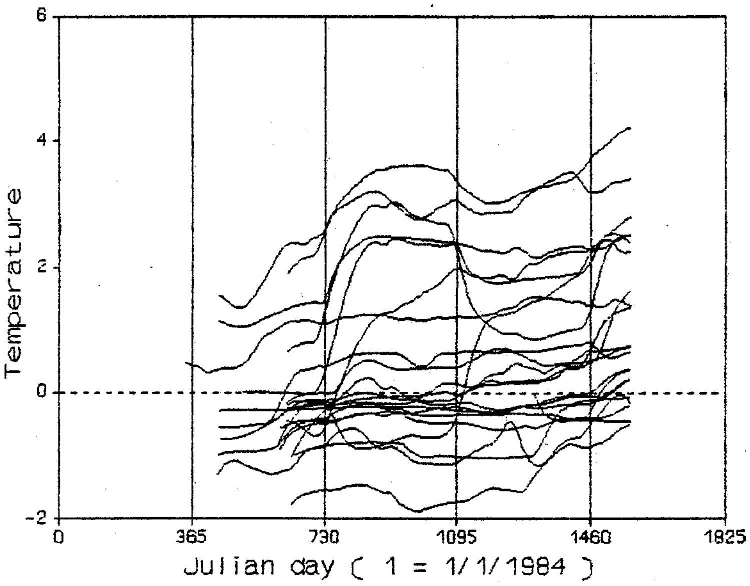


Figure 13 Mean annual trends at 1 meter depth on ROW for all sites.

all right-of-way (T3) monitoring sites combined. As with the pipe, an increase in mean annual temperature is apparent for most sites, though less consistently than for the pipe: Since November of 1985, mean annual temperatures have risen by an average of 1.2 degrees. Examination of the interpolated temperature curves shows that warming trends are most apparent in summer temperatures. Sites which clearly indicate warming winter temperatures (Canyon Creek A, both Great Bear sites and Table Mountain B) were (at least initially) permafrost sites with exceptionally cold winter ground temperatures.

In the 12 month period at the end of the temperature record, 1 meter ground temperatures on the right-of-way have risen more sharply than in previous periods, on average by 0.6 degrees.

5.4 Trends in 1 meter ground temperatures off of right-of-way

Figure 14 shows the running mean 1 meter ground temperature curves for all off right-of-way (T4) monitoring sites combined. In general, the temperature trends off of the right-of-way behave as demonstrated in the geothermal simulations in section 3: Mean annual ground temperatures change most rapidly when the mean annual tempreature is above zero, while sites with mean annual temperatures below 0^0C decrease their rate of change as the 0^0C threshold is approached.

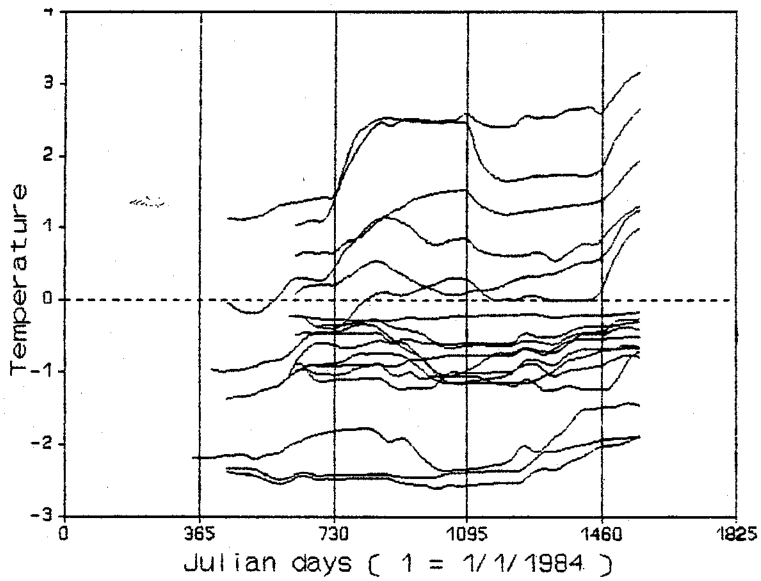


Figure 14 Mean annual temperatures off ROW at 1 meter depth for all sites.

In the 12 month period at the end of the temperature record, more sites off of the right of way experienced rapid temperature rises for the first time than in any period previous. Ground temperatures at 1 meter rose on average by 0.5 degrees in this period, as compared to the average 0.6 degree average temperature rise over the whole record.

5.5 Interpreting trends in running mean temperatures.

Figures 12 to 14 above show the running means for all thermal fence sites. They show the extent to which temperature trends behave in similar ways over large distances. The general conclusion from these figures is that, over the monitoring period, the ground is warming at almost all sites across the thermal fence (though by differing amounts, as earlier discussions have shown). Two aspects of the behavior of the trends provide insights into the factors to which the ground temperatures respond: the exceptionally warm summer temperatures of 1986, and thermal behavior near the melting point.

5.5.1 Summer of 1986.

A "hump" in mean annual pipe temperature trends is apparent for a number of sites in the year 1986: many sites show a rapid rise [illegible] in the mean annual just prior to the start of 1986, followed by a period of perhaps nine months of sustained high temperatures, followed then by a decline in temperature. Reference to the individual site records (Appendix I) shows that the sites which show this effect are all those between Trail River and Jean Marie Creek, and that the rise in the mean was due to very high temperatures in the summer of 1986. The rise in mean annual temperature varied from less than 0.5 degrees to approximately 1.5 degrees, corresponding to summer peak temperatures as much as 6 degrees warmer than the year previous. Sites south of Jean Marie Creek show the warming trend without the matching cooling trend.

The "hump" in the trends is apparent in a few of the T3 cables (Figure 13): 4A, 9, 10A, and 11. A geotherm plot (Figure 15) for cable T3 at Moraine South (monitoring site 11) shows that the thermal wave generated by the hump was not limited to the surface, penetrating to a depth of 6 m before being damped out. The timing of the onset and end of the hump again identifies the period of high temperature as the summer of 1986: an examination of the individual temperature records in the appendix confirms that summer temperatures were indeed significantly warmer in 1986 for these sites. The impact of the summer warming was as much as 2 degrees: this requires summer temperatures several degrees warmer to have such an impact on the annual temperature, and again is affirmed by consultation of the individual temperature plots. Climatic data show that this effect is not driven by the air temperature (Figure 8).

Off of the right-of-way, only the Trail River A site exhibits the "hump" of 1986. The Pump Station 3 and Mackenzie Highway South A sites show the warming trend in early 1986 without the cooling at the end.

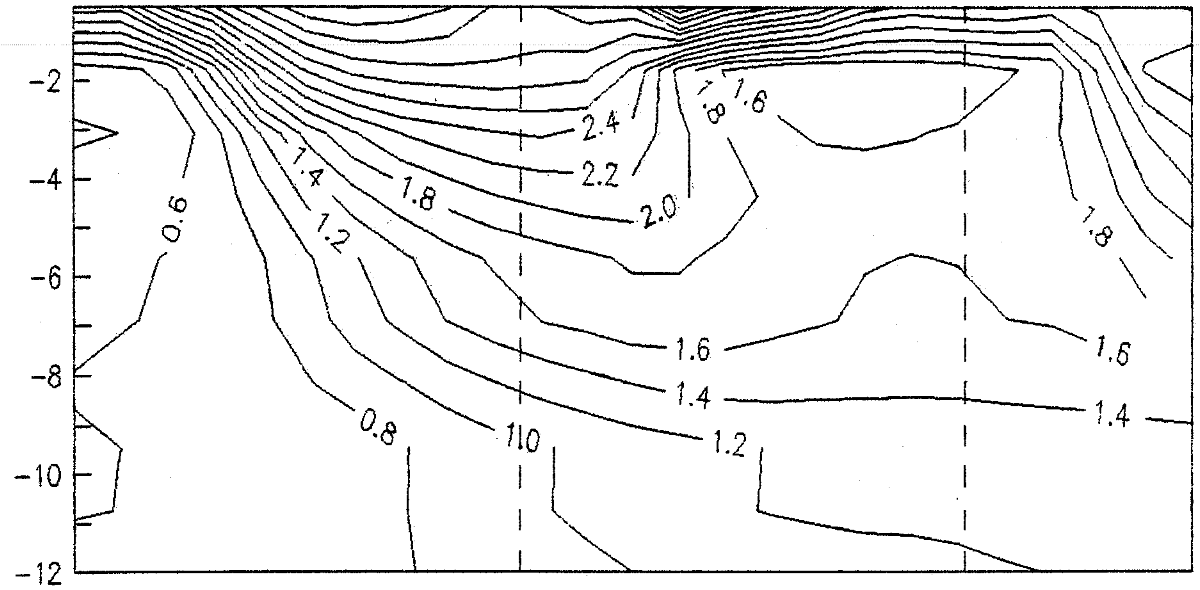


Figure 15 Mean annual geotherm plot for T3 at Moraine South (NWZ 11). Dashed lines are 1 year apart. Plot runs from Sept. 1985 to April 1988.

All of the sites which exhibited high pipe or ground temperatures in summer 1986 (whether on the pipe, on the right-of-way or off of the right-of-way) are non-permafrost sites. Further, the height of the hump correlates with the mean pipe temperature, with greater warming associated with higher temperature. As the geothermal simulations in section 3 revealed, an increase in surface temperature for a non-permafrost site will elevate temperatures more in summer than in winter at the 1 meter depth, even though the temperature increase at the surface is spread evenly through the year: explanation of the summer temperature rise may not therefore be confined to the events of the summer season exclusively. In addition, while the warm temperatures were experienced primarily at the pipe, they were not experienced there exclusively. Explanation of the effect cannot therefore be attributed to a direct effect of the pipe, though perhaps to an effect which is enhanced by the presence of the pipe or ditchline.

Examination of various climatological indicators from the weather station data for Norman Wells and Fort Simpson (average summer temperatures, average winter temperatures, annual freezing and thawing degree-days, deviations from normal summer temperatures, snow-on-ground, summer precipitation) reveals nothing unusual about this summer or the winter which preceded it. However, some fire tower weather stations in the area experienced record rainfalls which were not recorded at the AES weather stations, suggesting that the ground surface would be wetter than normal over some areas during that summer.

5.5.2 Thermal behavior near zero.

Figure 16 demonstrates the latent heat effect near the melting point for the off right-of-way sites. For each site, the rise in mean annual temperature over the period of the monitoring program (the portion of the program for which data is available for all sites) is plotted against the mean annual temperature at the start of the interval. The rate of change of temperature is reduced as 0^0C is approached. The consistency of this temperature rise as a function of initial temperature, despite significant distances between sites as well as differences in soil materials, suggests that all sites are responding to the same thing: the gradual rise in mean annual air temperature, as recorded at Norman Wells and Fort Simpson weather stations.

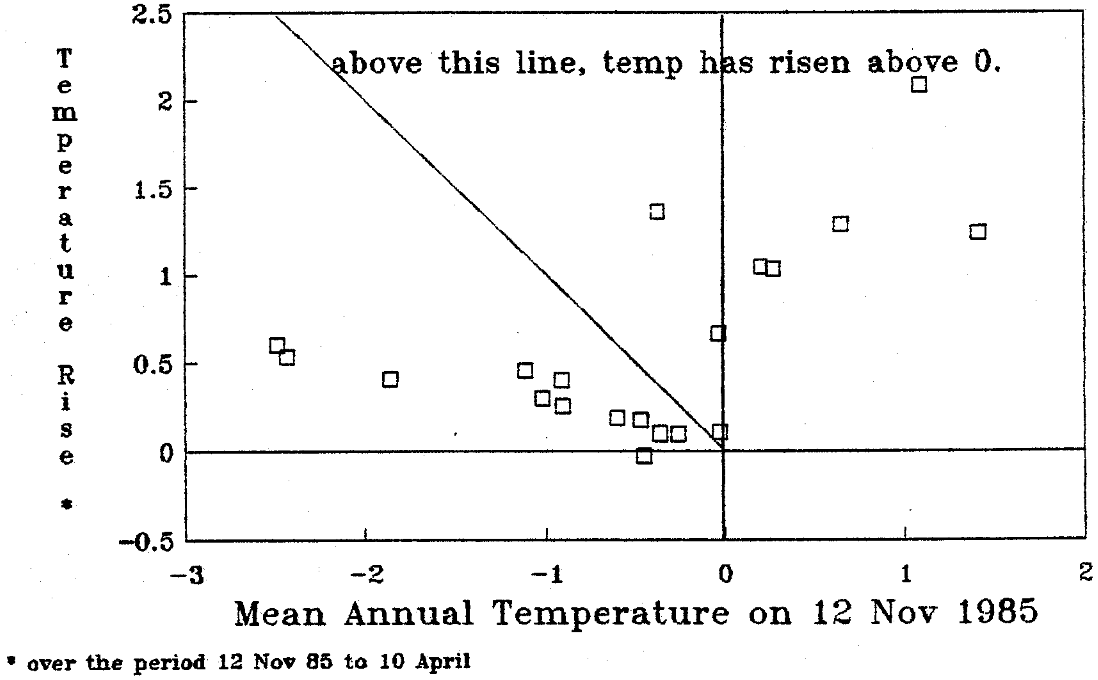
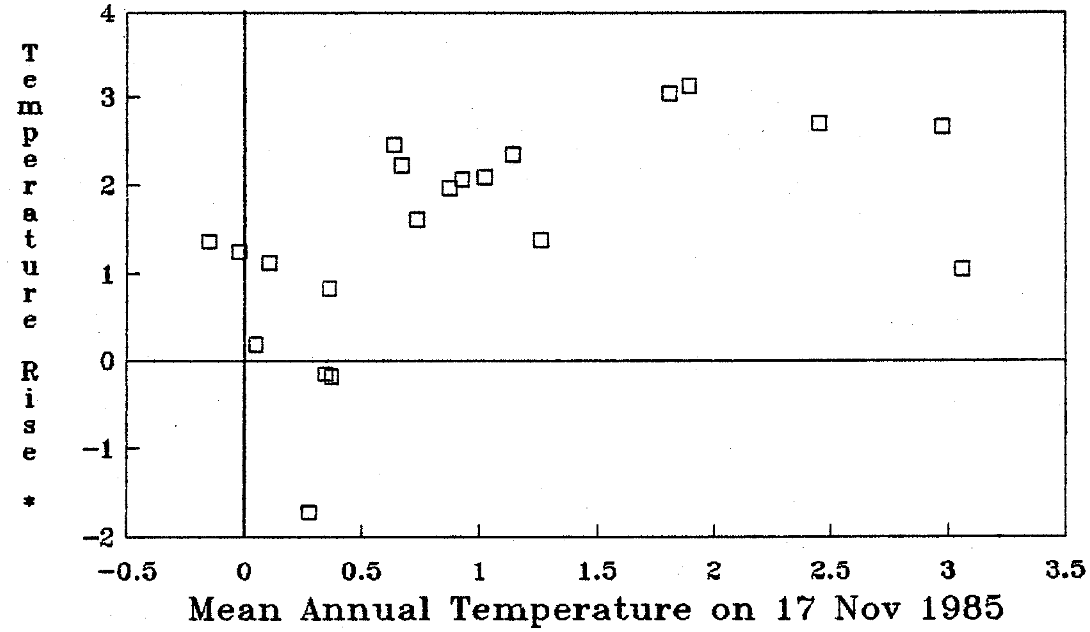


Figure 16 Off ROW (1 m depth) thermal response as a fuction of initial conditions.

A similar plot of temperature rise as a function of initial temperature for the pipe (Figure 17) shows behavior similar to that discussed above, though there is little data for sites initially below 0^0. A plot of this type for the 1 meter temperature on the right of way (Figure 18) shows little coherence: here, too many effects combine to produce a response predictable on the basis of initial temperature alone. In addition to the warming air temperature, ground surface temperatures are responding to new micro-climatic conditions at sites where the right-of-way has been cleared. In addition, surface settlement on the right-of-way has shifted many sensors from their initial positions, changing the thermal regime which the sensors record.

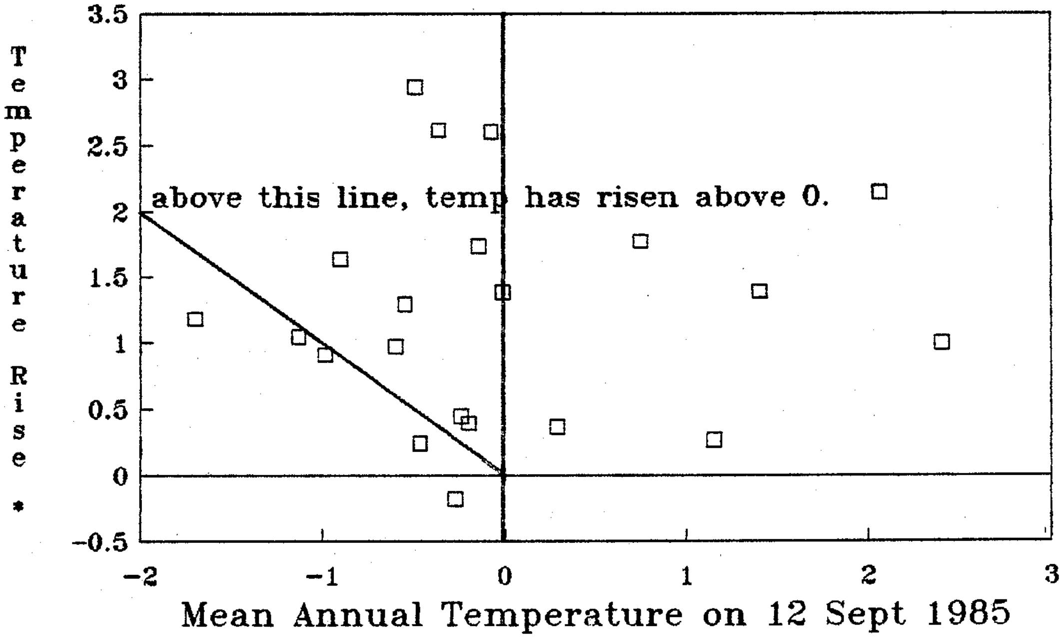
5.5.3 Possible interpretations.

In 1988, many of the off right-of-way sites experienced their greatest increases in temperature, and ground warming was more pervasive than in previous years. Total summer precipitation was also significantly higher than normal in 1988 at both of the AES weather stations, suggesting that the ground surface would be wetter than normal over a wide area during that summer.



* in the period 17 Nov 85 to 12 April 88

Figure 17 Pipe thermal response as a function of initial conditions.



* in the period 12 Sept 85 to 8 April 88

Figure 18 ROW (1 m depth) thermal response as a function of initial conditions.

In seeking explanation for the observed temperature trends, the length of the record (4 summers) precludes unambiguous conclusions. At all sites where the "hump" is apparent, summer temperatures are progressively warmer between 1985 and 1988, with the exception that summer of 1986 was exceptionally warm. The pattern may thus be interpreted as a four year trend with one anomalous year, or as a weak trend which incorporates significant inter-annual fluctuations. Two alternate interpretations of the trends in mean annual temperature are possible:

1. The high points in the running mean curves may be correlated to wet ground conditions as well as air temperature, so that the highs of 1986 and 1988 (where both are present) are related to precipitation rather than the trend in air temperature. In physical terms, this would suggest that heat transfer to the base of the active layer is facilitated by wet condtions, due either to heat associated with percolating surface water or to enhanced thermal conduction in more saturated conditions.

2 The long term trend in air temperature is reflected in a long term trend in ground temperature, with the high temperatures in 1986 (where present) explicable by other means.

Ultimately, only future data from the monitoring program can resolve which interpretation is correct.

5.6 Comparison of mean pipe and right-of-way ground temperatures.

Table III compares temperature trends at the pipe and at 1 meter depth on the right of way. The running means were examined and characterised as showing either stable temperatures, a warming trend, a cooling trend, or a variable pattern of change. The table also indicates whether mean pipe temperatures were warmer or cooler than mean ground temperatures in that period. Temperatures from the T3 cables were used to compare to pipe temperatures: cables T1 and T2 were found to be too close to the pipe to be indicative of ambient conditions along the right of way.

Over the same interval, the running mean annual air temperature derived from the monthly record at Fort Simpson does not show a consistent trend, with the mean annual temperature at the end of the interval slightly lower than at the beginning. At Norman Wells , the warming trend of the previous two years continued with some variation.

In total, about two thirds of the sites show a warming trend at the pipe. The artificial cooling of the oil at Norman Wells appears to influence oil temperatures as far down stream as Great Bear River (NWZ 3). With the exception of site 10A, all sites south of Great Bear River show a warming trend in pipe temperatures, while there is a trend to colder temperatures to the north.

As with the pipe, about two thirds of the sites experienced a warming trend on the right of way during this period. Of the remaining sites however, only one site showed a cooling trend: the wood chip insulated slope at Canyon

Table III Comparisons of mean annual temperatures for pipe sensors and at 1 meter on the pipeline right-of-way (May 1987-May 1988).

Monitoring sites
(arranged north to south)

	1	2	2	2	3	3	7	7	7	4	4	8	8	8	9	10	10	11	12	12	5	5	6
		A	B	C	A	B	A	B	C	A	B	A	B	C		A	B		A	B	A	B	
Temperature Trend :																							
Pipe:	C	C	C	C	S	S	W	W	W	W	W	W	W	W	W	C	W	W	W	W	W	W	W
R.O.W.	W	W	C	V		W	W	W	W	W	V	W	S	W	W	S	W	W	W	W	V	V	W
Temperature Relationship :																							
PIPE : ROW	V	V	W	C		W	W	C	W	C	C	W	W	W	C	W	W	W	W	W	W	W	W

CODES W = warmer or warming
C = colder or cooling
V = variable
S = stable or equal

Totals:

	W	C	V	S
TRENDS:				
Pipe:	16	5	0	2
R.O.W.	15	1	4	2
RELATIONSHIPS:				
PIPE : ROW	15	5	2	0

Note:
- based on comparisons of running means
- ground temperatures are from the 1 m sensors.

Creek (site 2B).

As in previous years, the mean annual pipe temperature is higher than the mean annual temperature on the right-of-way at most sites. Three of the exceptions to this relationship are non-permafrost sites where the pipe has previously traversed extensive permafrost (4A,4B, 9).

5.7 Comparison of ground temperatures on and off the pipeline right-of-way

Table IV summarises the running mean data on and off of the right-of-way in the same manner as in the previous section. Unlike previous years, a warming trend is apparent off of the right-of-way at two thirds of the sites. Almost all of the remaining sites are characterized as "stable". As the analysis in section 5.5.2 above suggests, many of these sites may be warming close to 0_0C. With the exception of two Petitot River sites, the mean annual temperature at 1 meter is higher on the right-of-way than off of the right-of-way.

Comparison of 1 meter ground temperatures on the right-of-way at Table Mountain shows that the age of the right-of-way does not nessesarily allow one to predict the thermal response of the ground. Site 7a, on the oldest right-of-way, has warmed by 1.5 C since 1985. Site 7c, the newest right-of-way section, shows the best agreement between trends on and off of

Table IV Comparisons of mean annual temperatures at 1 meter depth on and off of the pipeline right-of-way (May 1987 - May 1988).

Monitoring sites
(arranged north to south)

	1	2	2	2	3	3	7	7	7	4	4	8	8	8	9	10	10	11	12	12	5	5	6
		A	B	C	A	B	A	B	C	A	B	A	B	C		A	B		A	B	A	B	
Temperature Trend :																							
On R.O.W.	W	W	C	V		W	W	W	W	W	V	W	S	W	W	S	W	W	W	W	V	V	W
Off R.O.W.	W	W	W	W	S	W	W	W	V	W	W	S	W	S	W	W	S	W	W	S	W	W	S
Temperature Relationship :																							
ON: OFF	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	V	C

CODES
W = warmer or warming
C = colder or cooling
V = variable
S = stable or equal

Totals:

	W	C	V	S
TRENDS:				
On R.O.W.	15	1	4	2
Off R.O.W.	16	0	1	6
RELATIONSHIPS:				
ON: OFF	21	1	1	0

Note:
- based on comparisons of running means
- ground temperatures are from the 1 m sensors.

the right-of-way, and has warmed by slightly more than 1 degree since 1985. At site 7b, (in a helipad at a bend in the pipeline) the T3 data before mid 1986 is unreliable. Since then, however, temperature has risen by over 3 degrees.

5.8 Geotherm plots

The geotherm plots presented in Appendix II show that the trends apparent in the 1 meter sensors are propagating into the ground depth in predictable fashion. For most sites, the ground adjacent to and below the pipe is warming fastest, while the ground off of the right of way shows little fluctuation in the mean annual temperature at depth. With the exception of the site at Norman Wells, the T4 cables show very little change in temperature below 6 meters depth over the monitoring period (since the isotherms are parallel to the surface).

At some sites steep gradients are apparent in the surface layers (eg. Norman Wells NWZ1-T1), possibly indicating the effect of surface settlement on sensor cable positions in the thermal profiles. At other sites (eg. 7B-T3) similar steep gradients could represent the "warm permafrost" thaw situation demonstrated in Section 3.

Warming at the surface is propagating into the ground on the right-of-way (T3) at most sites. Site 7C-T3 (Table Mountain) cooled at the surface in the middle of monitoring period, with a "cold wave" propagated into the ground which was later overtaken by heat from above and below. At some sites (2A-T3,2B-T3) temperatures are warming from below as well as from above, possibly indicating the influence of heat from the pipe nearby. Adjacent to the pipe, the warming trend is dominated by heat flow from the surface only.

The plot for the T4 cable at Canyon Creek B has two interesting features. First, the geotherms shift suddenly toward the end of the record. Because the shift occurs simultaneously at all depths (i.e. without a time lag at depth), it is assumed that this represents a shift in the position of the cable rather than a change in actual ground temperature. Second, a relatively steep temperature gradient is being sustained between the surface and depth. This gradient evidently represents an equilibrium with current thermal conditions, since geotherms are parallel to the surface. Temperature increases with depth at a rate of about 1 degree every 10 meters. This site thus represents an island with a colder surface, with thermal equilibrium in the ground maintained by an exchange of heat between adjacent islands.

SECTION 6

Summary

1. Mean annual air temperature at Norman Wells and Fort Simpson has increased over the period of the monitoring program by 3 and 2.4 degrees, respectively. The air temperature increase is concentrated in the winter months. This has not been reflected in ground temperatures off of the right-of-way until this year, when a relatively rapid temperature rise was experienced at most T4 sites.

2. At most sites, the relative warming rates and temperature relationships between pipe, right-of-way and off right-of-way sensors is unchanged since the last report (Riseborough et al., 1987):

- Since November 1985, the mean annual temperature has increased on average by:
  - 1.5° at the pipe
  - 1.2° at the T3 cables
  - 0.6° at the T4 cables

- From May 1987 to May 1988, the mean annual temperature has increased on average by:
  - 0.6° at the pipe
  - 0.6° at the T3 cables
  - 0.5° at the T4 cables

- mean annual pipe temperature remains greater than the mean annual temperature in the T3 cables at most sites.

- mean annual temperatures in the T3 cables is warmer than in the T4 cables at most sites.

3. Non-permafrost sites show the most rapid changes in mean annual temperature. At 1 meter depth, the increase is expressed primarily as an increase in summer temperatures. Simulations demonstrate that a concentration of the warmer temperatures in the summer period is to be expected even with a increase distributed evenly over the year.

4. The pattern of mean annual temperature change off of the right-of way suggests that the temperature at these sites is responding to the increase in air temperature, at a rate controlled primarily by the initial ground temperature.

5. Similarly, rates of change in mean annual pipe temperature are controlled to a significant extent by the mean annual pipe temperature, with warmer sites showing more rapid change.

6. The dominance of initial conditions on the thermal response of the pipe and the 1 meter sensors off of the right of way is not apparent for the 1 meter sensors on the right of way. This suggests that the right of way is experiencing changes in the micro-climatic (surface temperature) responses to the climate (air temperature).

7. The geotherm plots show that short term fluctuations in mean annual temperature at the ground surface have propagated into the ground to depths of up to 8 m (Figure 15).

REFERENCES

Burgess, M., J. Pilon and K. MacInnes (1985) Permafrost thermal monitoring program : Norman Wells to Zama oil pipeline. Northern Hydrocarbon Development Environmental Problem Solving: Proceedings of the Eighth Annual Meeting of the International Society of Petroleum Industry Biologists, Banff, Alberta, Canada September 24-26, 1985. pp. 248-256.

Burns, B.M. (1973). The climate of the MacKenzie valley-Beaufort sea, volume 1. Climatological study 24, Atmospheric Environment Service, Environment Canada.

Burns, B.M. (1974). The climate of the MacKenzie valley-Beaufort sea, volume 2. Climatological study 24, Atmospheric Environment Service, Environment Canada.

Goodrich, L.E. (1982). The influence of snow cover on the ground thermal regime. Canadian Geotechnical Journal 19, pp.421-432.

Riseborough, D.W, (1988). On the Reliability of Temperatures Estimated using Cubic Spline Interpolation. Final report for Geological Survey of Canada, Energy, Mines and Resources. Addendum to DSS Contract No. 23233-7-0115/01-ST.

Riseborough, D.W, D.E. Patterson and M.W. Smith (1987). Computer Analysis of Norman Wells Pipeline Thermal Data. Final report for Geological Survey of Canada, Energy, Mines and Resources. DSS Contract No. 23233-7-0115/01-ST. 120 p.

Smith, M.W. and D.W.Riseborough (1985). Sensitivity of Thermal Predictions to Assumptions in Soil Properties. in Proceedings, Fourth International Symposium on Ground Freeezing, Sapporo, Japan.

APPENDIX I

Interpolated ground and pipe temperatures

Included are :

1: Estimated temperature curves for:
  - -mean pipe temperature (mean of 5 sensors)
  - -nominal 1 m sensor on deep ROW cable (usually T3)
  - -nominal 1 m sensor off of ROW (usually T4)

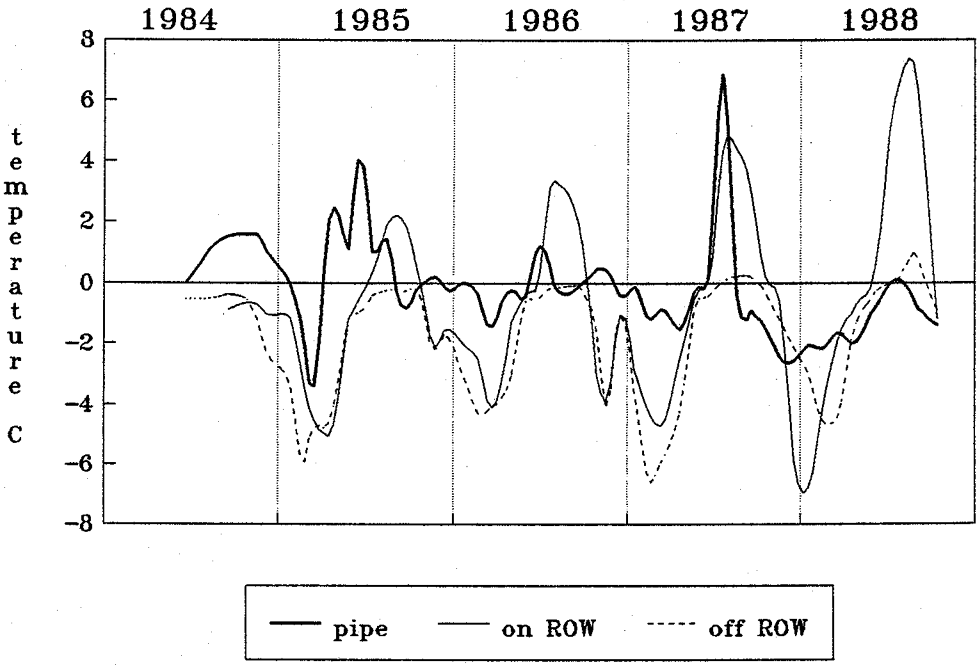
for each typical thermal fence.

2: Estimated running mean annual temperatures for sensors above (means estimated using interpolation curves.

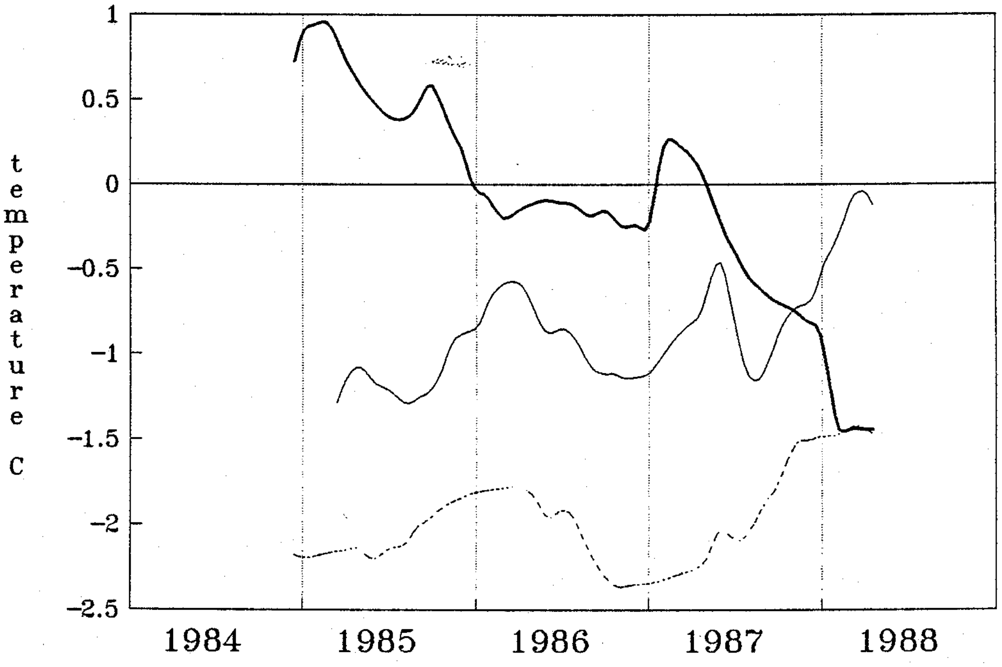
Refer to the main body of the report for explanation (Section 2) and interpretation (Section 5).

NORMAN WELLS PUMP STATION - PT1-1

Interpolated pipe/1 m ground temperature

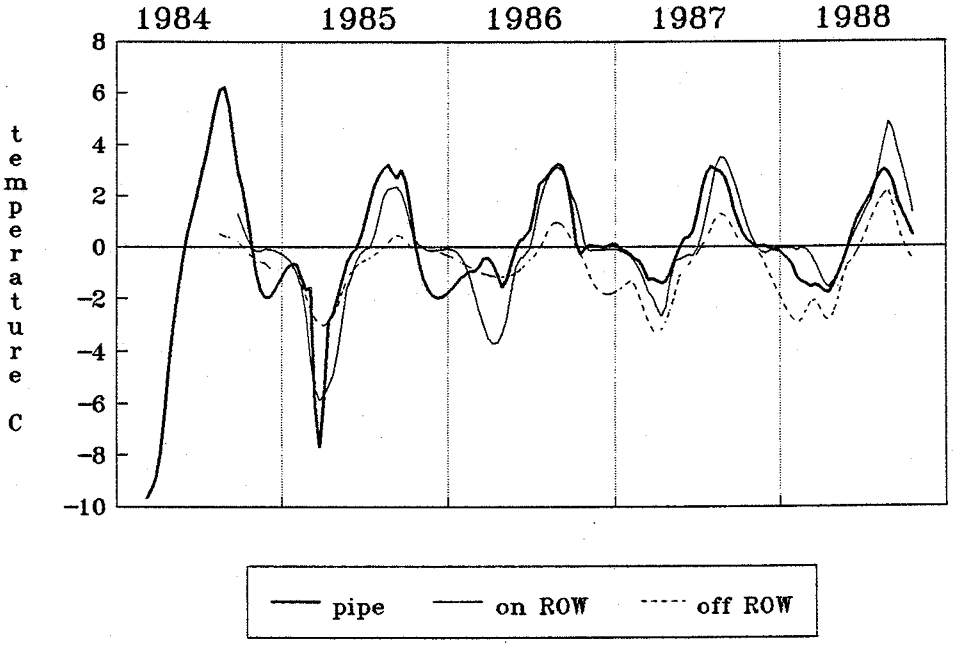


Running mean pipe/1 m ground temperature



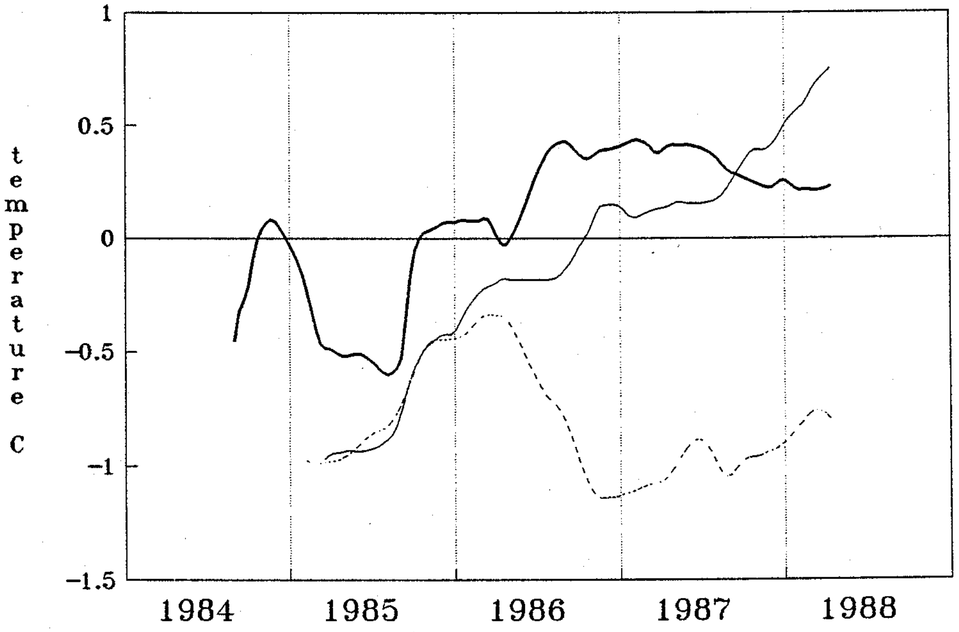
CANYON CREEK NORTH A - PT1-3

Interpolated pipe/1 m ground temperature



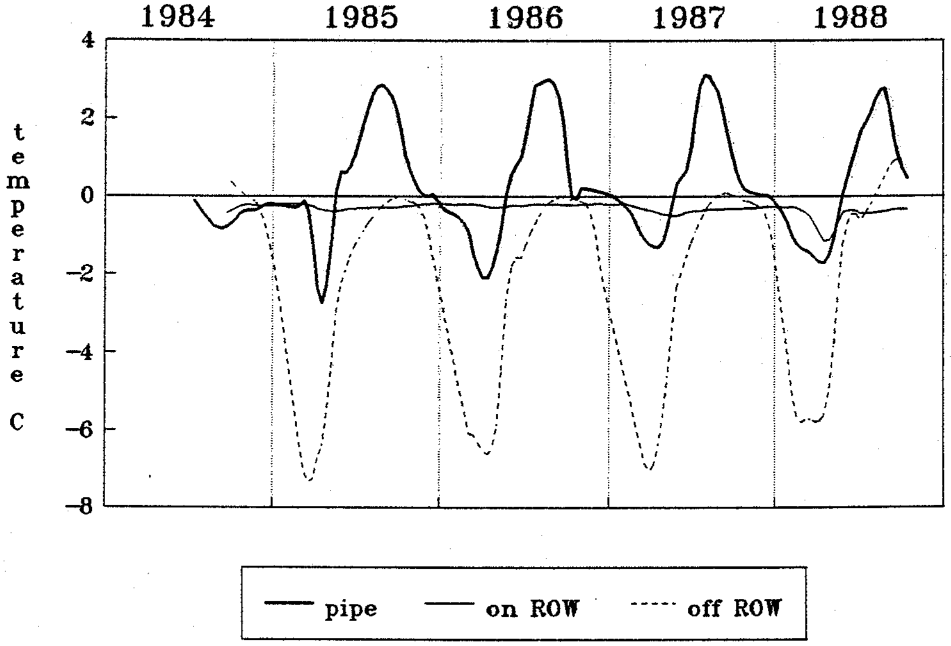
CANYON CREEK NORTH A - PT1-3

Running mean pipe/1 m ground temperature



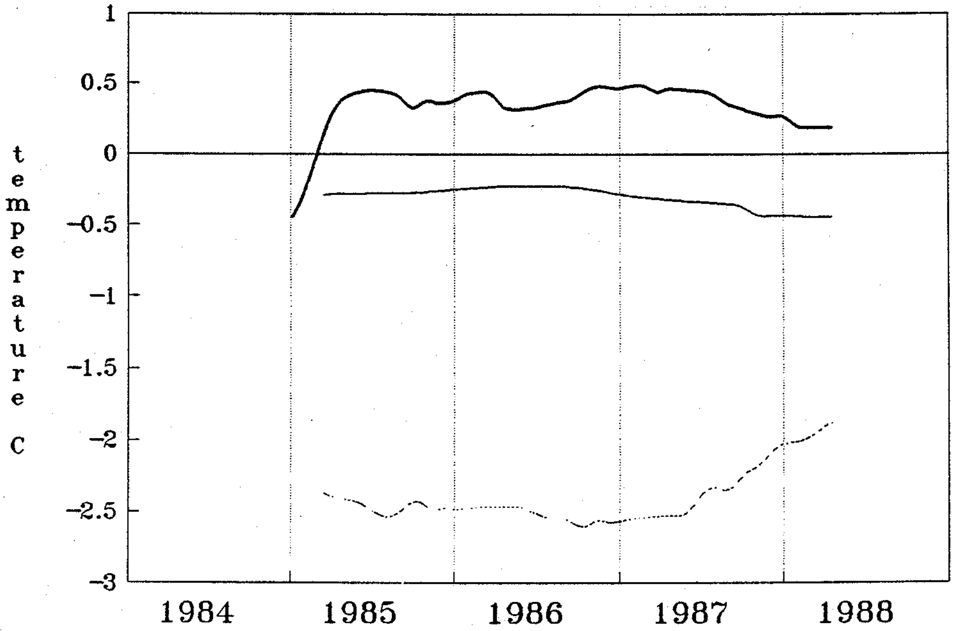
CANYON CREEK NORTH B – PT1–4

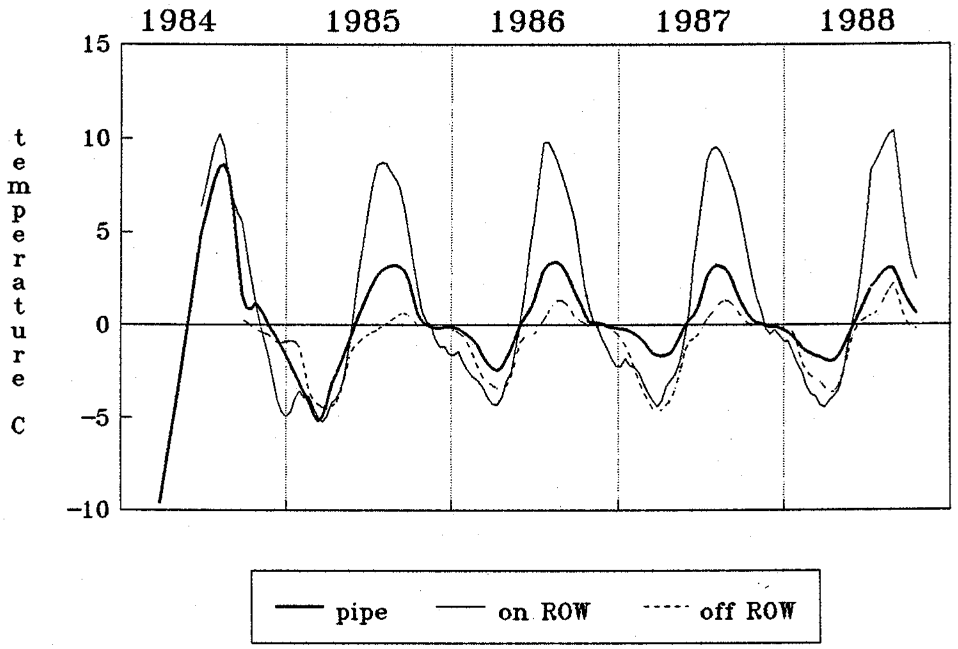
Interpolated pipe/1 m ground temperature



CANYON CREEK NORTH B – PT1–4

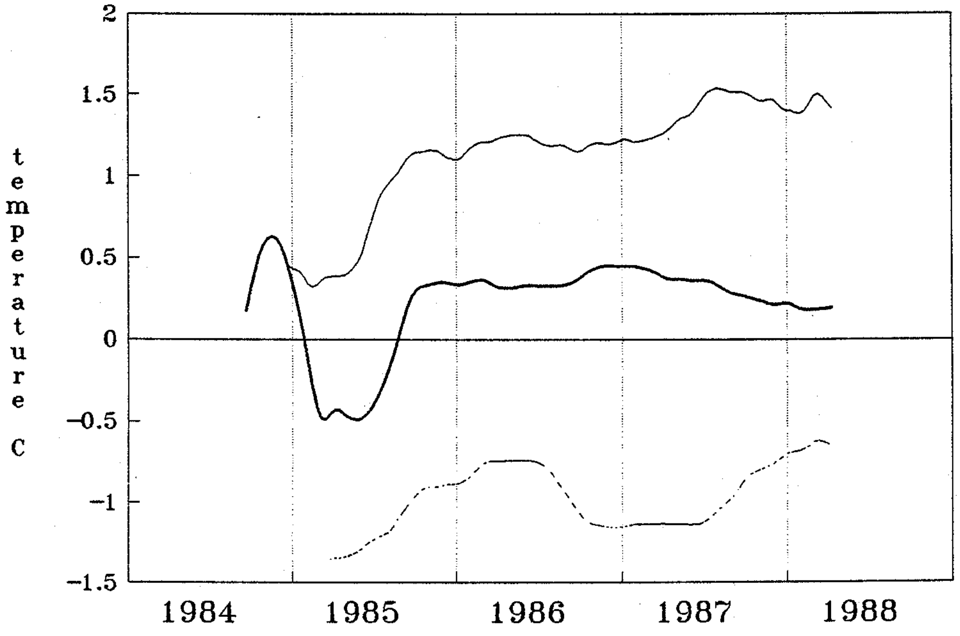
Running mean pipe/1 m ground temperature





CANYON CREEK SOUTH C - PT1-5

Interpolated pipe/1 m ground temperature

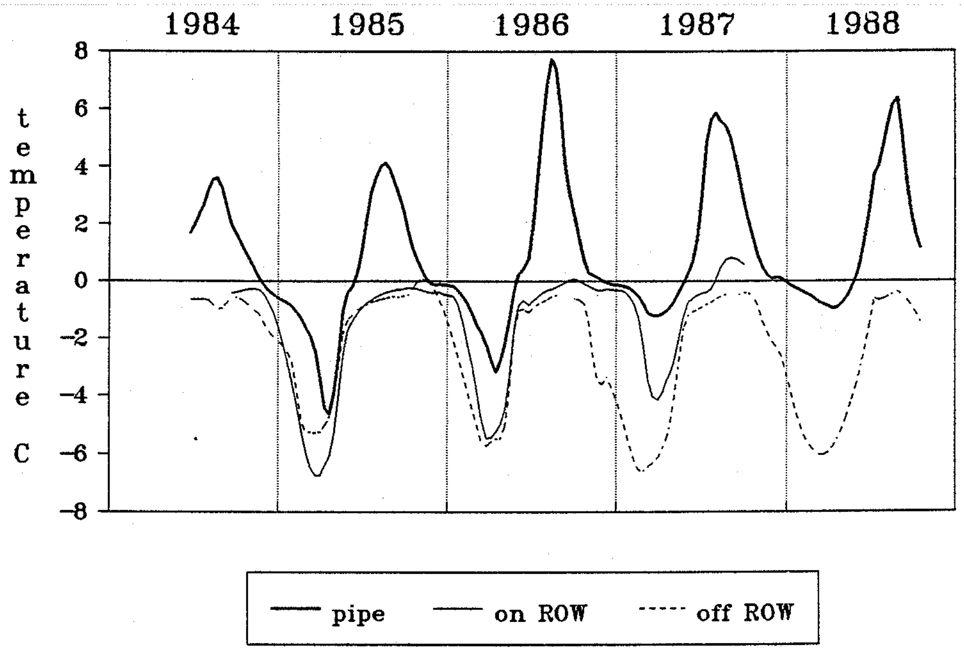


CANYON CREEK SOUTH C - PT1-5

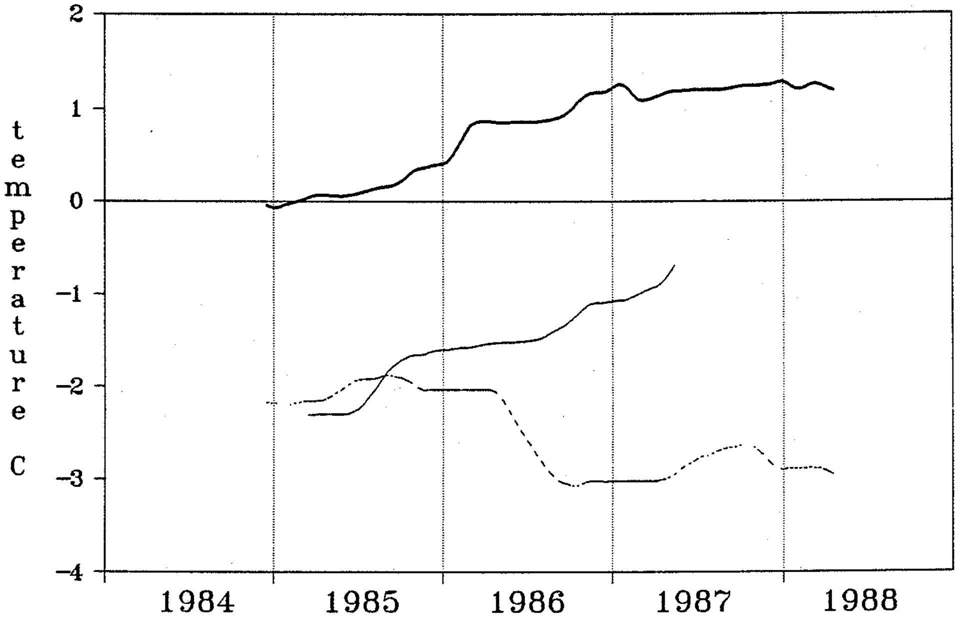
Running mean pipe/1 m ground temperature

GREAT BEAR RIVER A - EMR11

Interpolated pipe/1 m ground temperature

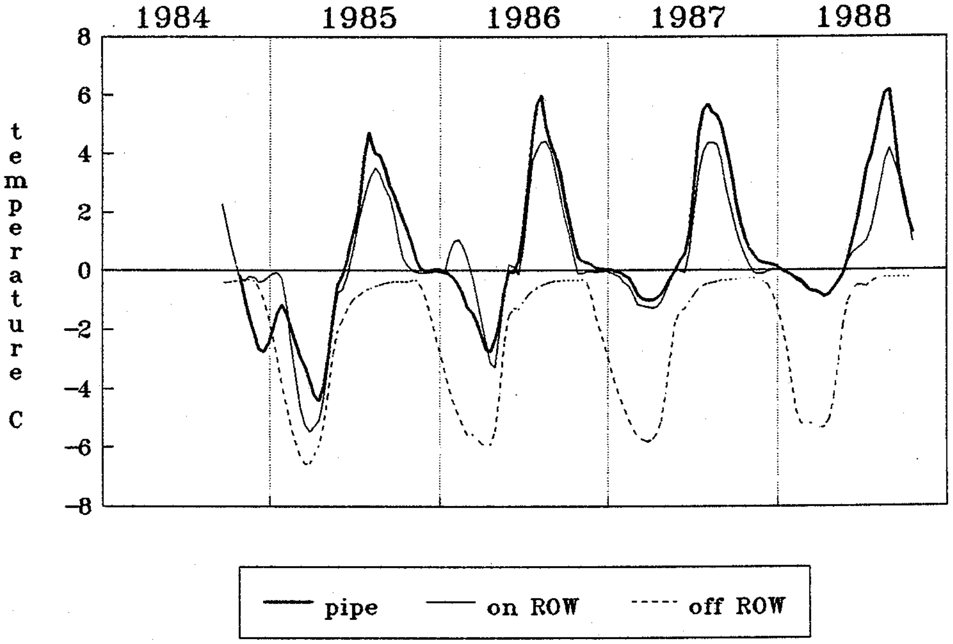


Running mean pipe/1 m ground temperature



GREAT BEAR RIVER B - PT1-10

Interpolated pipe/1 m ground temperature



Running mean pipe/1 m ground temperature

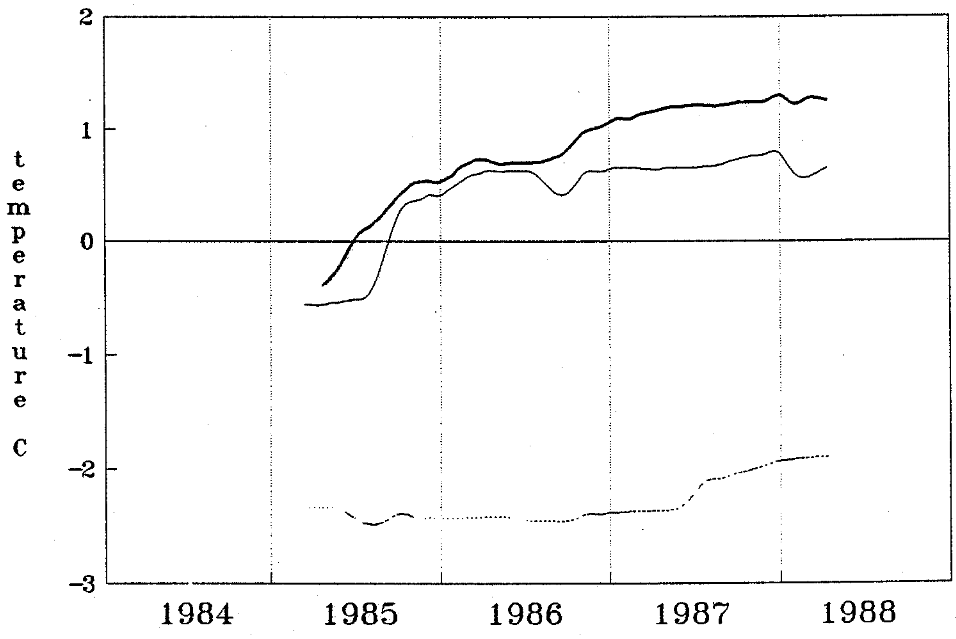


TABLE MOUNTAIN A – 85–EPT 1
Interpolated pipe/1 m ground temperature

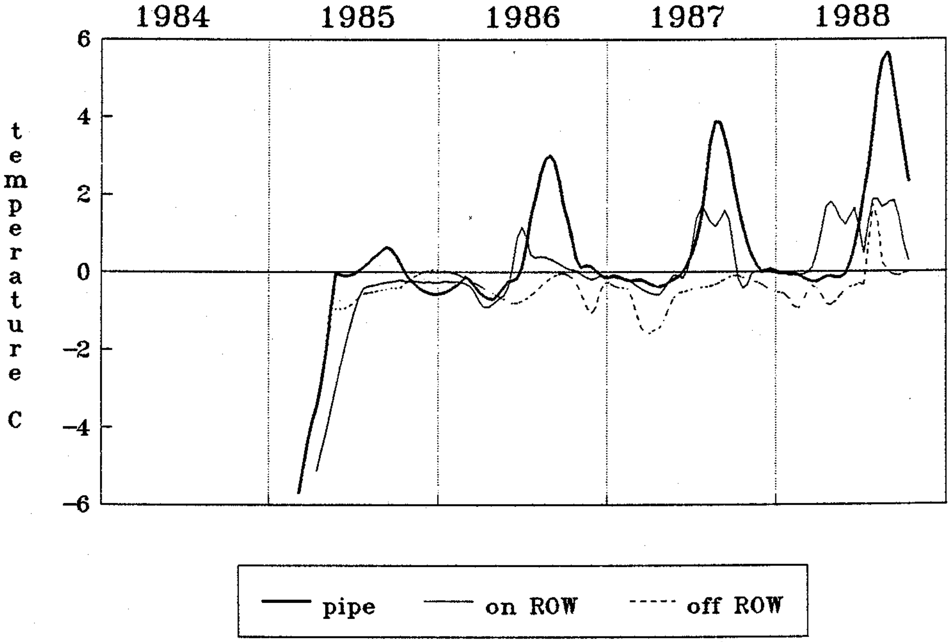


TABLE MOUNTAIN A – 85–EPT 1
Running mean pipe/1 m ground temperature

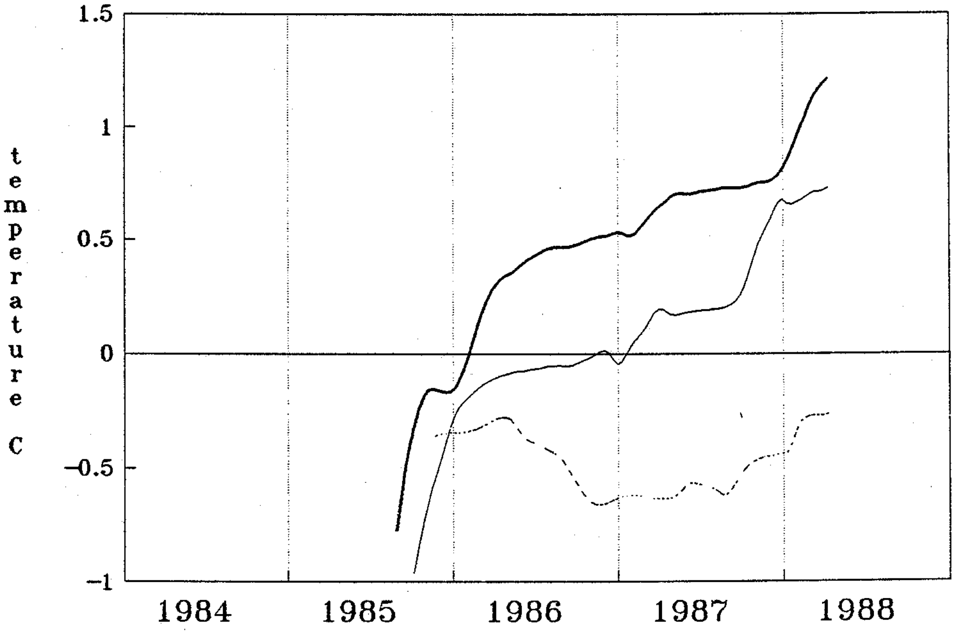


TABLE MOUNTAIN B – 85–EPT 3
Interpolated pipe/1 m ground temperature

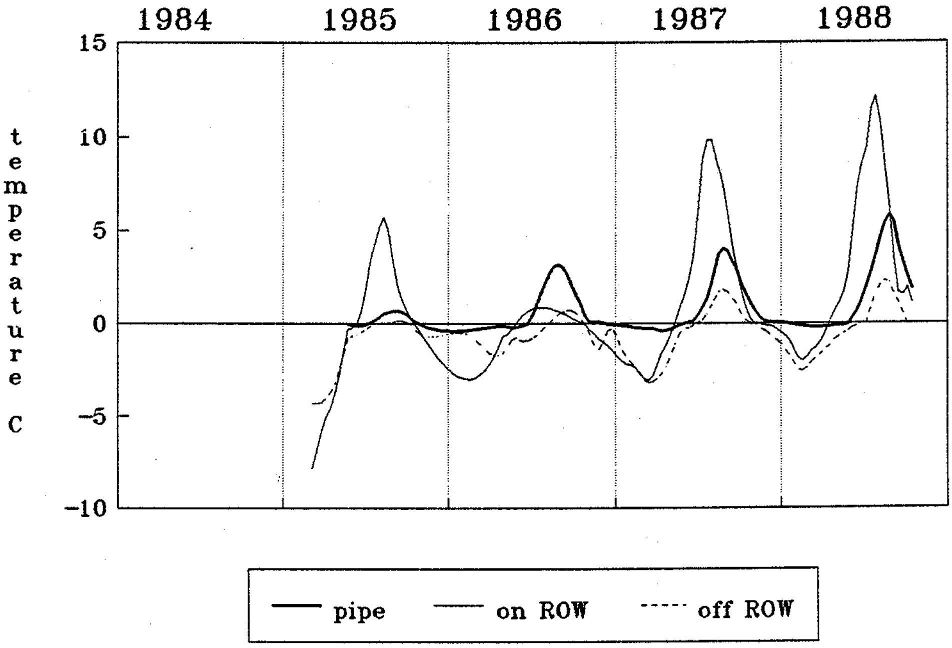


TABLE MOUNTAIN B – 85–EPT 3
Running mean pipe/1 m ground temperature

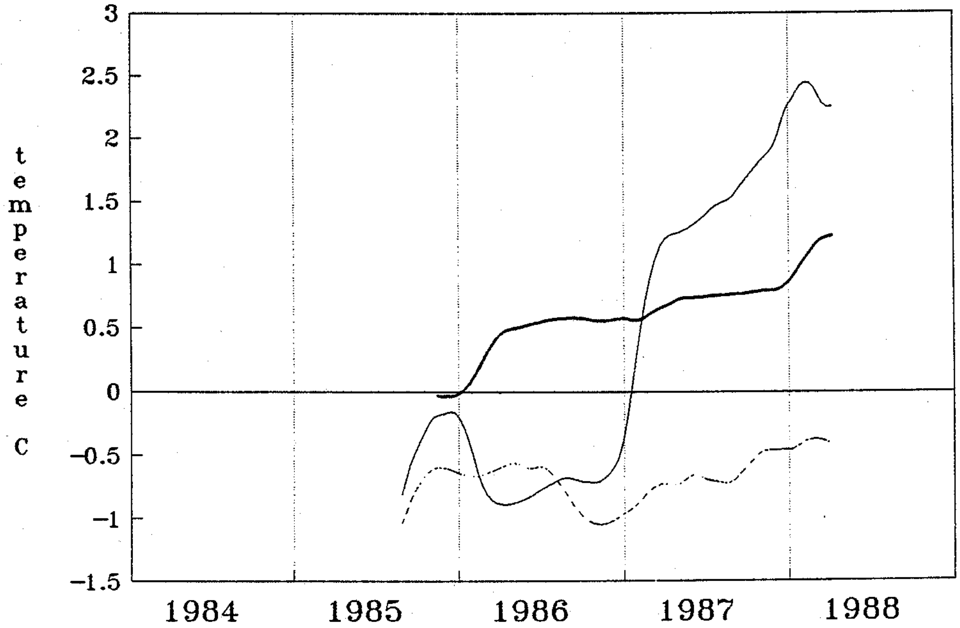


TABLE MOUNTAIN C - 85-EPT 2
Interpolated pipe/1 m ground temperature

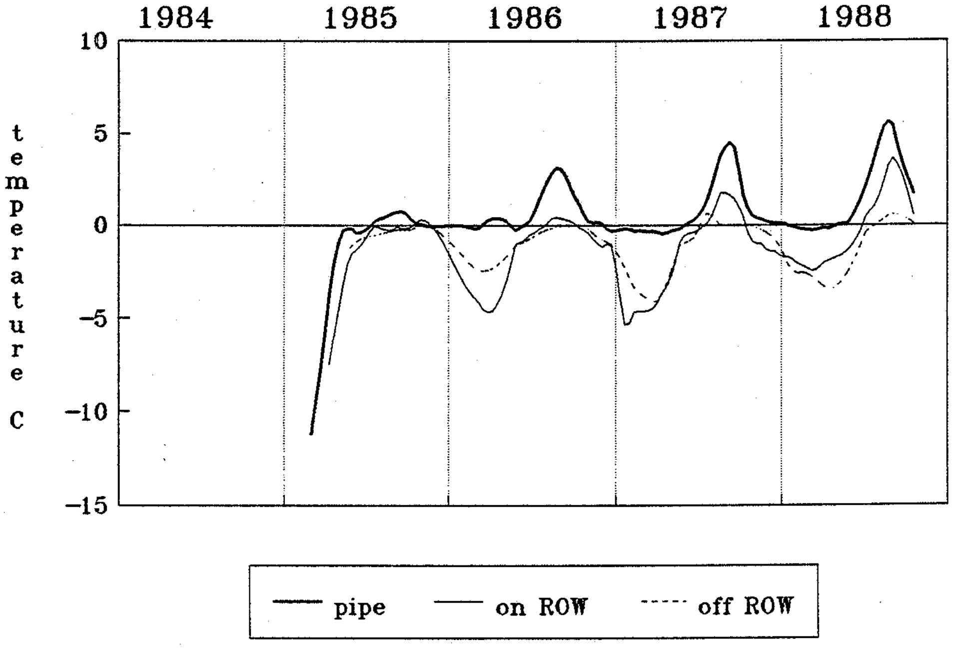
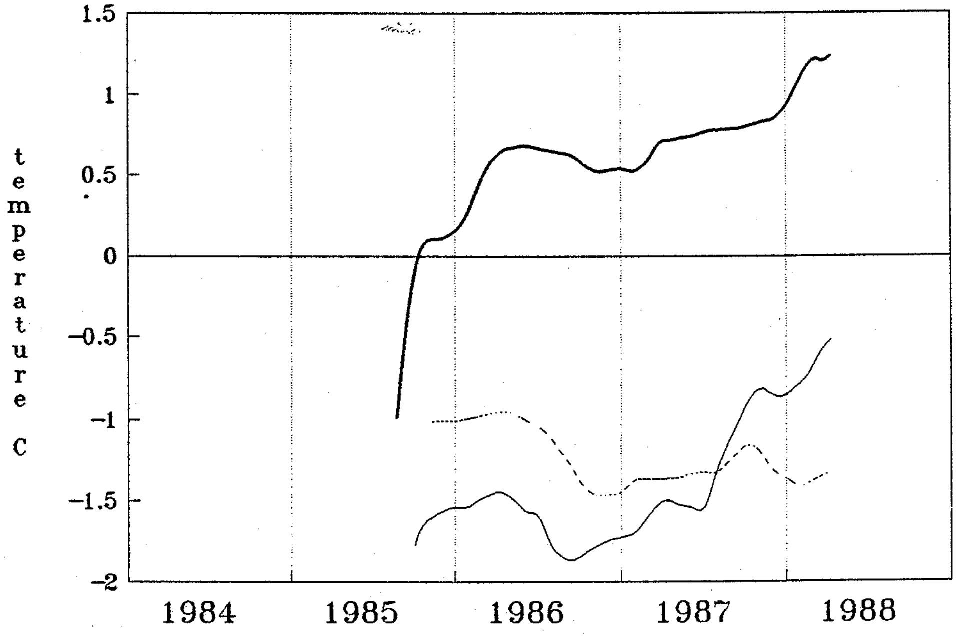
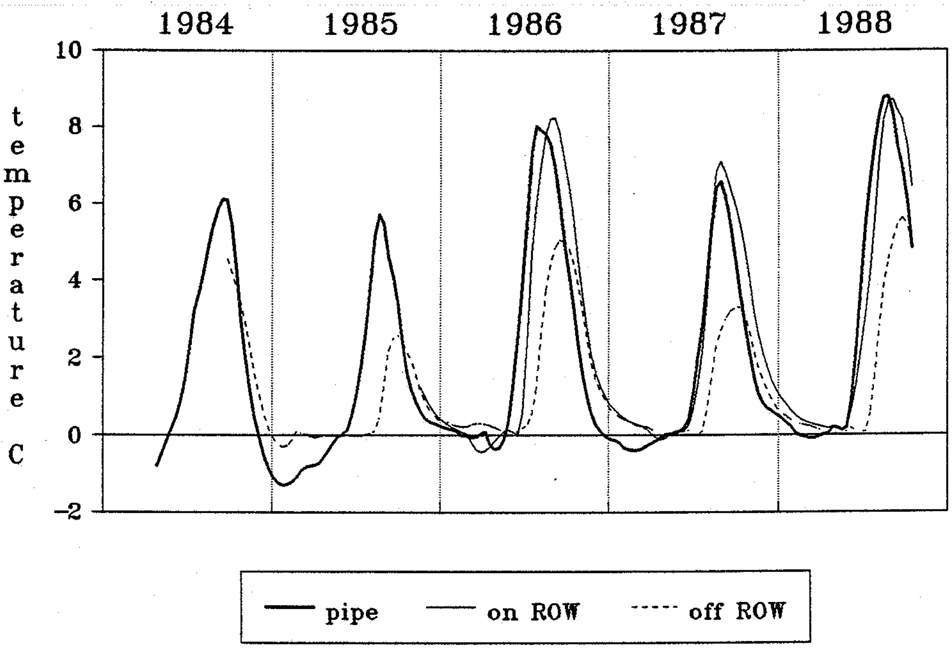


TABLE MOUNTAIN C - 85-EPT 2
Running mean pipe/1 m ground temperature

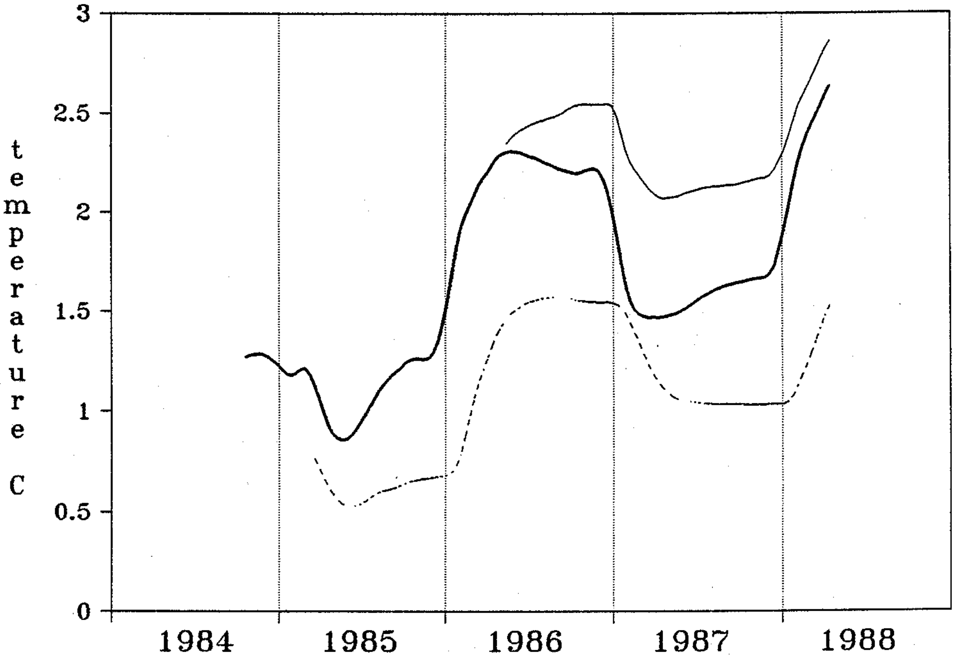


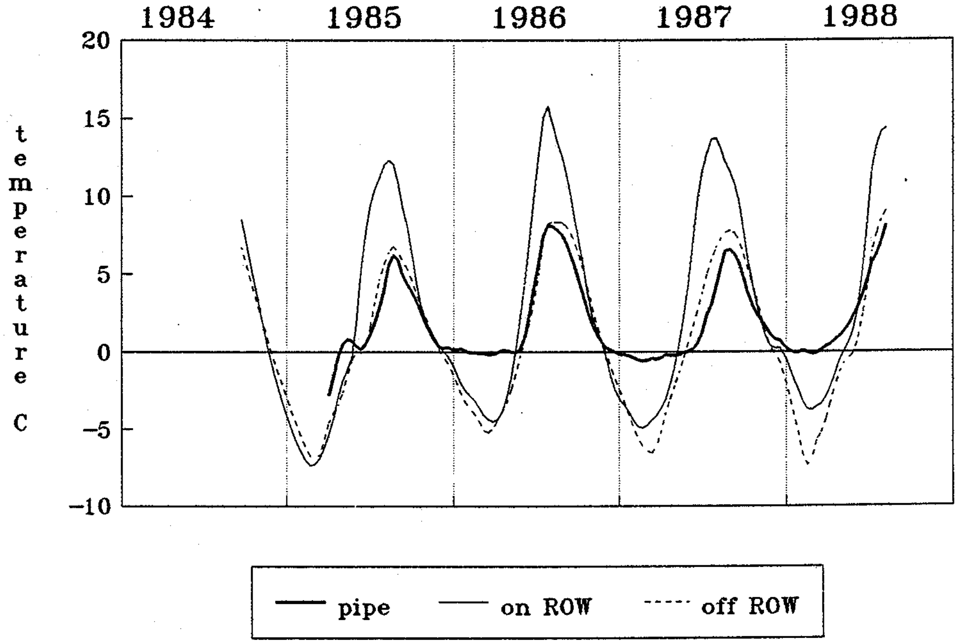
TRAIL RIVER A - EMR1

Interpolated pipe/1 m ground temperature

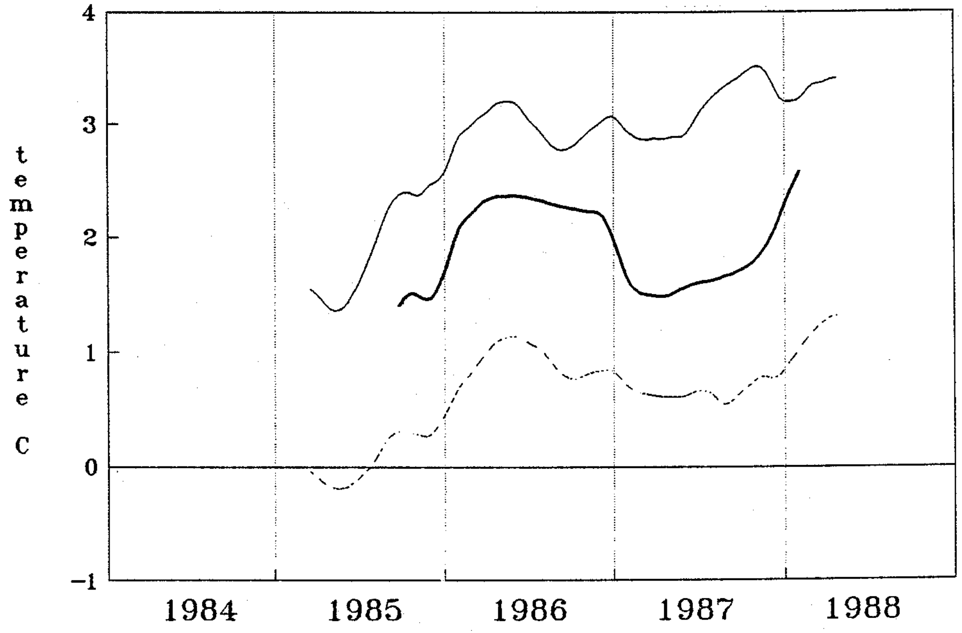


Running mean pipe/1 m ground temperature



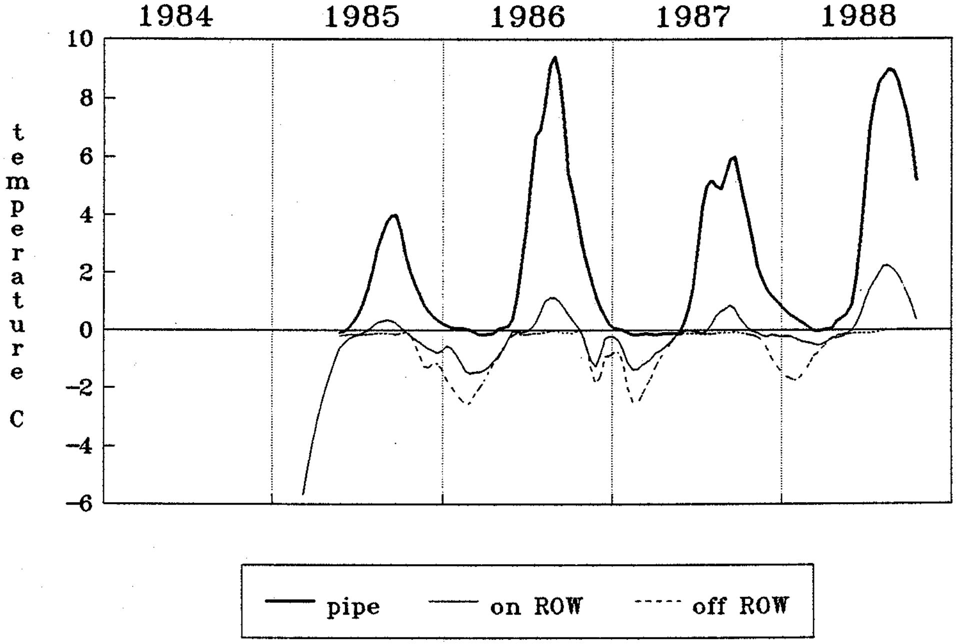


TRAIL RIVER B − PT1−9
Interpolated pipe/1 m ground temperature

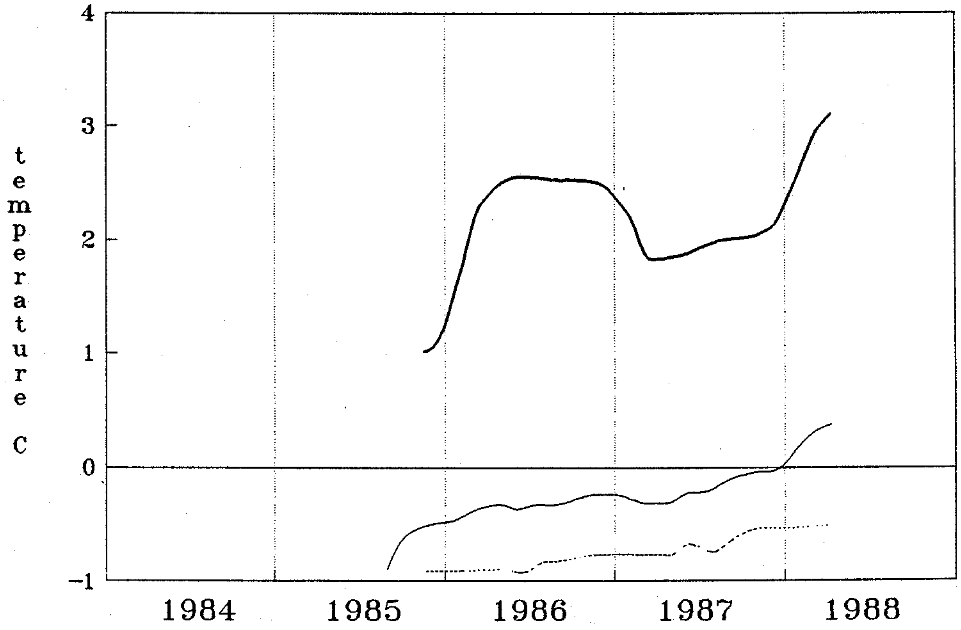


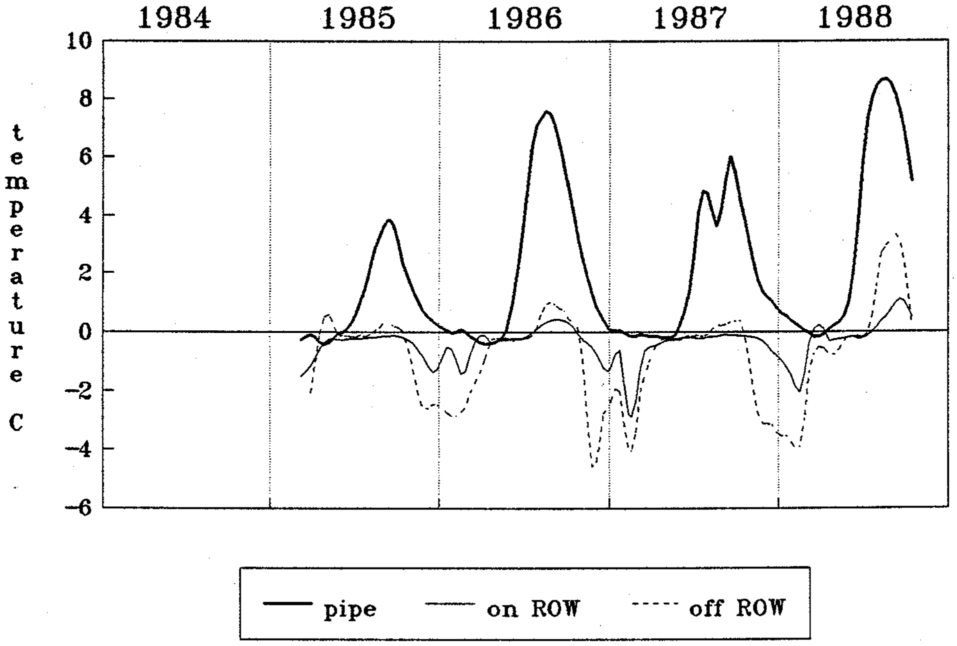
TRAIL RIVER B − PT1−9
Running mean pipe/1 m ground temperature

MANNERS CREEK A – 85 EPT8
Interpolated pipe/1 m ground temperature



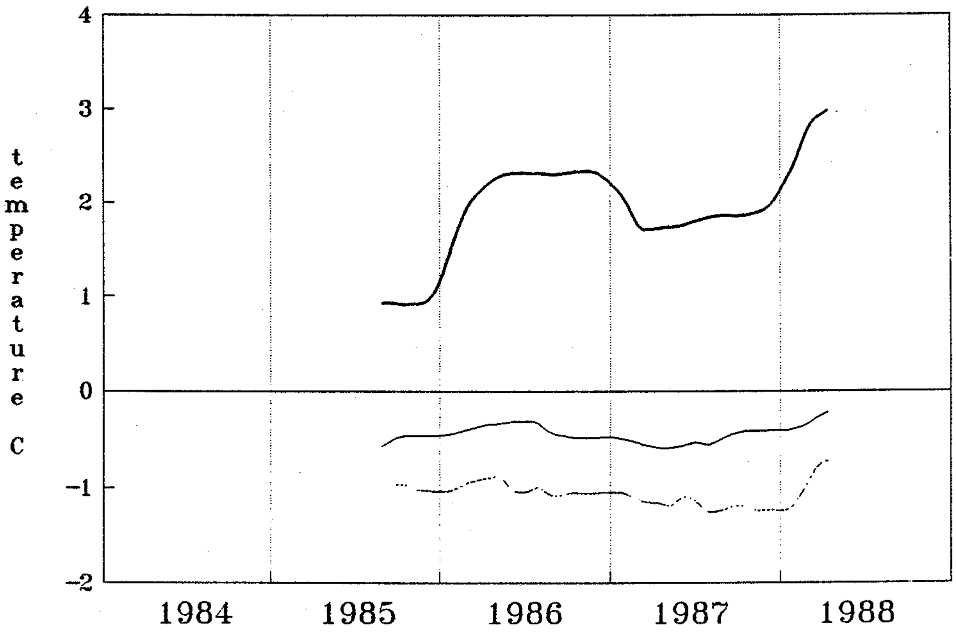
MANNERS CREEK A – 85 EPT8
Running mean pipe/1 m ground temperature





MANNERS CREEK B – 85 EPT7

Interpolated pipe/1 m ground temperature

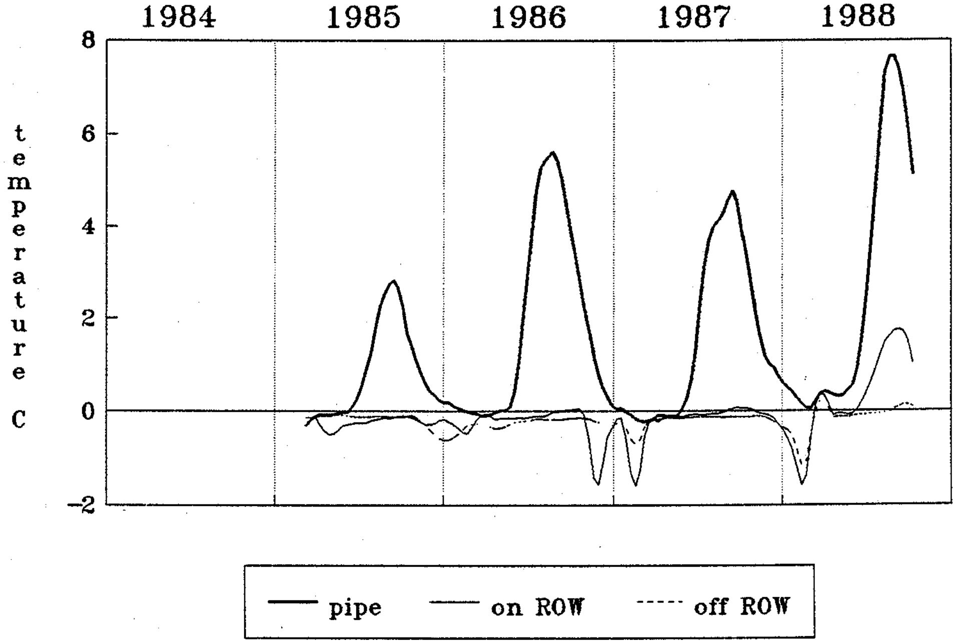


MANNERS CREEK B – 85 EPT7

Running mean pipe/1 m ground temperature

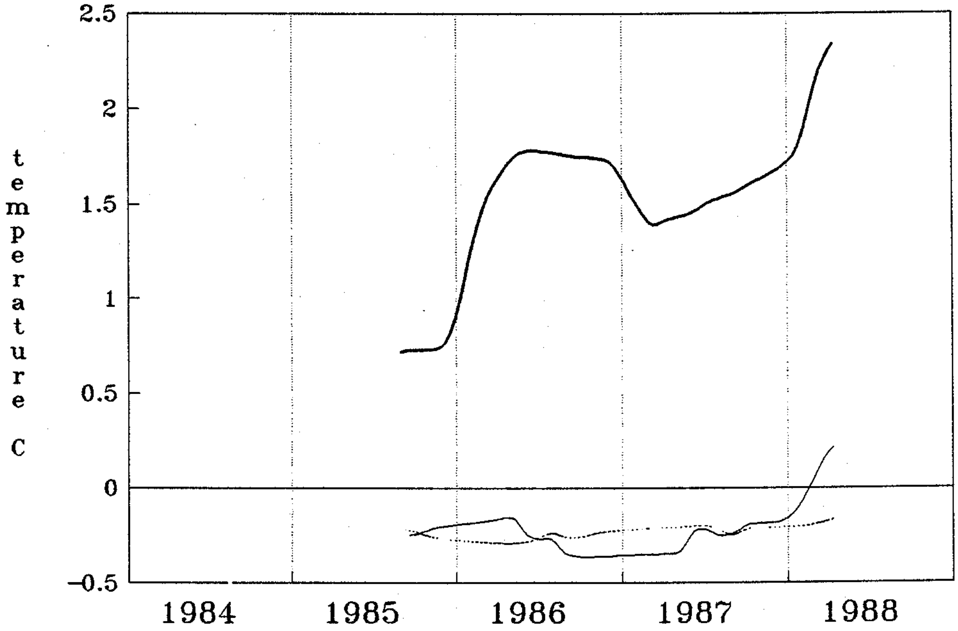
MANNERS CREEK C – 85 EPT12

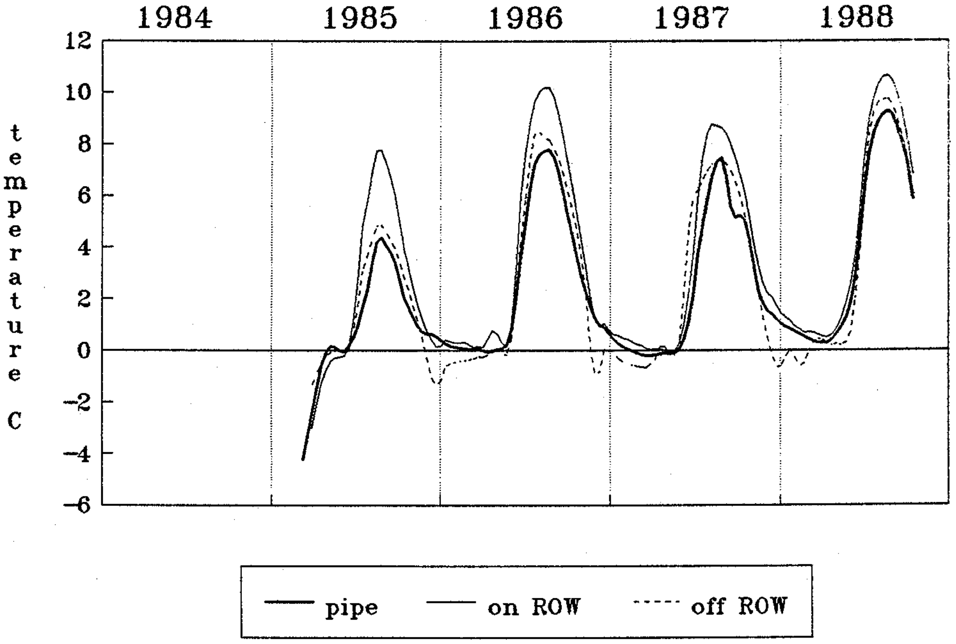
Interpolated pipe/1 m ground temperature



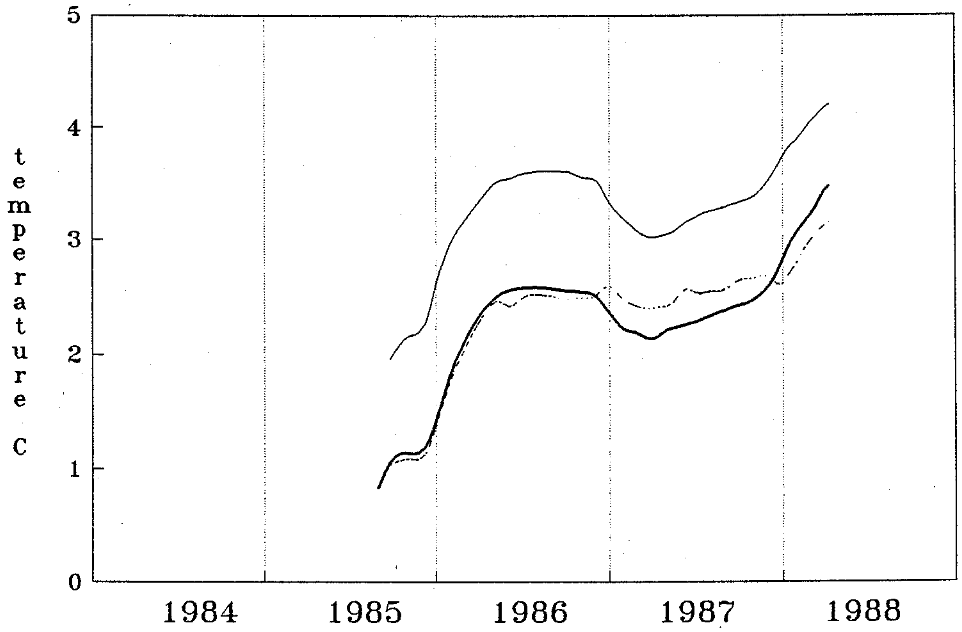
MANNERS CREEK C – 85 EPT12

Running mean pipe/1 m ground temperature





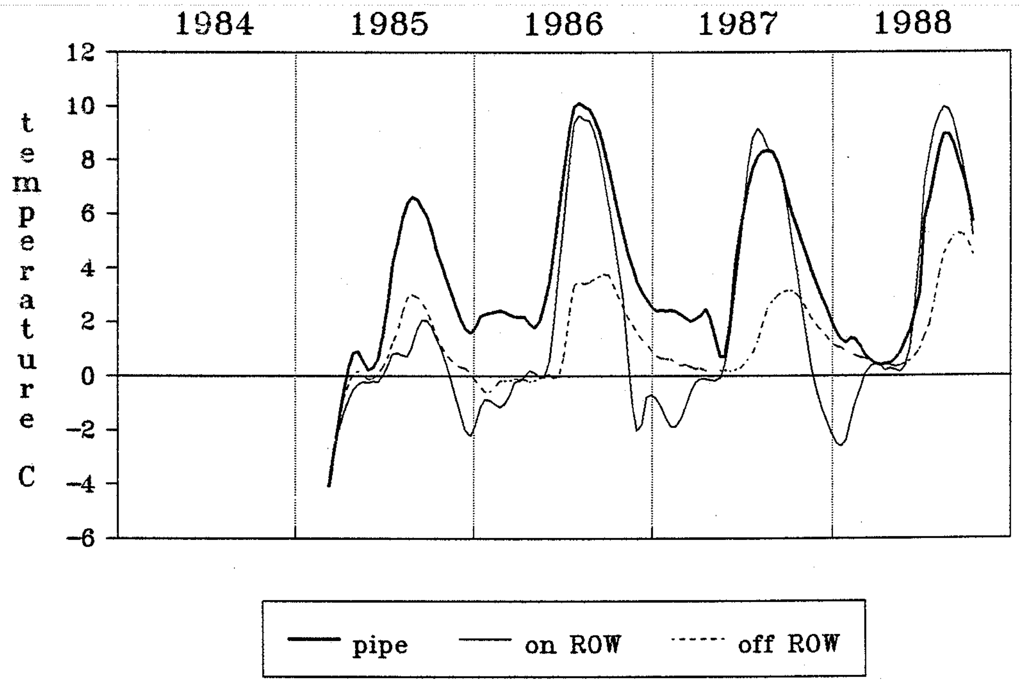
PUMP STATION 3 - 85 EPT9
Interpolated pipe/1 m ground temperature



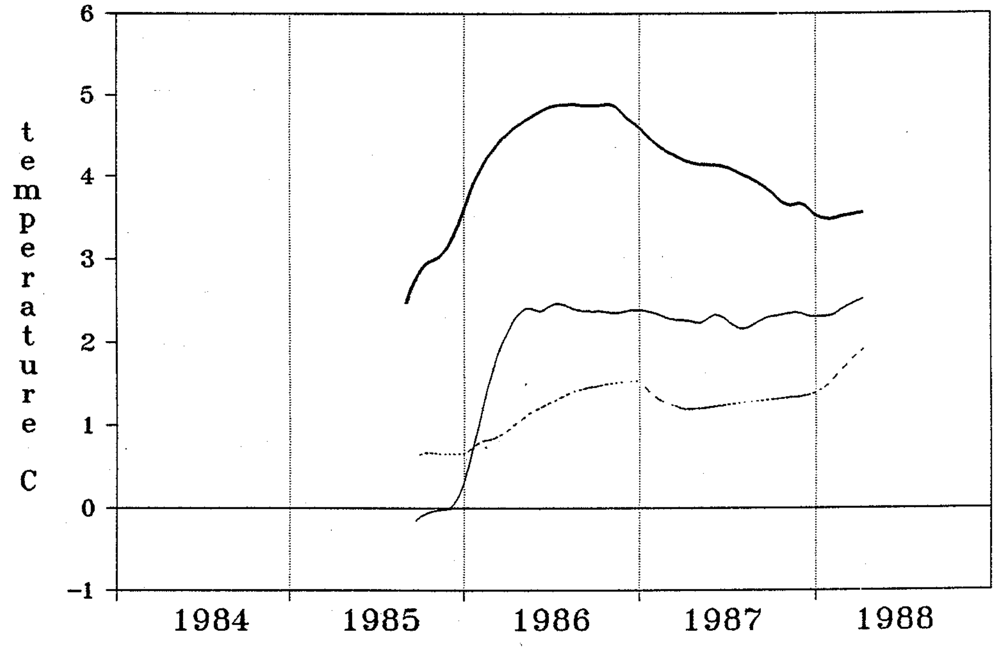
PUMP STATION 3 - 85 EPT9
Running mean pipe/1 m ground temperature

MACKENZIE HIGHWAY SOUTH A – 85 EPT4

Interpolated pipe/1 m ground temperature

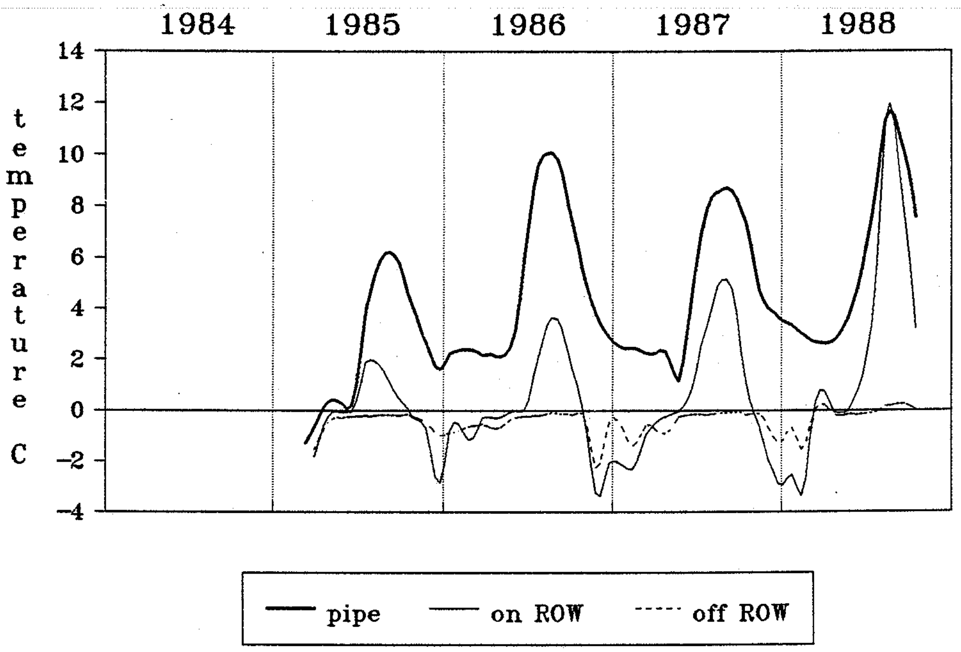


Running mean pipe/1 m ground temperature

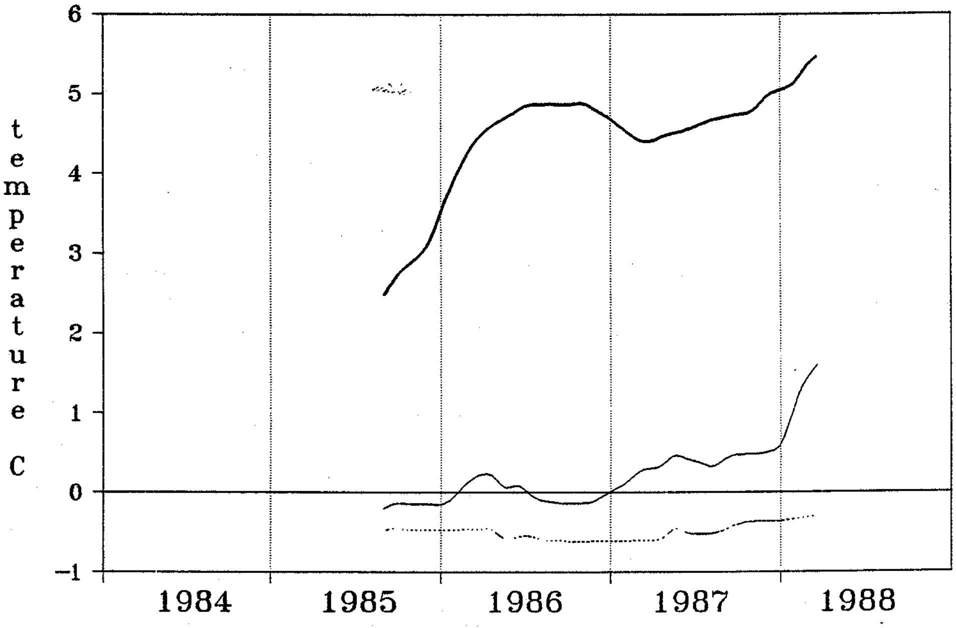


MACKENZIE HIGHWAY SOUTH B - 85 EPT5

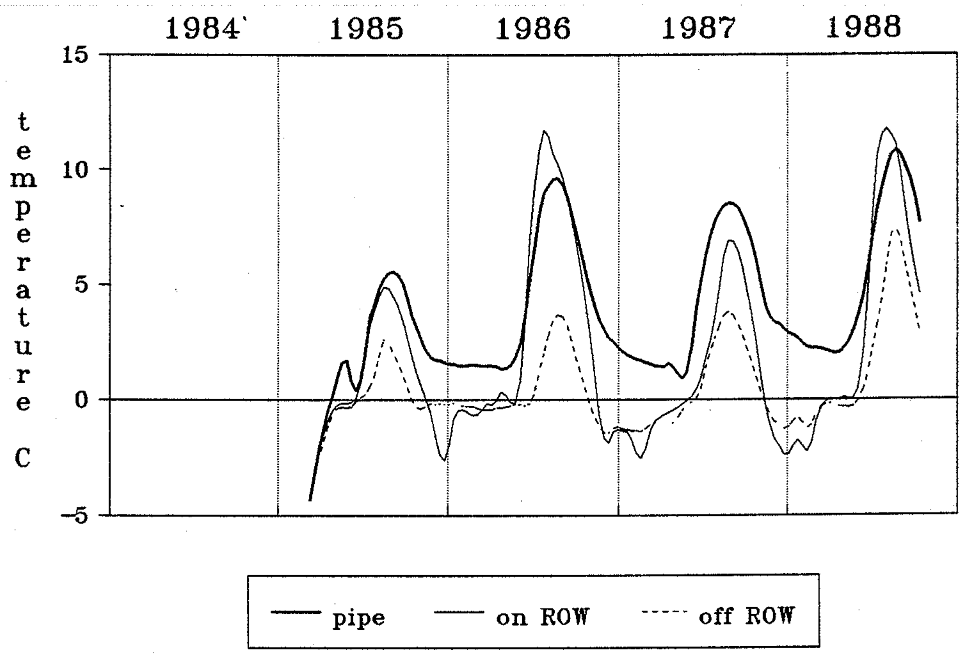
Interpolated pipe/1 m ground temperature

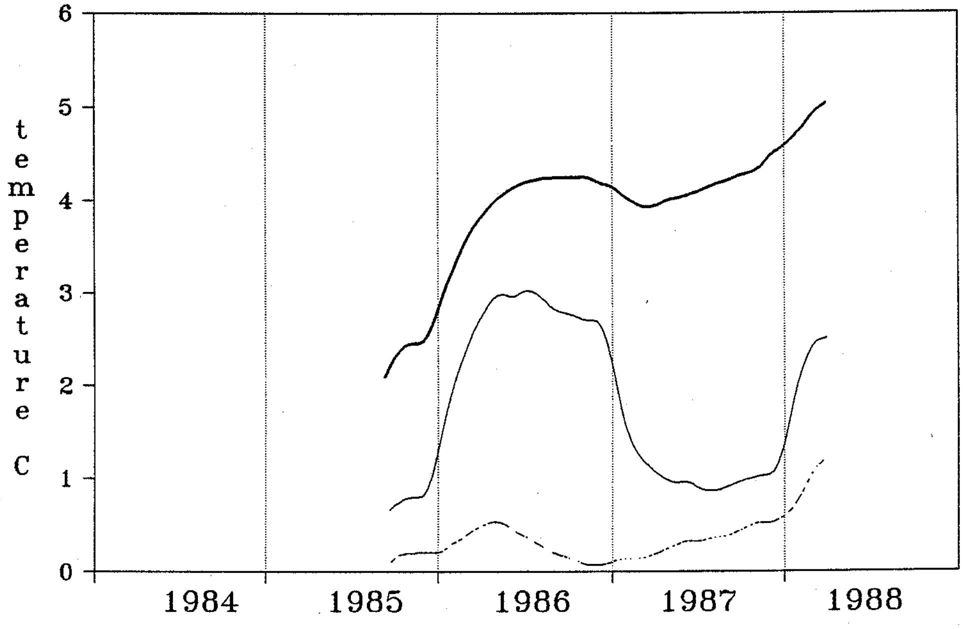


Running mean pipe/1 m ground temperature

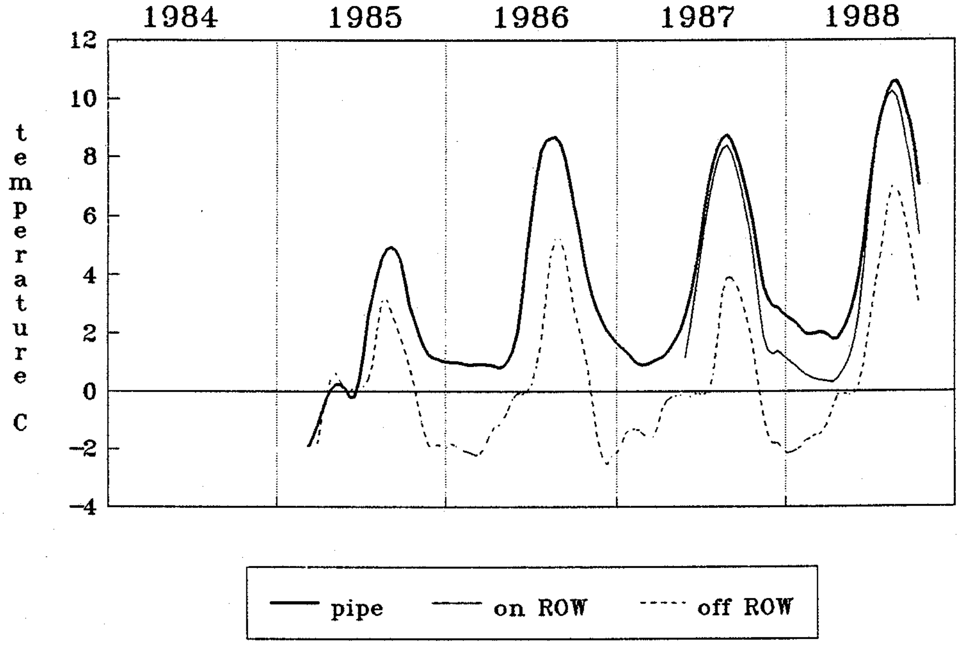


MORAINE SOUTH - 85 EPT11

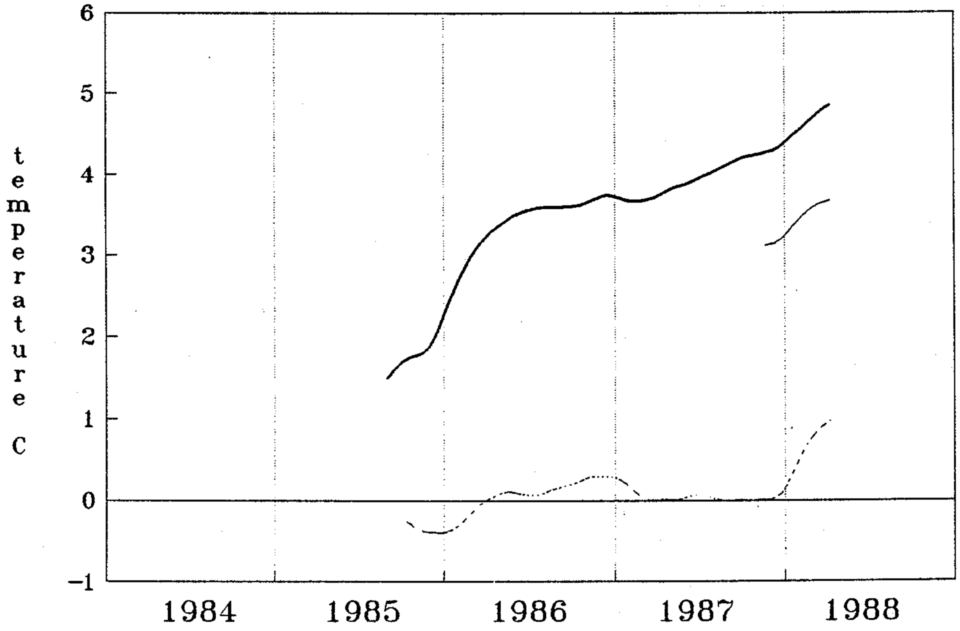

Interpolated pipe/1 m ground temperature


Running mean pipe/1 m ground temperature

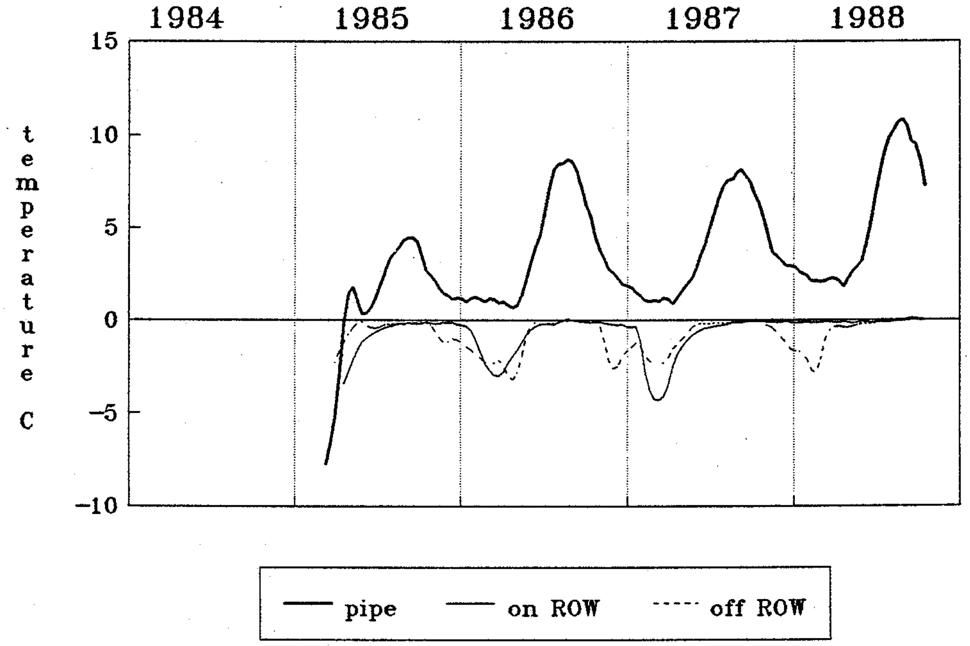
JEAN MARIE CREEK A – 85 EPT6
Interpolated pipe/1 m ground temperature



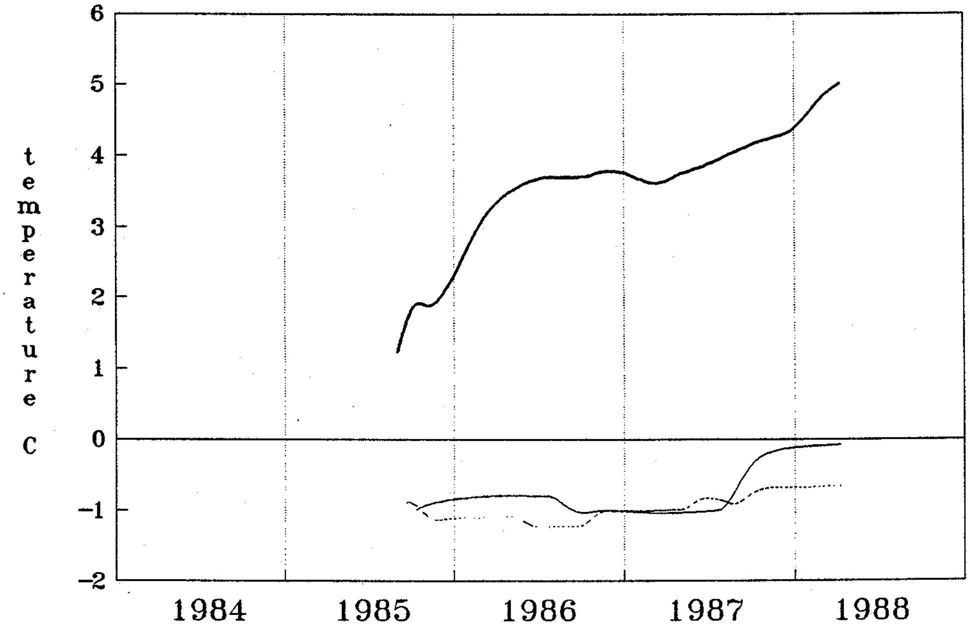
JEAN MARIE CREEK A – 85 EPT6
Running mean pipe/1 m ground temperature



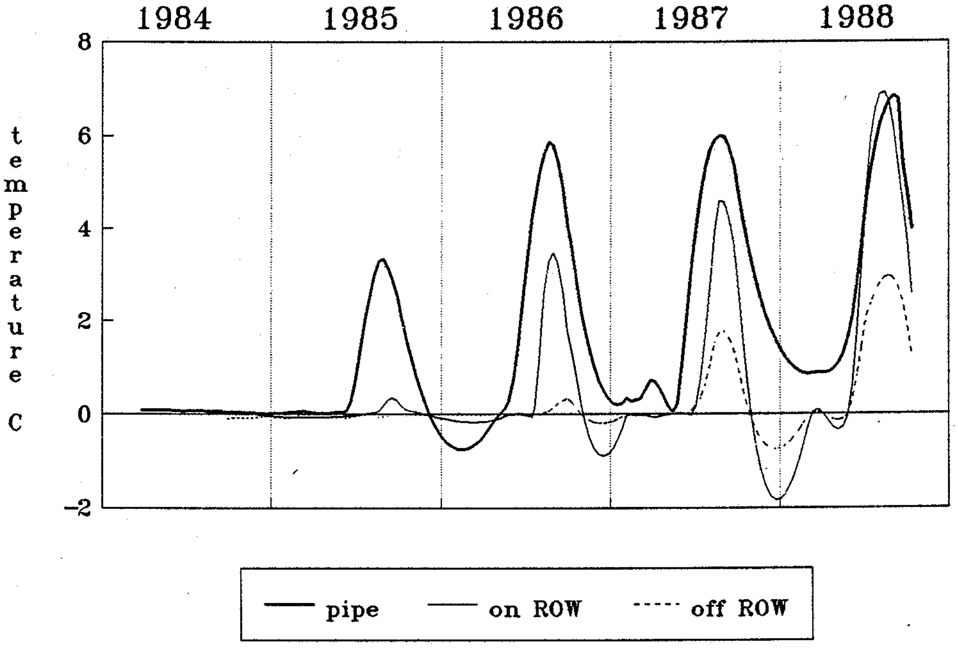
JEAN MARIE CREEK B – 85 EPT10
Interpolated pipe/1 m ground temperature



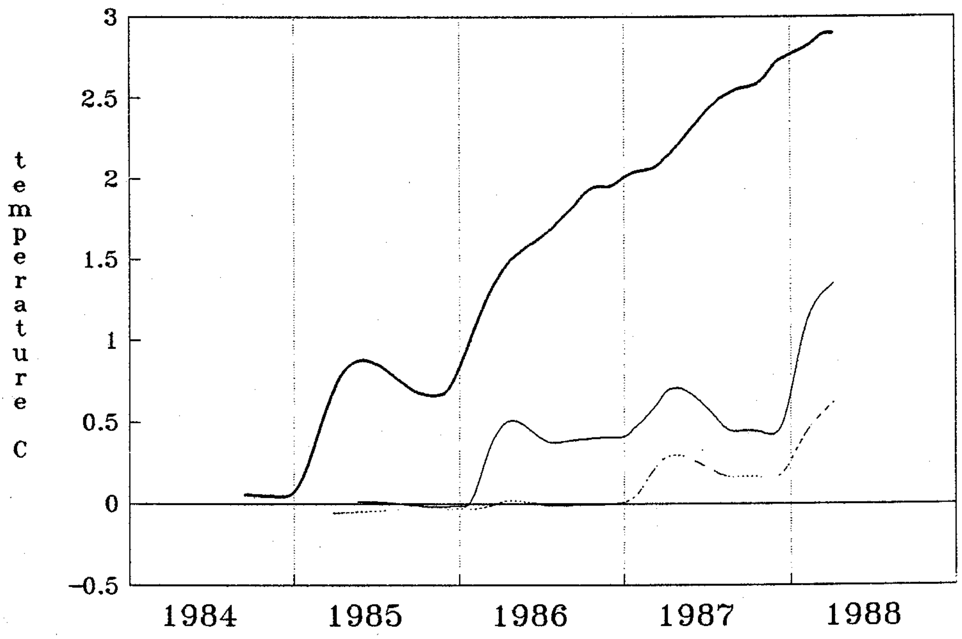
JEAN MARIE CREEK B – 85 EPT10
Running mean pipe/1 m ground temperature



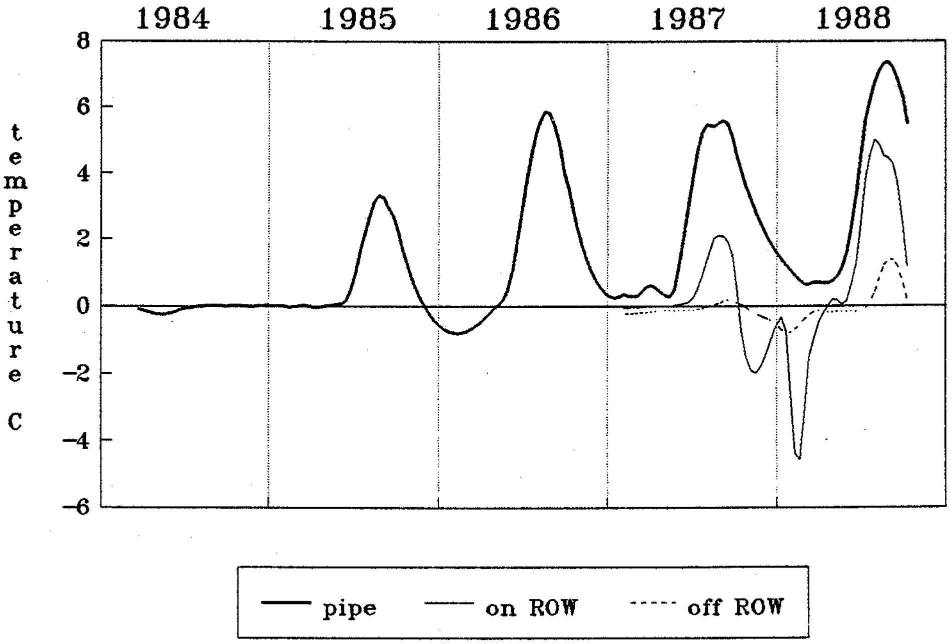
PETITOT RIVER NORTH A – EMR4
Interpolated pipe/1 m ground temperature



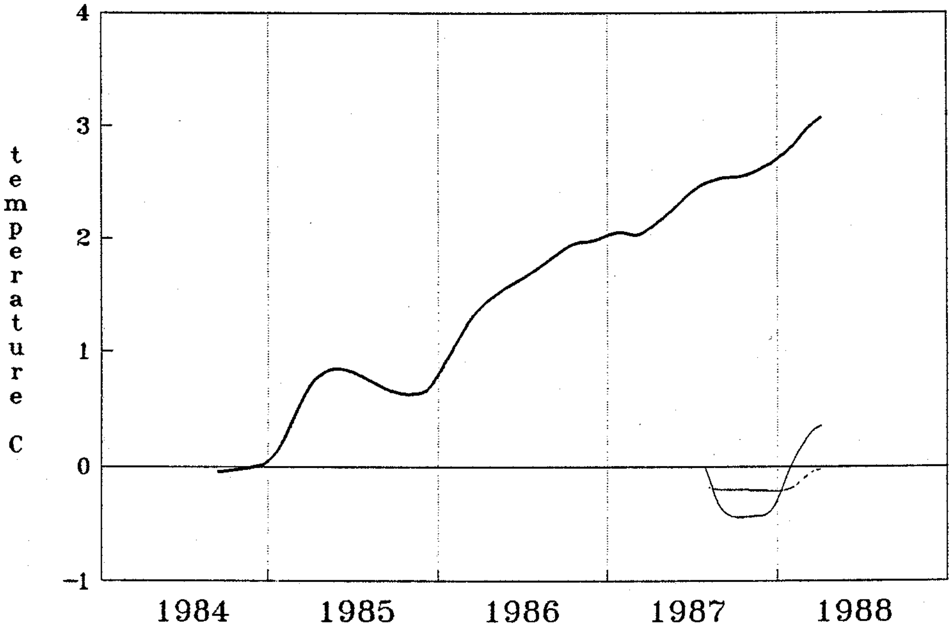
PETITOT RIVER NORTH A – EMR4
Running mean pipe/1 m ground temperature



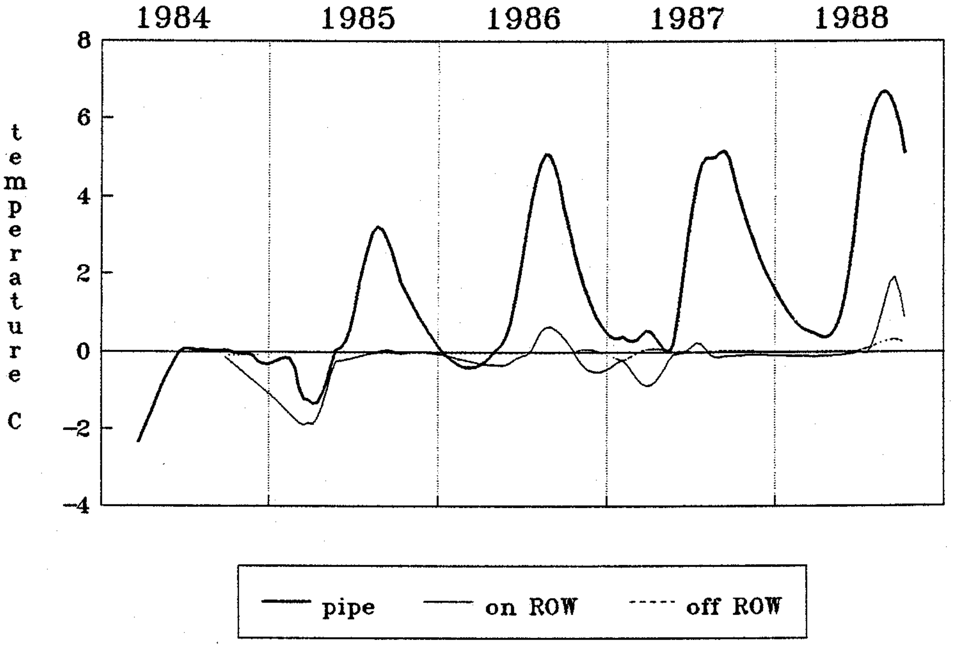
PETITOT RIVER NORTH B – EMR5
Interpolated pipe/1 m ground temperature



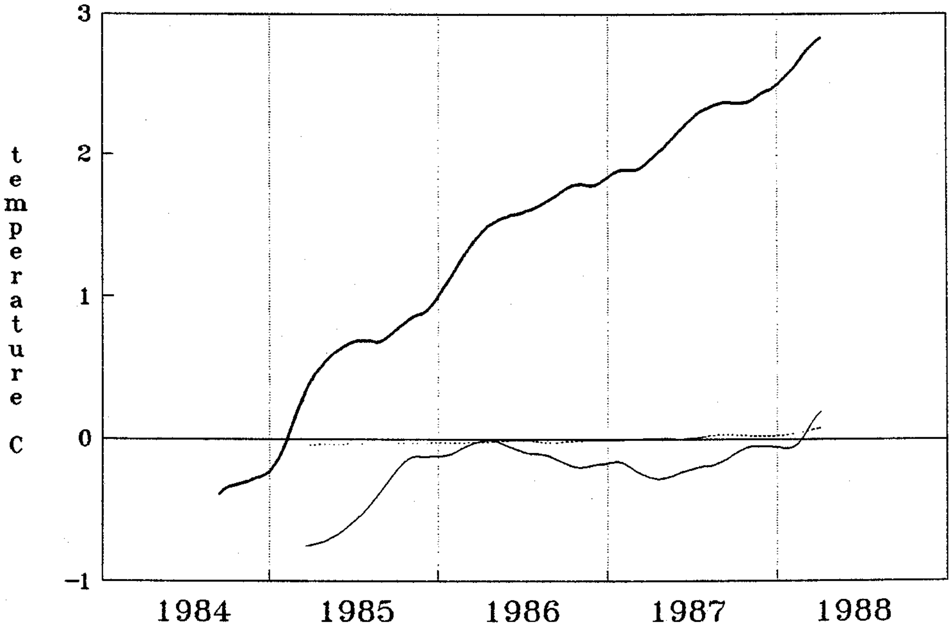
PETITOT RIVER NORTH B – EMR5
Running mean pipe/1 m ground temperature



PETITOT RIVER SOUTH – EMR6
Interpolated pipe/1 m ground temperature



PETITOT RIVER SOUTH – EMR6
Running mean pipe/1 m ground temperature



APPENDIX II

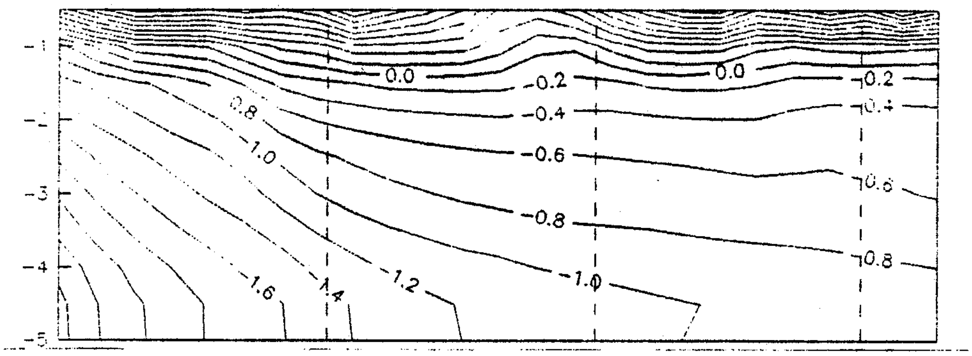
Geotherm Plots

Geotherms are similar to contour lines on topographic maps, except that they are lines of equal temperature rather than equal elevation. A geotherm plot may be drawn showing a thermal cross section (with depth and distance for y- and x-axes), or showing depth along the y-axis and time on the x-axis. The second type of plot is presented in this report. In a geotherm plot, the spacing between lines indicates the rate of change of temperature over both time and depth. Unfortunately, the distance between sensors on the cables is too coarse to permit accurate plots to be prepared for the monitoring program temperatures, particularly in the upper 2 meters of the ground. Fortunately, however, the rate of change of the mean annual temperature is much more gradual, both over time and with depth, permitting "mean annual geotherms" to be plotted instead. Mean annual geotherms are similar to simple temperature geotherms except that they are lines of equal mean annual temperature.

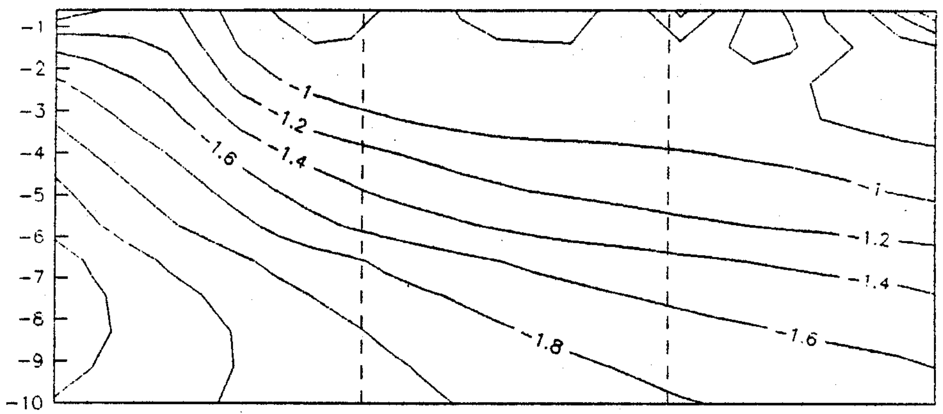
Geotherm plots were prepared for Sites 1, 2A and B, and 7A, B, and C, using the running mean annual temperatures estimates generated from the interpolations. For each site, plots were prepared for the cable closest to the pipe (T1 or T2) as well as cables T3 and T4.

The data were supplied to a three dimensional plotting computer program to generate contour (i.e. geotherm) plots. Producing the plots was somewhat cumbersome, since the program was designed for height-contour plotting, and assumes that x and y co-ordinates are in the same units. The program generated a grid 25 divisions wide (the time axis), with the number of height divisions (the depth axis) determined by the ratio of the ranges of the y- and x-values supplied. This required that the units of time on the x axis be adjusted so that the plot produced a plot of reasonable proportions. For this reason, the time axis is unlabeled, since the units supplied to the program were for proportionality only. To help in interpretation, the vertical dashed lines are included at one year intervals. The leftmost dates for all of the plots presented is approximately April 10, 1988.

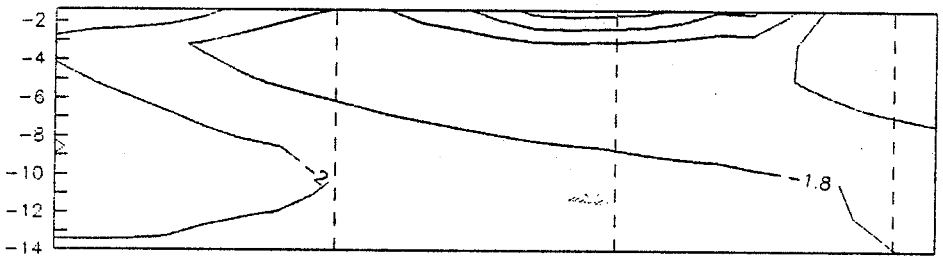
NWZ 1-T1



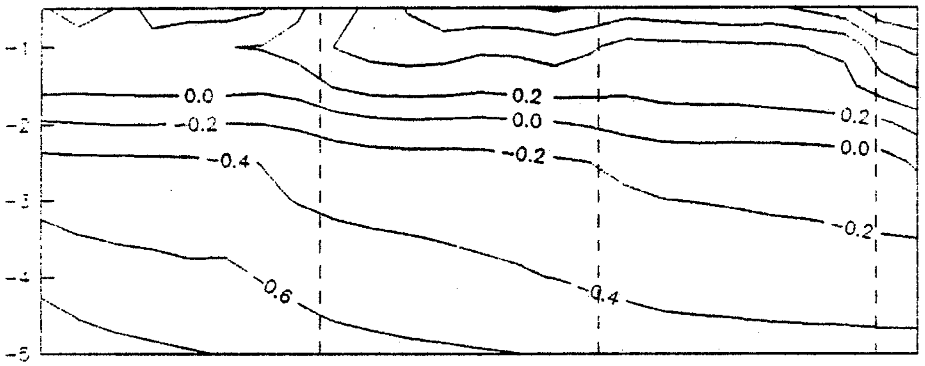
NWZ 1-T3



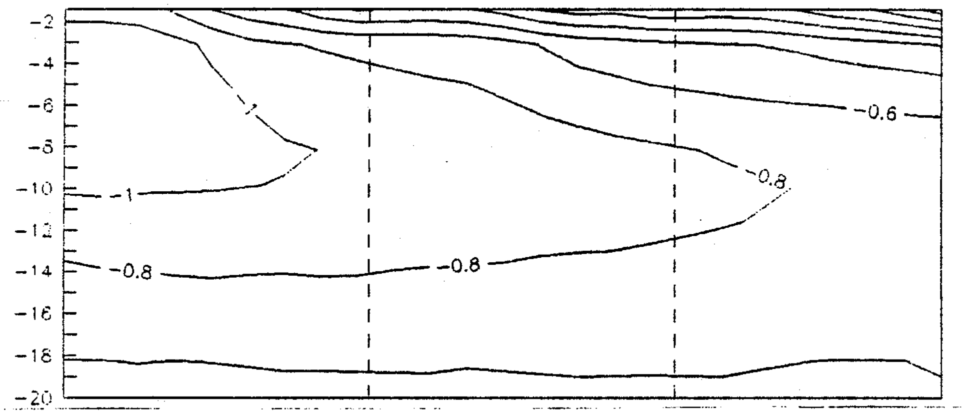
NWZ 1-T4



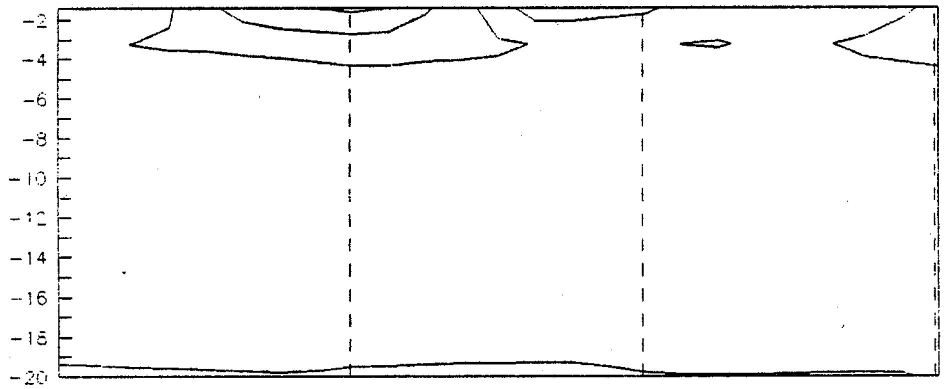
NWZ 2A–T1

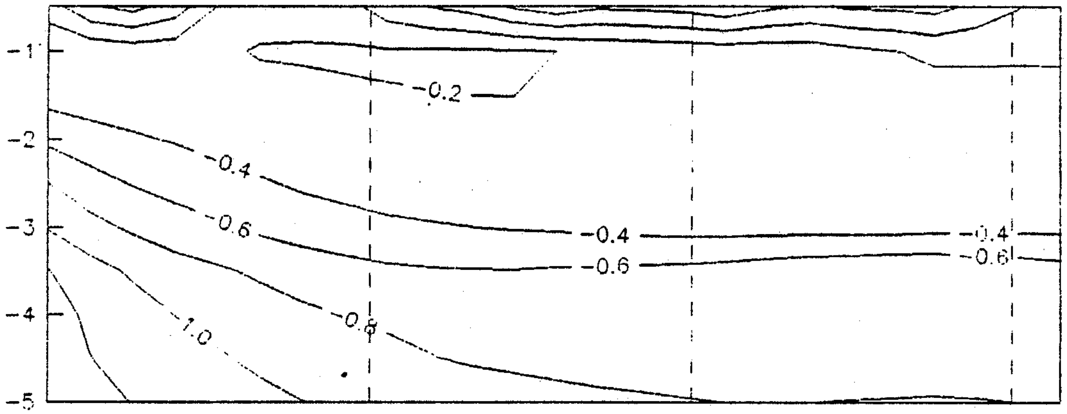


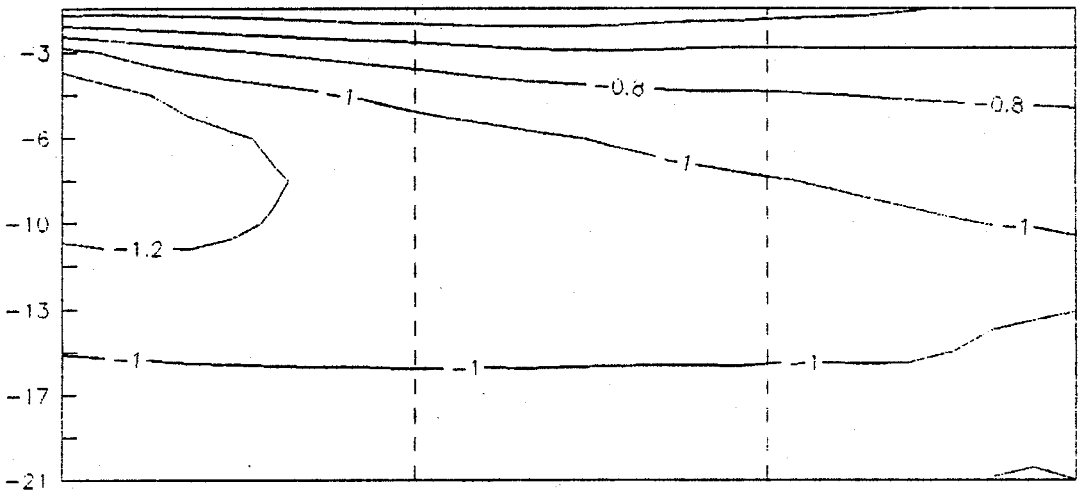
NWZ 2A–T3

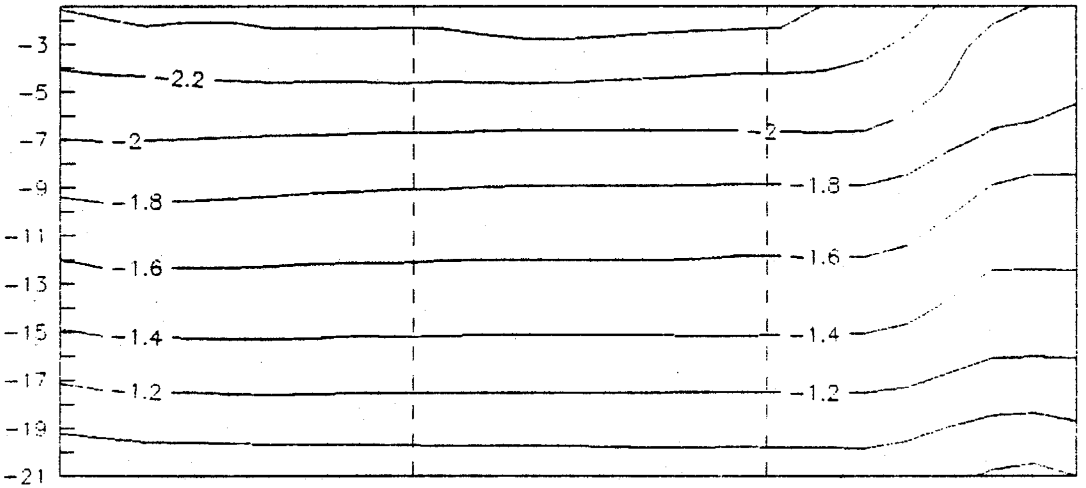


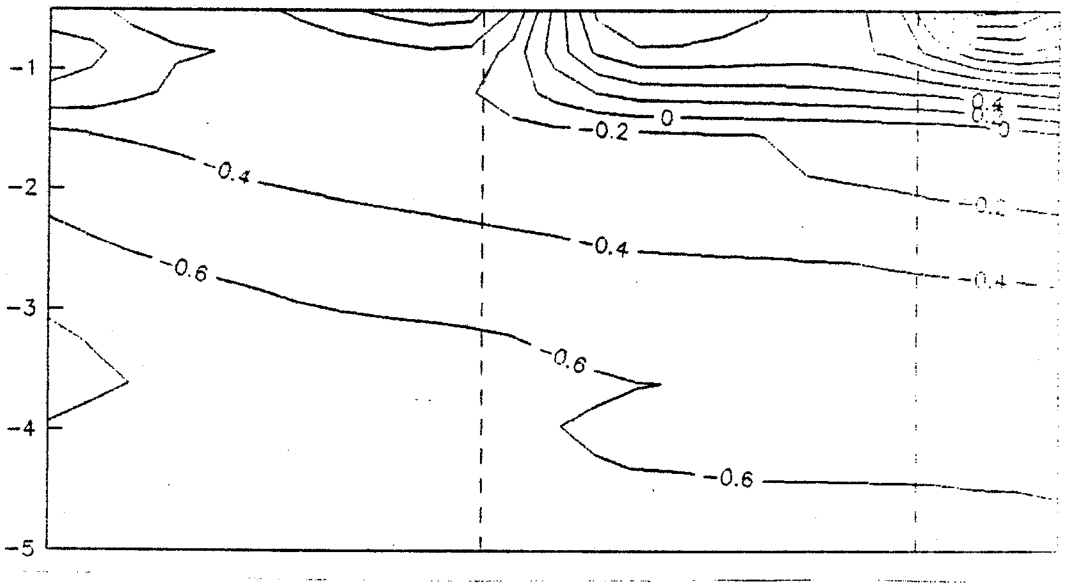
NWZ 2A–T4



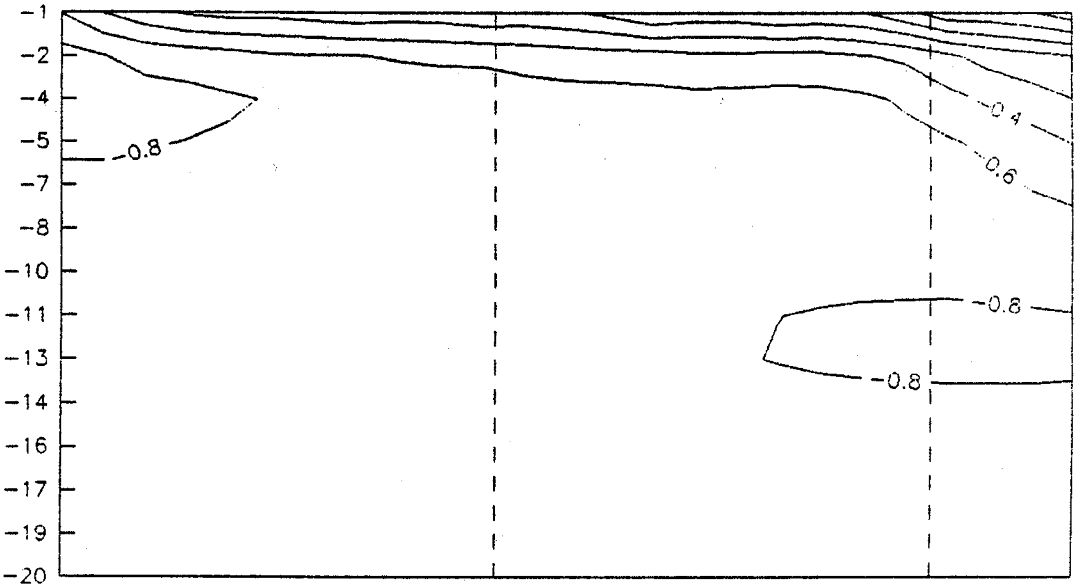

NWZ 2B-T1


NWZ 2B-T3

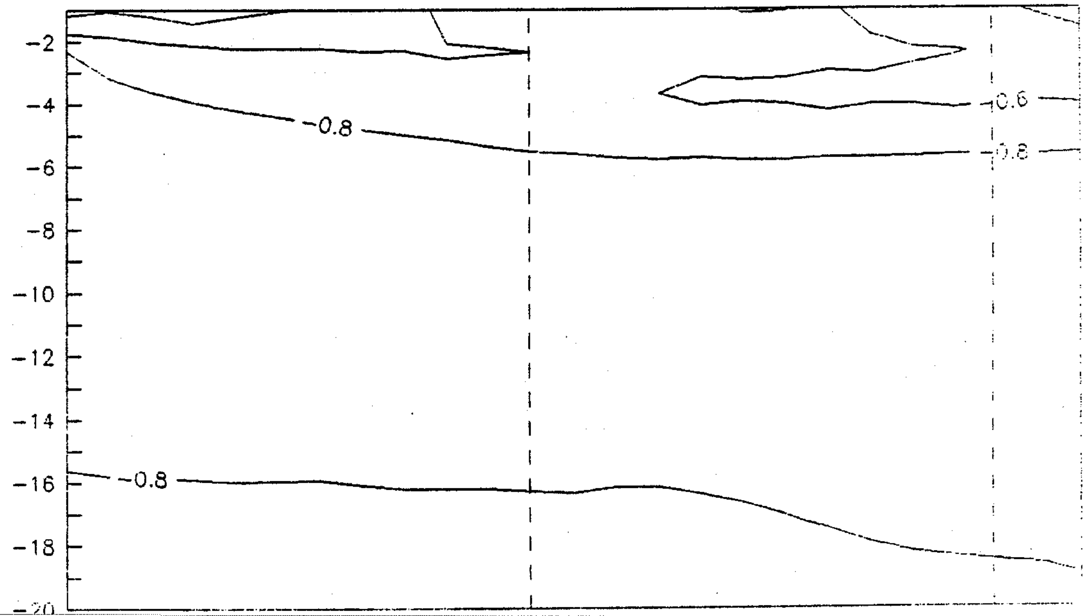

NWZ 2B-T4

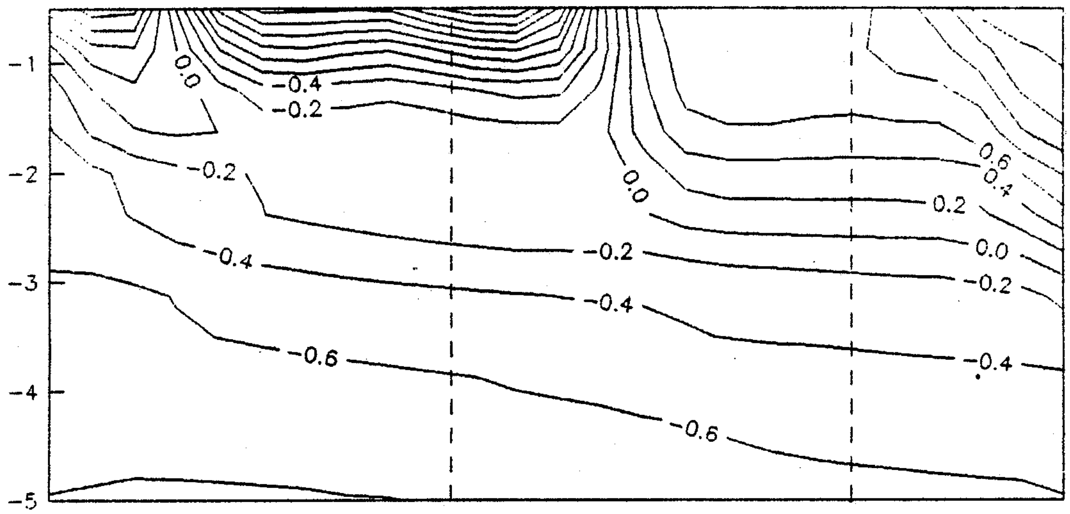


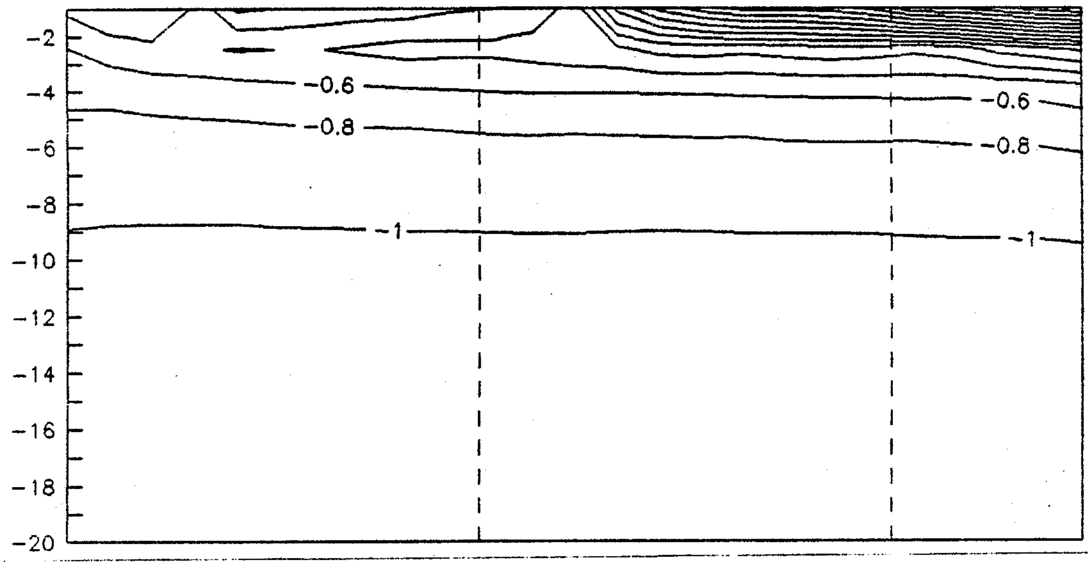
NWZ 7A–T3

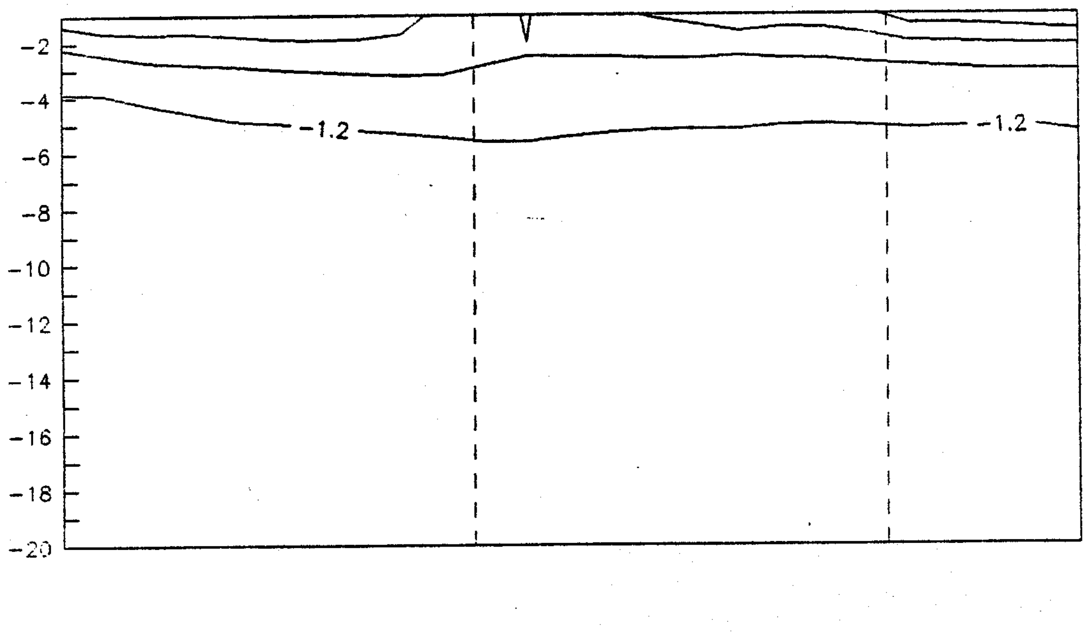


NWZ 7A–T4

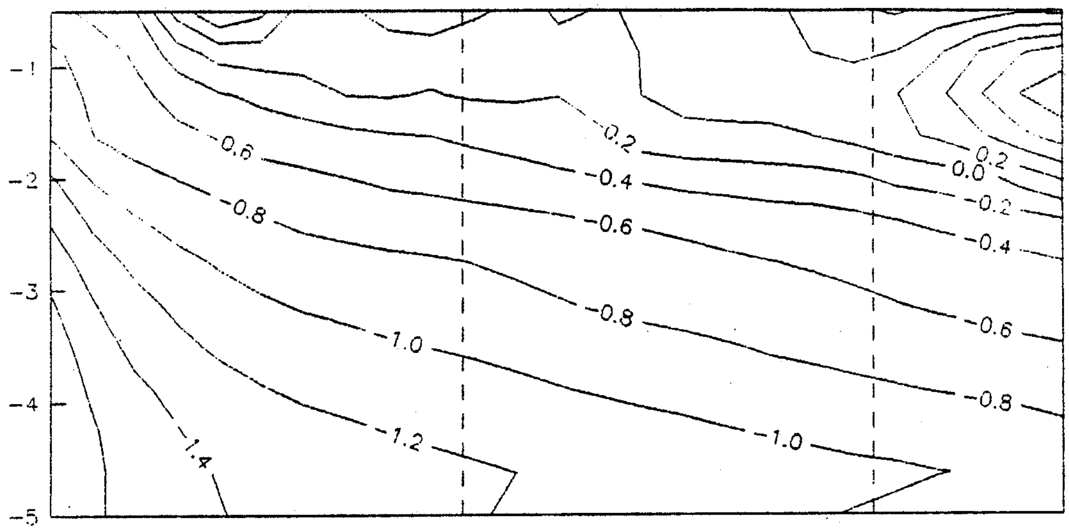



NWZ 7B-T2

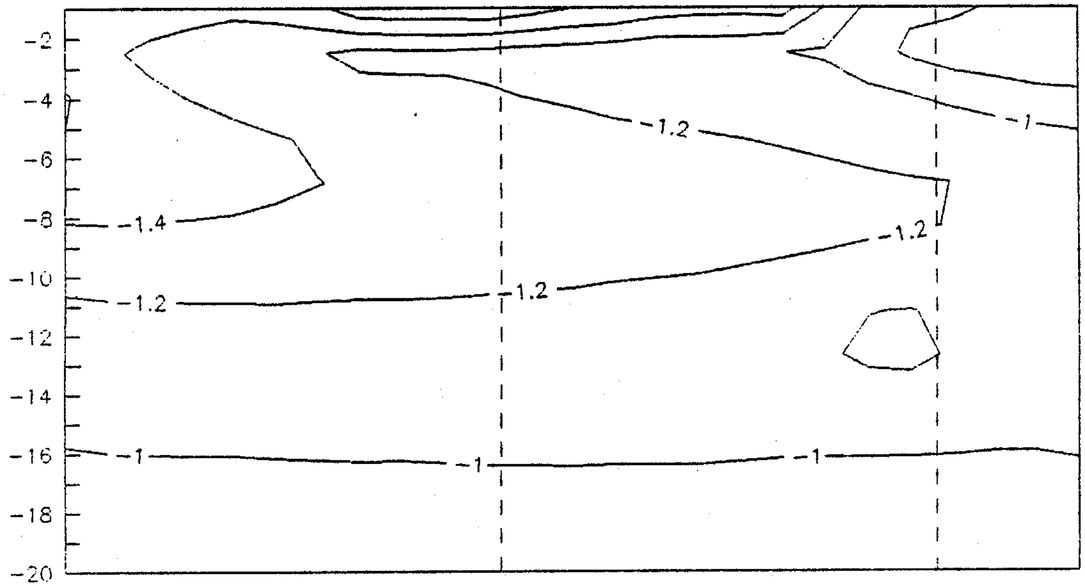

NWZ 7B-T3


NWZ 7B-T4

NWZ 7C-T2



NWZ 7C-T3



NWZ 7C-T4