GEOLOGICAL SURVEY OF CANADA

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COMPUTER ANALYSIS OF NORMAN WELLS PIPELINE THERMAL DATA

to the

Permafrost Research Group
Terrain Sciences Division
Geological Survey of Canada
Energy Mines and Resources
1 Observatory Cres.
Bldg. 3, Ottawa

by

D.W. Riseborough, D.E. Patterson, and M.W. Smith
Geothechnical Science Laboratories
Carleton University
Ottawa, Ontario
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Canada

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FINAL REPORT

Computer Analysis of Norman Wells Pipeline Thermal Data

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FOREWORD

This report documents work undertaken as part of the federal government's Permafrost and Terrain Research and Monitoring Program along the 868 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, with contributions from the Northern Oil and Gas Action Program (NOGAP).

Margo Burgess
Scientific Authority
Permafrost Research Section
Geological Survey of Canada

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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, D.E. Patterson, and M.W. Smith

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SECTION 1

INTRODUCTION

Ground temperature data have been collected along the Norman Wells - Zama pipeline route, at several monitoring sites established in 1984 or later (Burgess et al. 1985). In this report, we summarize the results of several analyses performed using the data collected to the end of October 1987.

Ground temperature sensors were usually installed in a standard configuration at the monitoring sites. At each site, a set of thermistor temperature sensor cables (referred to collectively as a "fence") were installed. 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 m (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. In this report, the relationships between these regimes are examined.

In addition to the ground temperature data, information on the physical properties of the soil were available for some sites (Patterson et al. 1987). These data made it possible to make some predictions about possible future behavior of the soil around the pipe and on the right-of-way.

The work comprised the following:

1. Obtain weekly estimates of pipe and ground temperatures by interpolating between approximately monthly temperature measurements.
2. Use interpolated values to obtain running mean annual temperatures (i.e. running means of 52 weeks)
3. Compare pipe temperatures to temperatures on the adjacent right-of-way.
4. Compare right-of-way ground temperatures to temperatures in the adjacent cable off of the right-of-way.
5. Examine the spatial scale of pipe temperature variation.
6. Estimate the thaw settlement potential of the soils at some sites using physical property data (from Patterson et al. 1987) for borehole core samples.

7. Estimate long term thaw and settlement.

Weekly temperature estimates and running mean annual temperatures were obtained for all sensors: due to the volume of numbers they are not included in this report. A printed copy of all measured, interpolated, and running mean temperatures, for all sensors on all cables has been supplied to the scientific authority. A floppy disk copy of the printed record has also been supplied.

1.1 Factors influencing ground temperatures

Interpretation of the observed changes in ground temperature requires an appreciation of the many factors which can have an influence. Gold and Lachenbruch (1973) and Brown and Pewe (1973) give excellent overviews of the factors which control and influence permafrost temperatures. In the present case, temperature observations on the oil pipeline and in the ground (both on and off of the right-of-way) were examined: the practical problem is to distinguish human-induced ground temperature change from a background of "natural" temperature variation. Before presenting results, some possible influences on ground temperatures of particular significance in the present context are described.

Snow

In general, a greater snow cover will result in higher winter ground temperatures, and hence a higher mean annual temperature (Goodrich 1982). While maps presented in Burns (1974, pp. 97-105) indicate that annual snow accumulation is fairly uniform along the pipeline route, local snow cover variability is too great to permit general conclusions about the influence of snow on ground temperatures along the route. Of more importance is that the clearing of the right-of-way and construction of the pipeline involved clearing of snow. In general this shows up as significantly cooler ground temperatures at all sites in the year during which snow clearing took place.

Changes to the microclimatic regime of the surface

Disturbances to the physical state of the ground surface will almost certainly lead to a change in the energy balance of the surface, leading to a change in the temperature regime of the ground surface.

Changes such as :

- clearing of vegetation from the right-of-way,
- surface compaction by construction equipment,
- changes to the water table, possibly including ponding of water on the surface,
- scraping away the organic layer,
- thaw settlement

may change any or all of:

- the thermal properties of the soil surface layer,
- the radiative properties of the surface,
- the evaporative regime of the surface,
- the aerodynamic properties of the surface,
- the ability of the surface to trap snow.

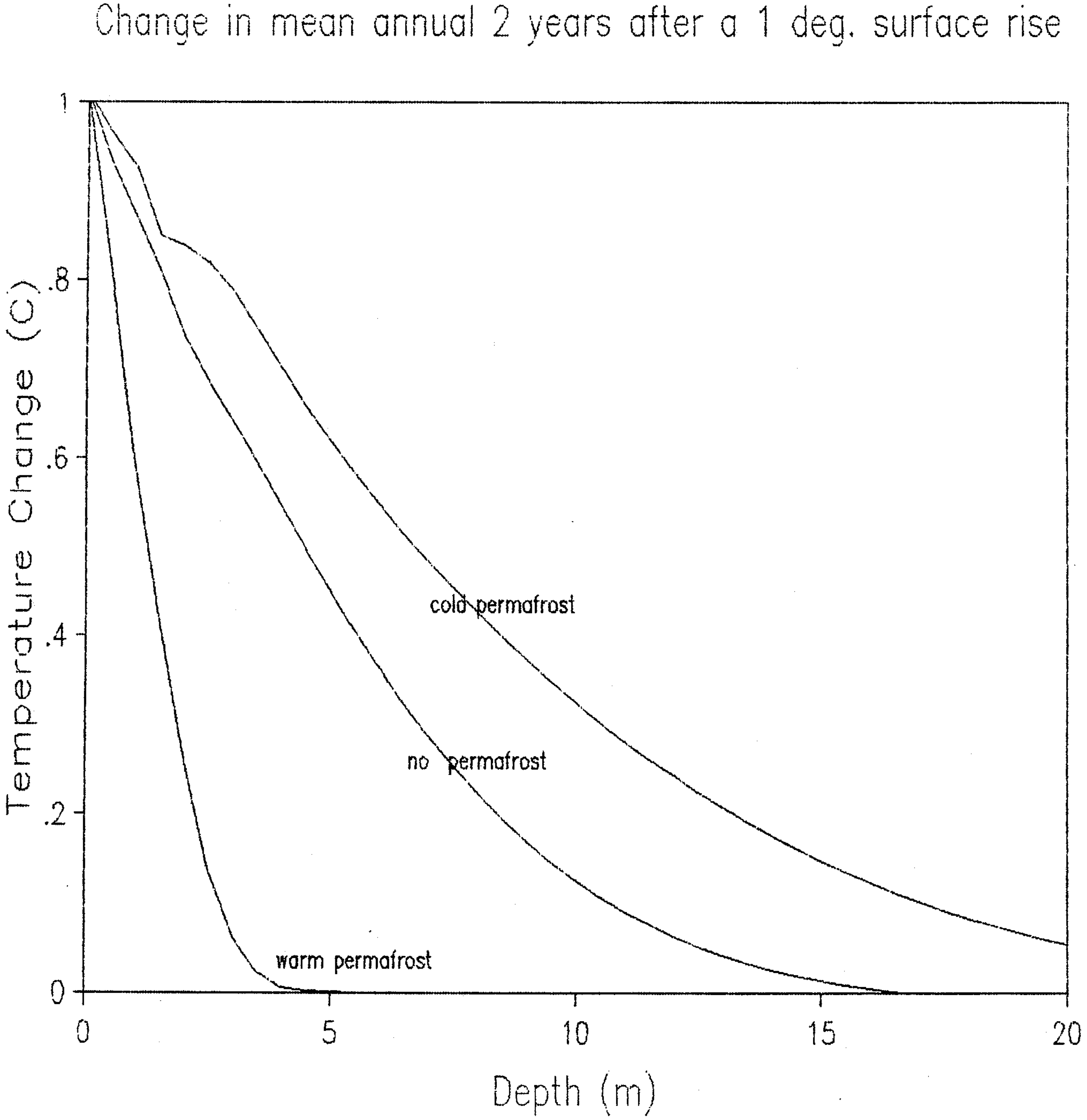
The ground thermal regime

Changes in temperature at the ground surface always take time to be felt at depth. For example, the annual temperature wave at the ground surface will normally experience its maximum during July, while the maximum temperature experienced at the base of the active layer is not felt until late fall. The lag in ground temperature response to the changes at the surface is due to the thermal diffusivity of the surface. This can make it difficult to compare temperature trends at different sites with differing thermal properties (such as adjacent sites on and off of the right-of-way): temperature measurements taken at the same depth but in different materials will differ in both the magnitude and in the time lag of their response to change at the surface. Similarly, if the mean annual temperature of the surface is changed, the change is propagated into the ground at a rate determined by the thermal diffusivity of the soil.

At temperatures below 0°C, the thermal properties of soils containing water can change significantly with small changes in temperature, since the volume fractions of ice and water are temperature-dependent. The presence of water in frozen materials influences the thermal properties primarily because of the effect of latent heat release associated with the temperature change. As a result of this effect, the rate at which deep ground temperatures respond to changes at the surface depends upon the ground temperature regime at the time that the change occurs.

To illustrate this point, the rate of change of ground temperature following warming at the surface was examined for three types of ground thermal regime: (using the geothermal simulation 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)
- a non-permafrost site (mean annual temperature of +0.5)



Change in mean annual 2 years after a 1 deg. surface rise

A sinusoidal temperature wave with a period of one year and an amplitude of 10 degrees was imposed at the ground surface. 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 equilibrium ground temperature profiles. Following this, the temperature waves imposed at the surface were warmed by 1 degree. Figure 1.1 shows the changes in mean annual ground temperature (at depths down to 20 m) at each of the sites, two years after the step change was imposed.

The results show the relative rates at which the temperature change at the surface is propagated into the soil. The effects of latent heat and thermal diffusivity are also apparent. The warm permafrost site changed the least, since the change of 1 degree requires the absorbtion of the entire latent heat of fusion of the soil as it warms above zero. 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 difference in the rate of propagation between 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 : by five meters depth, the 1^{o}

Table 1.1

Physical Properties Specified for Step Change Example

Thermal Conductivity : Frozen: 3.0 $Wm^{-1}K^{-1}$
Thawed: 1.5 $Wm^{-1}K^{-1}$
Soil Bulk Density : 1.55 g cm^{-3}
Unfrozen Heat Capacity: 2.760 E+06 Jm^3K
Frozen Heat Capacity: 2.200 E+06 Jm^3K
Total Water Content : 41%
Unfrozen water content below -0.5^oC : 13.3%
(Latent heat is released/absorbed over the temperature range 0 to -0.5^oC)

temperature wave is attenuated completely at the warm permafrost site, to only 0.45° at the non-permafrost site, and to 0.62° at the cold permafrost site. Thus, both the depth of measurement and the initial ground thermal regime must be considered before the significance of ground temperature changes can be evaluated.

Smaller differences in diffusivity (not nessesarily due to latent heat effects) 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.

"Thermal offset" and thaw settlement

Goodrich (1978) has noted that the mean annual temperature of permafrost will normally shift to colder temperatures as depth increases, down to the depth of zero annual amplitude, or to that depth where "thermal conductivity is not significantly dependent on time". This phenomenon, ("thermal offset") is a result of the difference between frozen and thawed thermal properties, and does not signify a net annual heat exchange between the atmosphere and the soil.

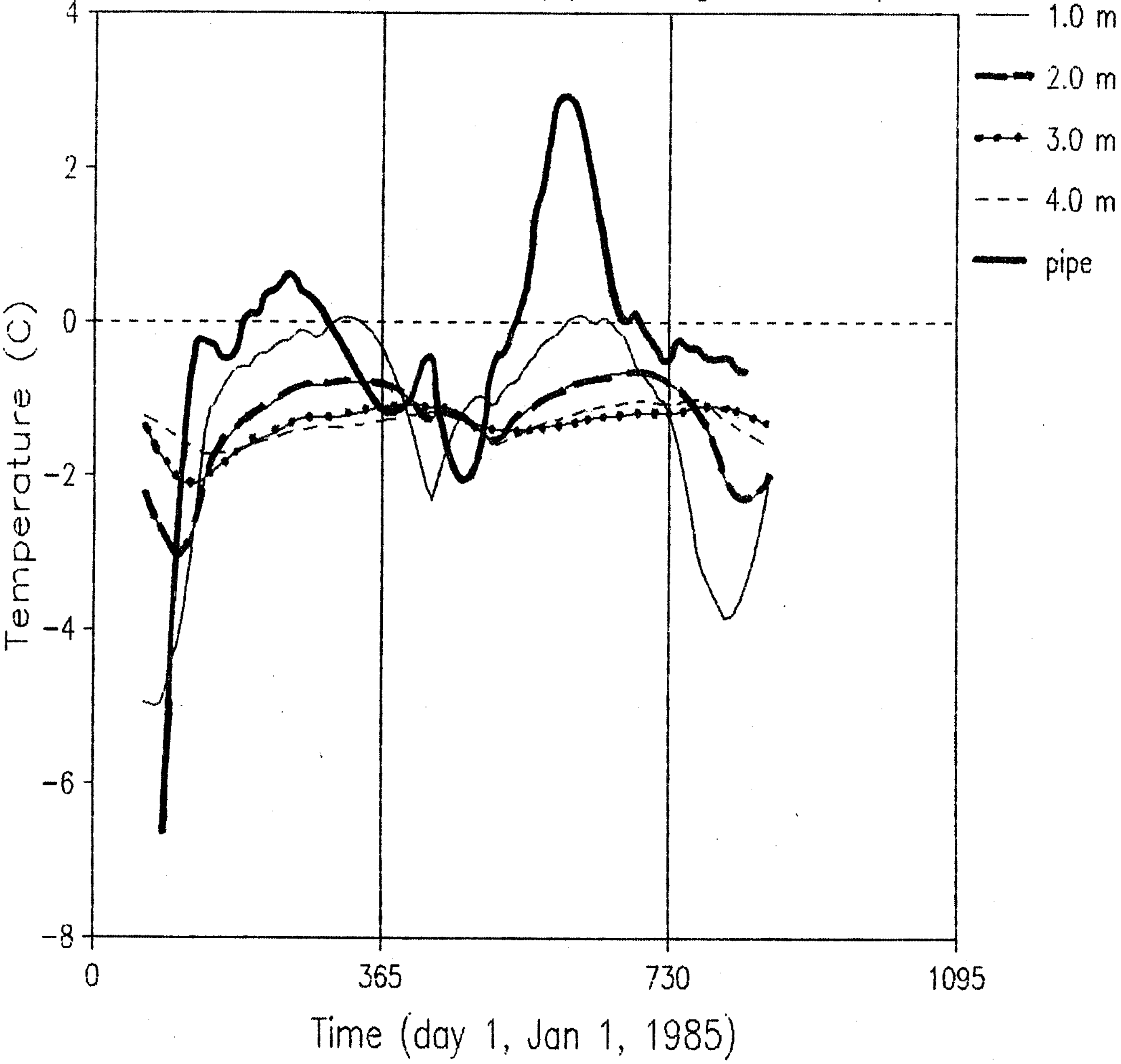
This effect can produce an apparent rise in the mean annual temperatures at sites where settlement has occured: If sensors are shifted upward in the soil profile as a result of soil settlement, then the mean annual temperature measured by the sensor will increase. Any measured temperature change will include a component due to the shift in position of the sensor as well as a component due to the true change (if any) in mean annual temperature at the surface.

Similarly, if there are differences in thermal properties between sites on and off of the pipeline right-of-way, their relative positions in the curved portion of mean annual temperature profile will not be the same, so that their responses to surface temperature changes will differ.

For the reasons outlined above, choosing the best depth of ground temperature measurement to discern changes in the ground thermal regime is nessesarily a compromise. If it is too shallow, temperatures will be too variable to be adequately characterized by infrequent temperature measurements, and will be subject to other uncertainties such as thaw settlement and the thermal offset effect. If it is too deep, the signal will be attenuated to such an extent that the true magnitude of changes at the surface will be impossible to evaluate. In the present case, the choice is made simpler by the presence of the pipeline: the best measurement depth for analysis of ground temperatures will be that whose rate of temperature change is most synchronous with pipeline temperature variations.

The increasing time lag between temperatures at the ground surface and those at depth affords the best method for choosing the depth of soil temperature measurement to compare with pipe temperature measurements. Figure 1.2 shows the temperature curves at several depths for a typical T3 cable, and for the adjacent pipe. With increasing depth, the time lag in the temperature wave

Figure 1.2: Comparison of pipe and ground temperatures



is clearly visible. The temperature cycle in the pipe is most nearly syncronized with the 1 meter ground measurement. As a result, all comparisons of ground and pipe temperatures shown in this report use the 1 meter ground temperatures as the basis for comparison.

1.2 The meteorological record at Norman Wells and Fort Simpson

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 1.3a. These data were used to obtain running mean annual temperatures (i.e. 12 month running means), which are shown in Figure 1.3b.

Monthly average temperatures change smoothly throughout the spring, summer, and fall. In winter, however, monthly average temperatures fluctuate significantly, perhaps reflecting variations in the position of the polar front. These variations show up in the running means (Figure 1.3b) 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.

The trends in the running means are the same at both stations: following a short, moderate cooling period (of about 9 months), the mean annual temperature rises continuously until the end of the record. The overall change in the mean annual (from the low point to the high point) is approximately 2 degrees at

Figure 1.3a: Monthly mean air temperature

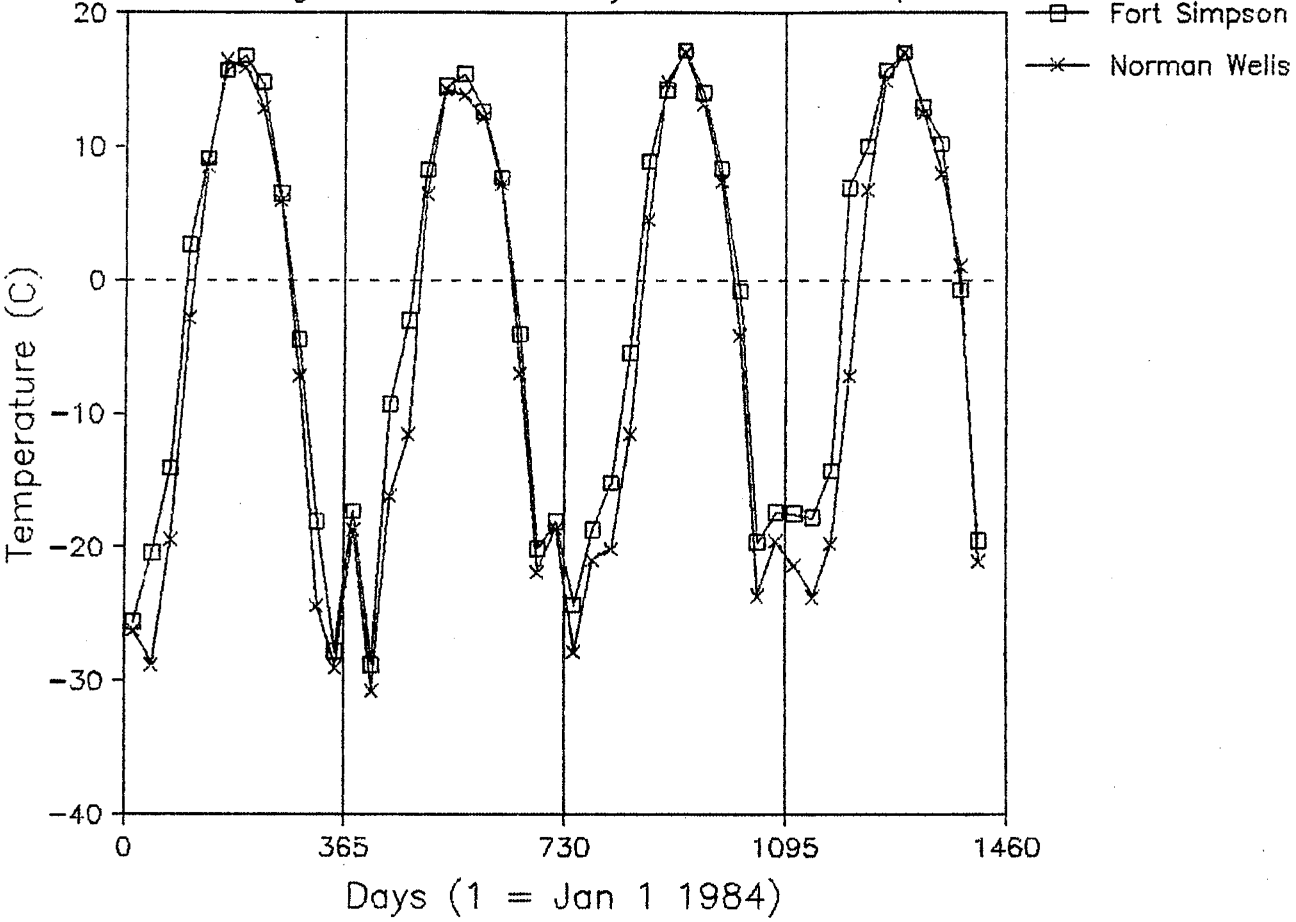
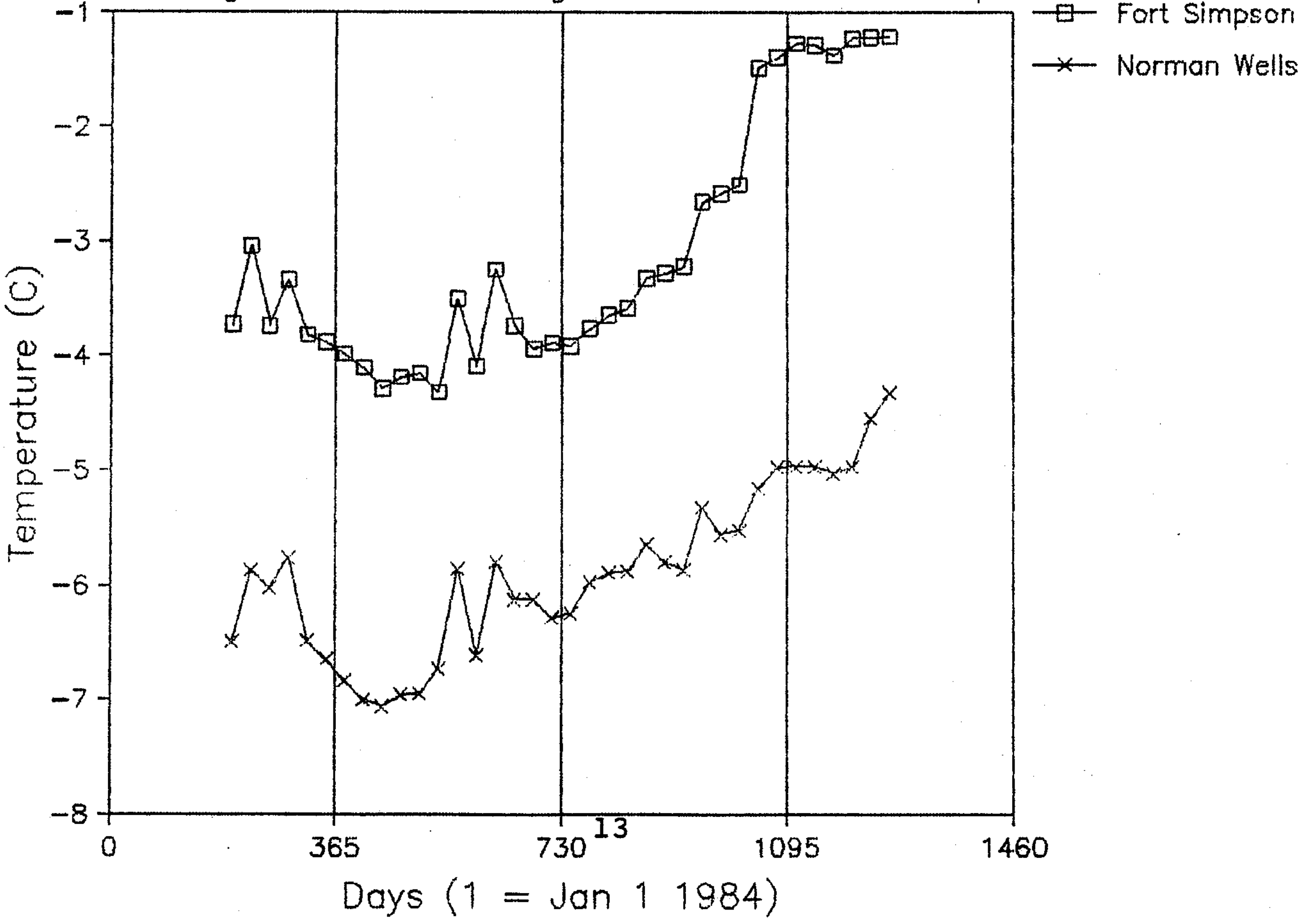


Figure 1.3b: Running mean annual air temperature



Norman Wells, and 2.5 at Fort Simpson.

Figure 1.3a shows that the warming in the mean annual air temperature is primarily due to warmer winter temperatures. As a result, the full effect of the warming trend in the air may not be transmitted to the ground surface, due to the buffering effect of the snow.

SECTION 2

METHODS OF ANALYSIS

2.1 Interpolation of ground and pipe temperature data.

Interpolation can be defined as mathematical curve fitting in order to obtain estimates between measured values. In the present case, estimated soil and pipe temperatures were obtained for intermediate times between temperature measurements. The results make it possible to estimate mean annual temperatures based on the interpolated curves. For the present analysis, interpolations between all pipe and ground temperature data (with time as the independent variable) were performed using a cubic spline interpolation routine supplied by the scientific authority.

Cubic spline interpolation uses the measured values to generate a series of third degree polynomial equations ("cubic" polynomial curves) which pass through the data points in succession. The polynomials are "splined" (i.e. they form a smooth curve) at each data point by ensuring that the first and second derivatives (i.e. the slope and rate of change of the slope) of adjoining curves are matched at each data point. Interpolated temperatures for particular dates are obtained using the equations generated.

Ground and pipe temperature data stored on the EMR CYBER computer were transferred to a micro-computer for subsequent analysis. The interpolation routine was incorporated into a program which:

- read the data in their original format;
- performed the spline interpolation for all sensors on each cable. Interpolated temperatures were obtained at intervals of 1 week over the complete measurement period (more than two years for many sites);
- created a data file containing the original and interpolated temperatures in a format which could be used in a spreadsheet program for subsequent analysis and graphic presentation.

Table 2.1 gives 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.

The interpolation method used is not infallible, since it is sensitive to the rate of change of the dependent variable (temperature) relative to the measurement interval of the independent variable (time). An example of this sensitivity to the rate of change of the dependent variable can be seen in Figure 3.3~~6~~ 3.37, where the transition from rapidly changing temperatures in summer to more slowly changing temperatures in winter causes the winter interpolations to oscillate somewhat about the measured values.

Most of the unsatisfacory interpolations were for the shallowest depths (2 m and less). This suggests that the current

Table 2.1

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	22-05085	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

Table 2.1 (continued)

Sites with Gaps Between Measurements
Exceeding 60 Days.

Site	Cable	Gaps		Duration (Days)
		From	To	
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
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
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
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

measurement program does not always provide sufficient information about the shape of the temperature curve at these depths for accurate temperature estimates using this interpolation method. Paradoxically however, some of the interpolations for these depths were improved significantly by eliminating data where measurements were less than one week apart. In these cases, small variations (possibly due to small errors, or to small diurnal variations) between the two closely spaced measurements were magnified in the intervals on either side. While these oscillations are a problem for some interpolated temperature curves, their impact on the running mean curves is minor, since the overall trend of the oscillations does not deviate significantly from the actual temperature trend.

In general, ground temperatures below 6 meters change so little between measurements that a sophisticated interpolation procedure is probably not nessesary. None the less, cubic spline interpolations were performed for these depths.

2.2 Running mean annual temperature estimates

In the present study, the mean annual temperature is of vital importance, since any change upward indicates the potential vulnerability of the permafrost sites to future thaw. By eliminating the annual temperature cycle from the data, the underlying trend can be revealed.

Running means are commonly used to eliminate short term fluctuations from long term trends. If the long term trend includes cyclical variations, then the choice of an averaging period equal to the period of the cycle will eliminate the cycle from the trend of the mean.

Running mean annual temperatures were calculated from the weekly interpolated temperatures. For each sensor, the first mean annual temperature was obtained as the average of the first 52 weekly values: this mean was assigned to the midpoint of the first year of data (i.e. week 26). For each subsequent week, the mean annual temperature was re-calculated by dropping the first week's value and adding the next week's value to the year. This shows the week to week trend in the mean annual ground temperature. Obviously, at least one year's data are required: the running means commence 26 weeks after the first value (i.e. one half of the averaging period), and end 26 weeks before the last value.

2.4 Quasi-static analysis of thaw around the pipe

Estimated long term (30 year) depth of thaw due to the heat supplied by the pipe was estimated using Porkhayev's quasi-static method (Hwang 1977). Hwang (1977) compared results from this approximate approach (an exact analytical solution does not exist) to those obtained using a two dimensional finite element model. He found that thaw depth beneath the pipe was underestimated by the quasi-static method, by 4 to 18 percent in simulations of up to 12 years. This is sufficient for the present application, since precise information about field conditions are not available.

The model requires values for :

- surface temperature (constant for the duration);
- pipe temperature;
- initial ground temperature (initially uniform);
- pipe burial depth;
- pipe diameter;
- frozen and thawed ground thermal properties;
- latent heat of phase change for the soil.

A discussion of the limitations of this model of long term thaw prediction is given with results in section 5.3.

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.

Depending upon the type of surface temperature regime, the time steps for calculation vary from 6 hours to 4 days; time is incremented in steps of 1 day in most applications.

SECTION 3

PIPE - SOIL INTERACTION

3.1 Comparison of ground and pipe temperatures

At the suggestion of the scientific authority, the fence thermistor cables designated as T3 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.

Interpolated pipe and 1 meter ground temperatures (in the T3 cables on the-right-of-way), and running mean pipe and 1 meter ground temperatures for all sites are presented in Figures 3.1 through 3.46. Ground temperatures and running means for the sensor at 1 meter in the T4 cables (off the pipeline right-of-way) are presented in the same figures. The relationship between pipe temperatures and R.O.W. ground temperatures is examined in this section. Comparison of ground temperatures on and off of the R.O.W. is presented in the next section of this report.

Tables 3.1-3.3 summarise the running mean data. The total period from April 1985 to October 1987 was divided into three intervals of 10 months duration (April 1985-February 1986, March 1986 - December 1986, and January 1987-October 1987), each period including a summer. The running means in each period were examined and characterised as showing either stable temperatures, a warming trend, a cooling trend, or a variable pattern of change. The tables also indicate whether mean pipe temperatures

Figure 3.1

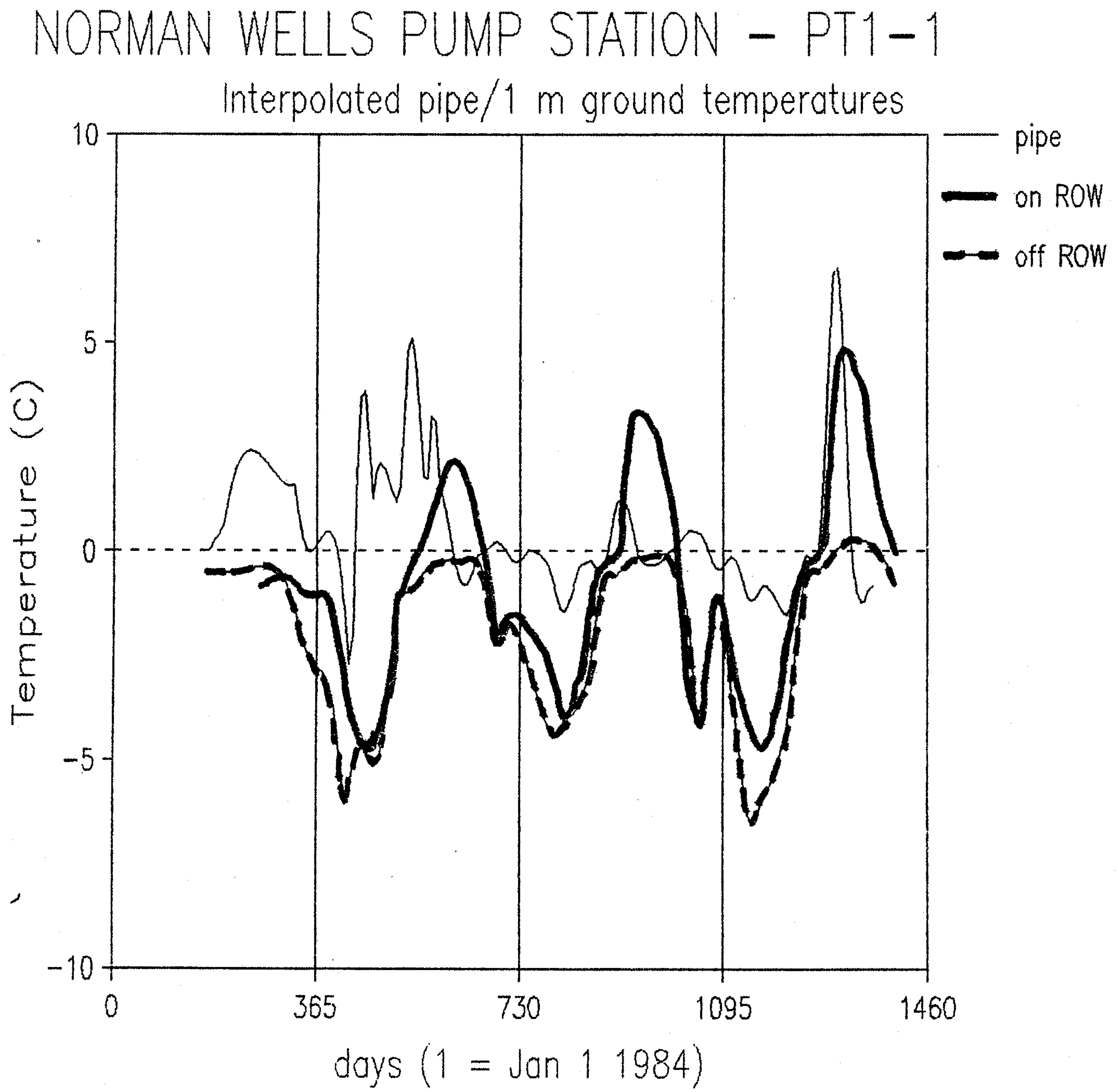

NORMAN WELLS PUMP STATION - PT1-1
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
10
5
0
-5
-10
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.2

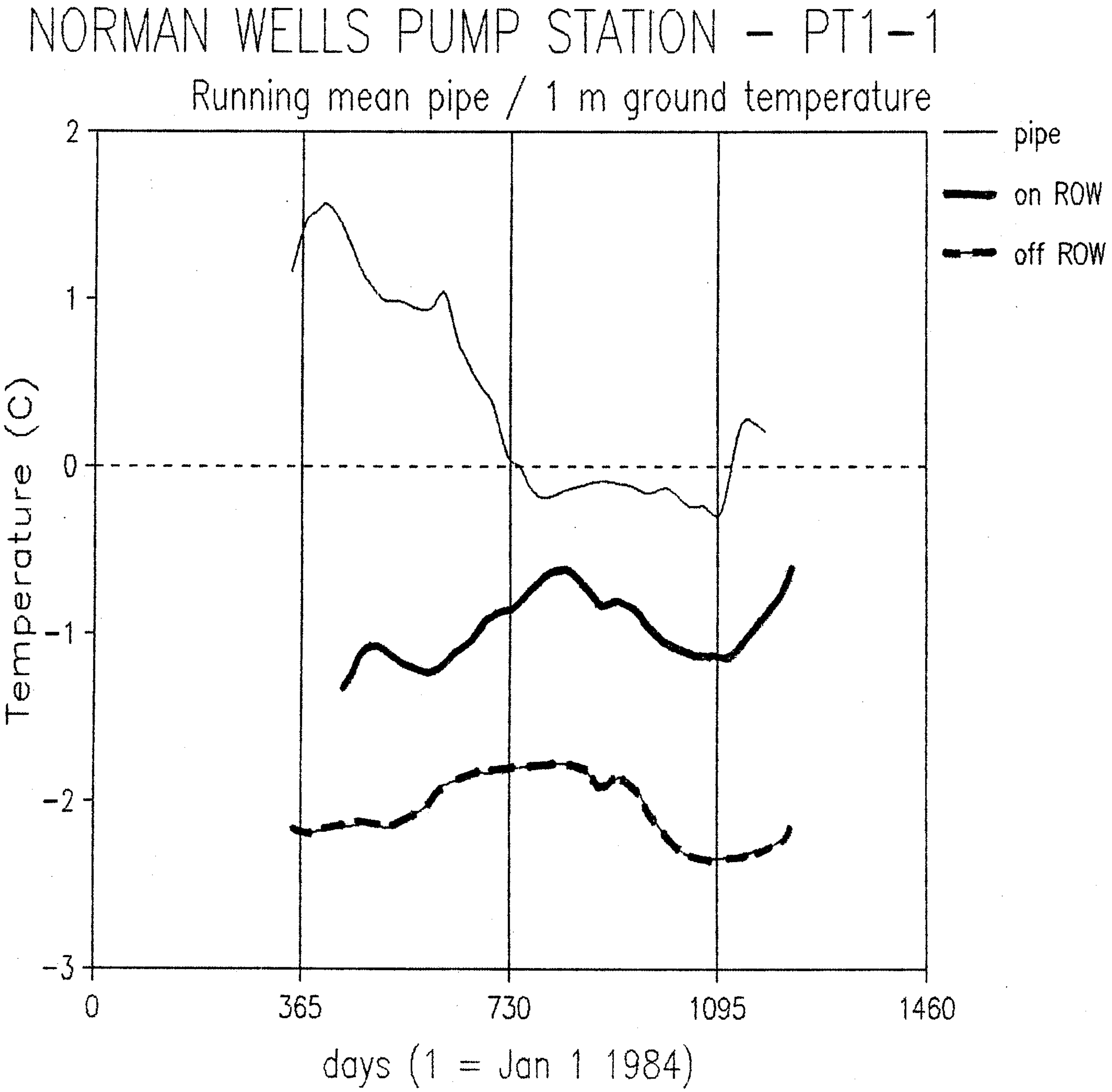

NORMAN WELLS PUMP STATION - PT1-1
Running mean pipe / 1 m ground temperature
Temperature (C)
2
1
0
-1
-2
-3
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.3

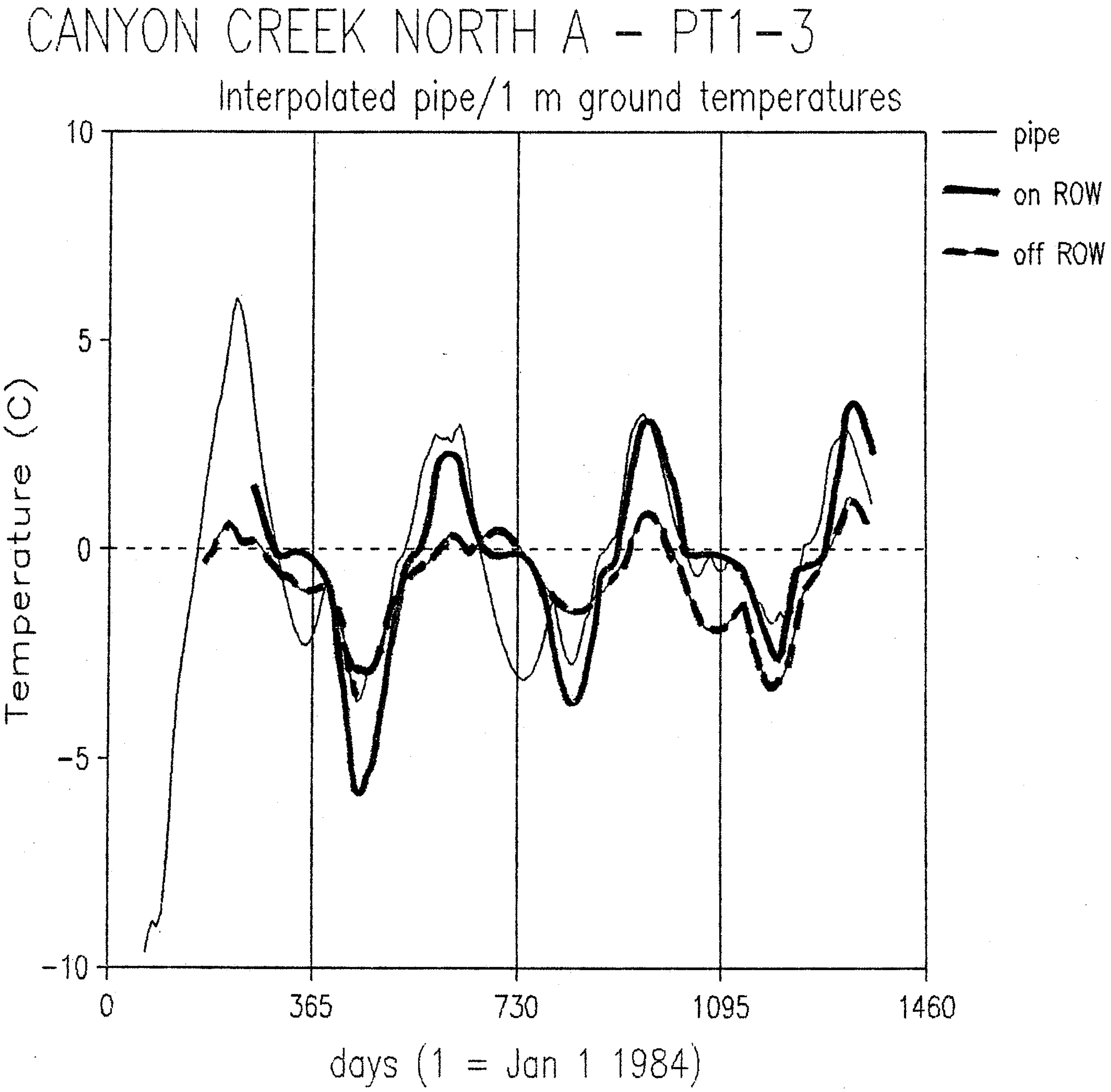
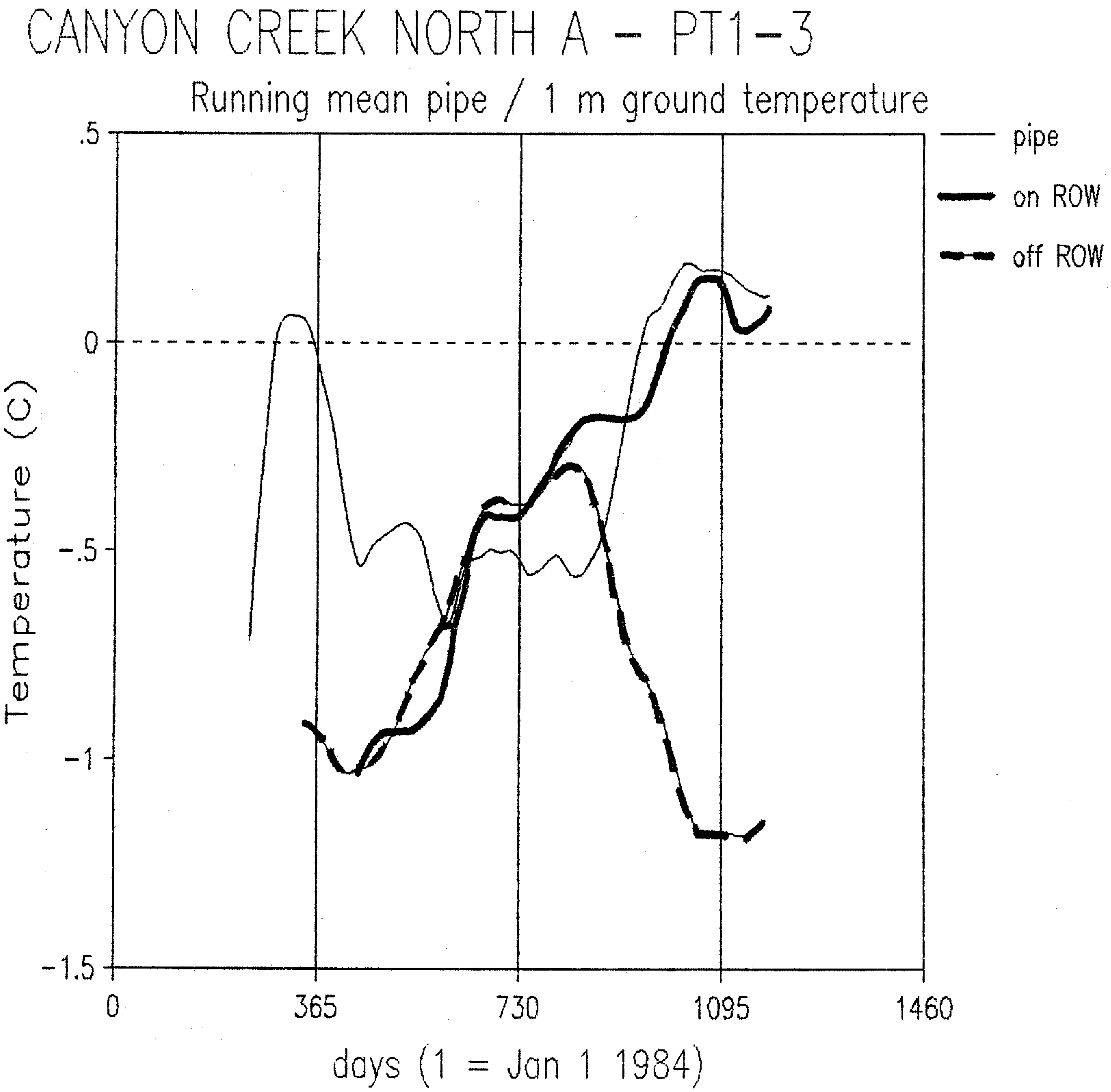

CANYON CREEK NORTH A - PT1-3
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
10
5
0
-5
-10
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.4



CANYON CREEK NORTH A - PT1-3
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
.5
0
-.5
-1
-1.5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.5

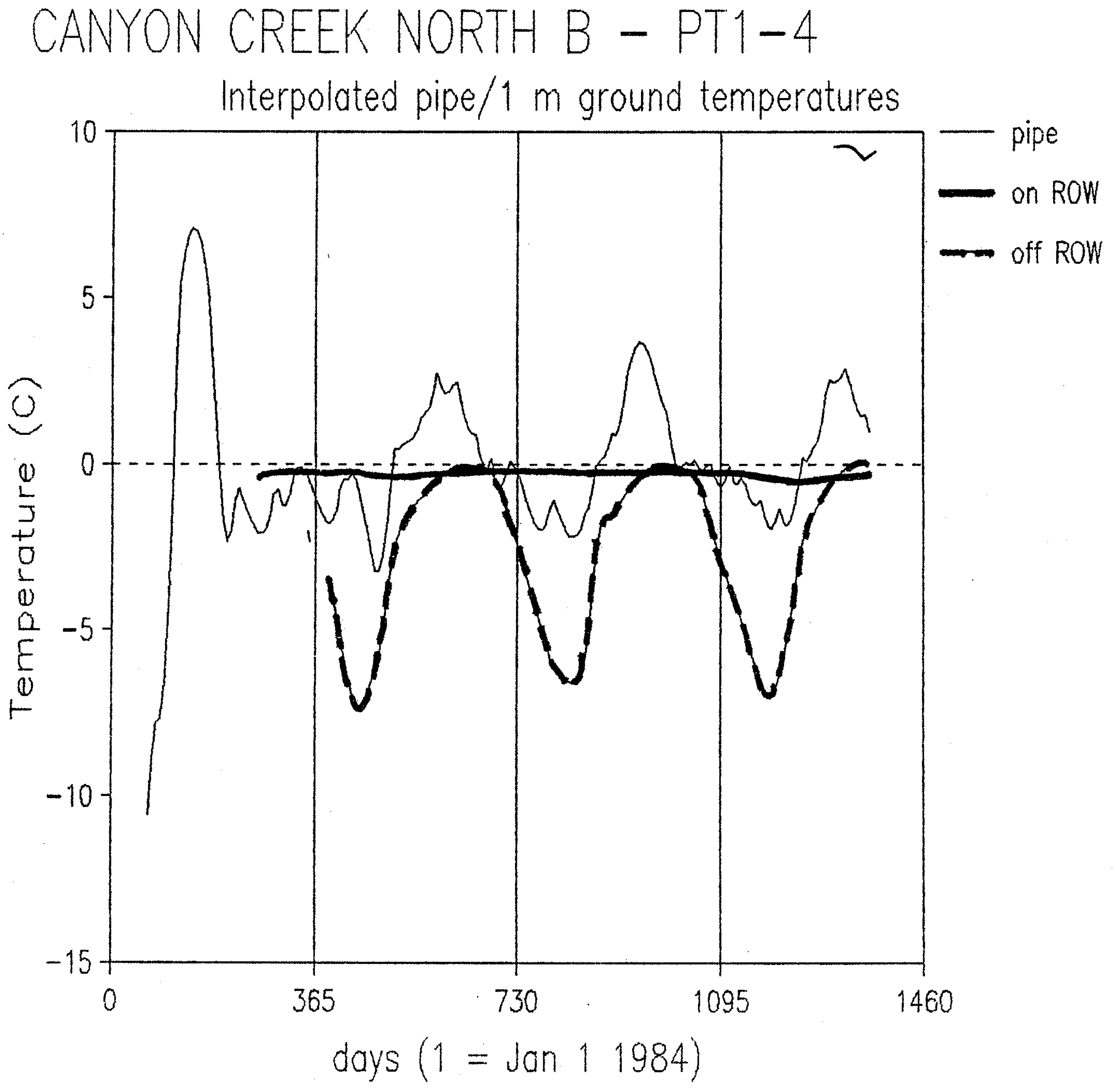

CANYON CREEK NORTH B - PT1-4
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
10
5
0
-5
-10
-15
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.6

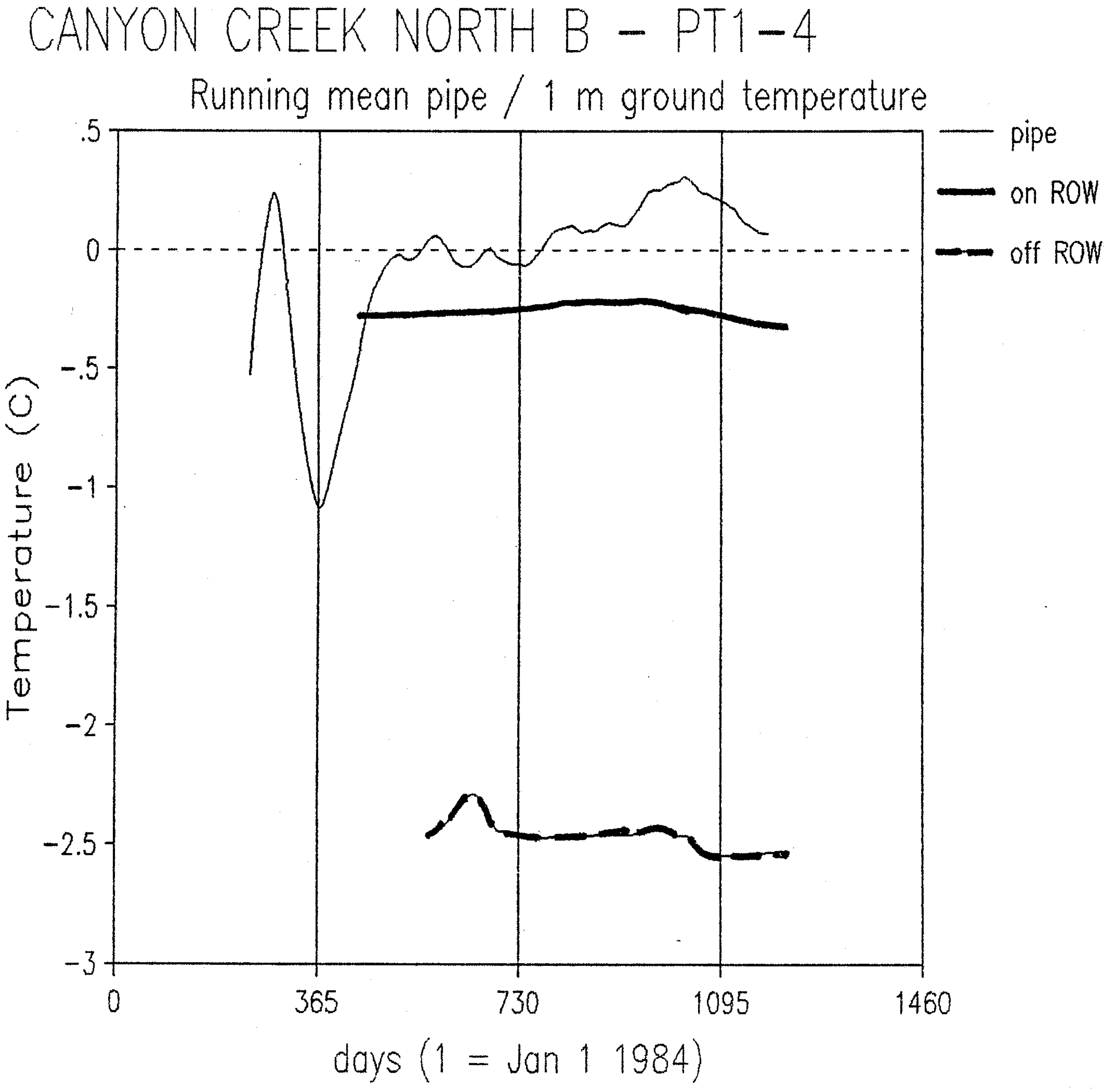

CANYON CREEK NORTH B – PT1–4
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
.5
0
-.5
-1
-1.5
-2
-2.5
-3
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.7

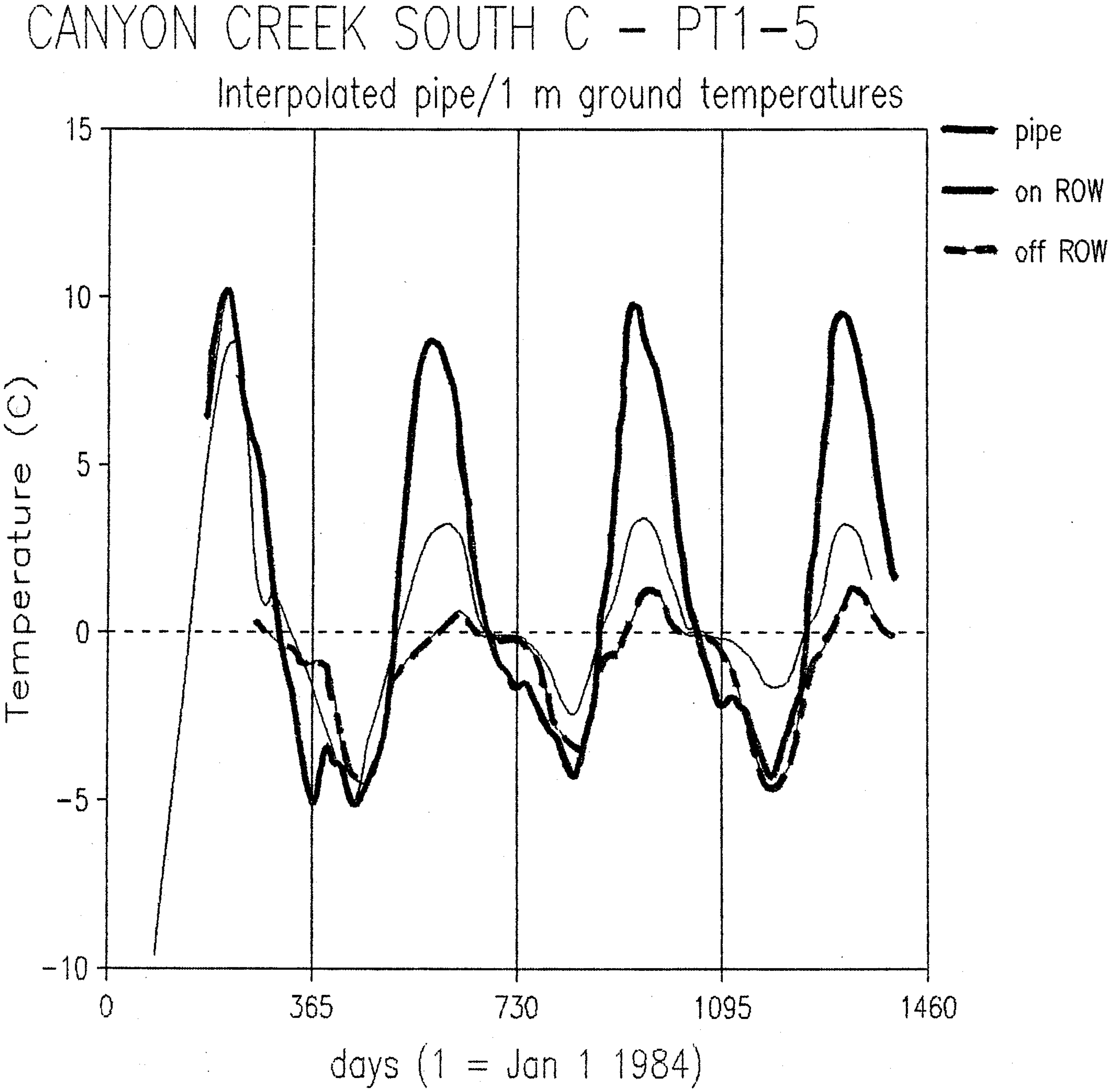

CANYON CREEK SOUTH C - PT1-5
Interpolated pipe/1 m ground temperatures
15
10
5
0
-5
-10
Temperature (C)
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.8

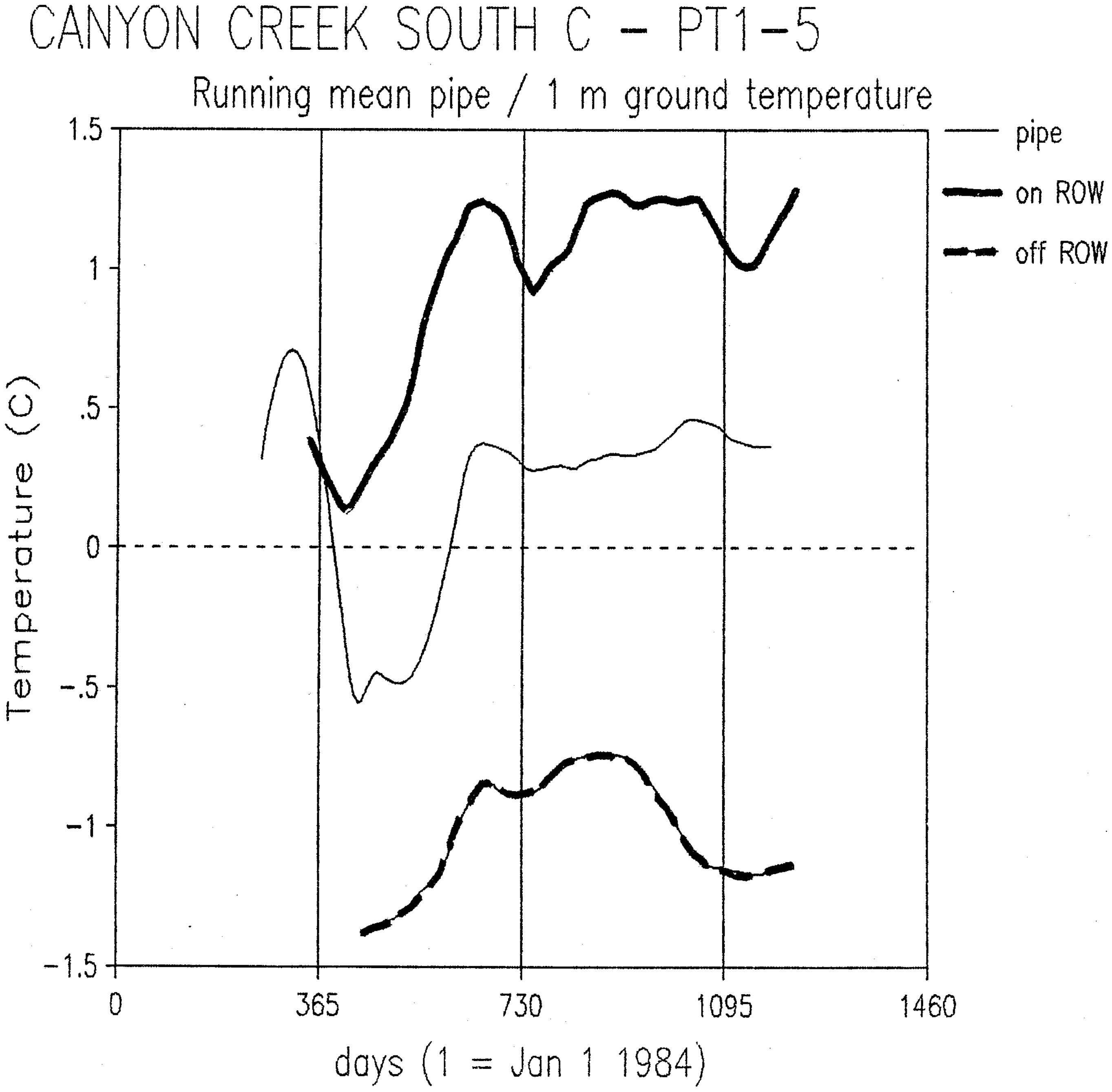

CANYON CREEK SOUTH C - PT1-5
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
1.5
1
.5
0
-.5
-1
-1.5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.9

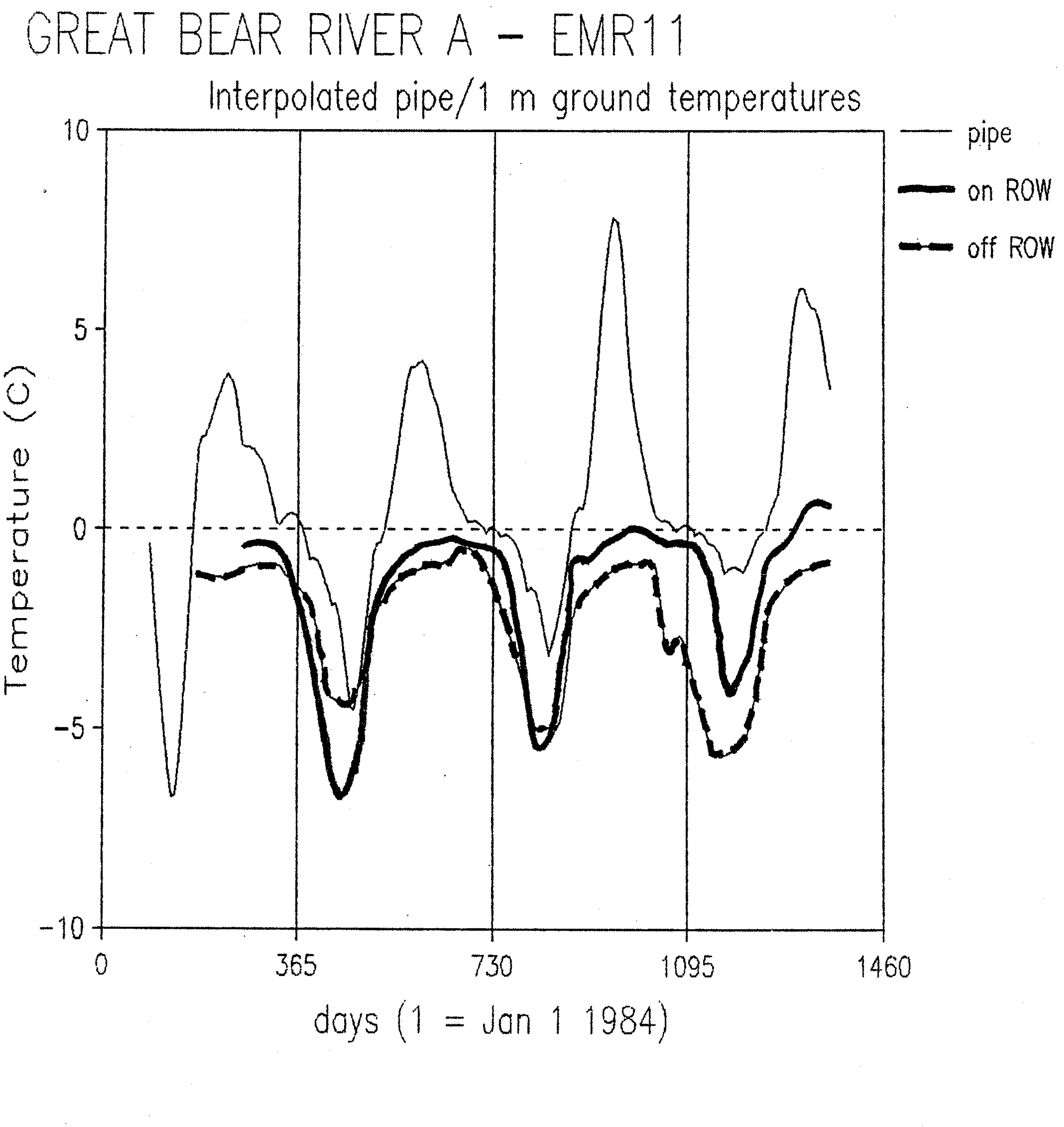

GREAT BEAR RIVER A - EMR11
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
10
5
0
-5
-10
Temperature (C)
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.10

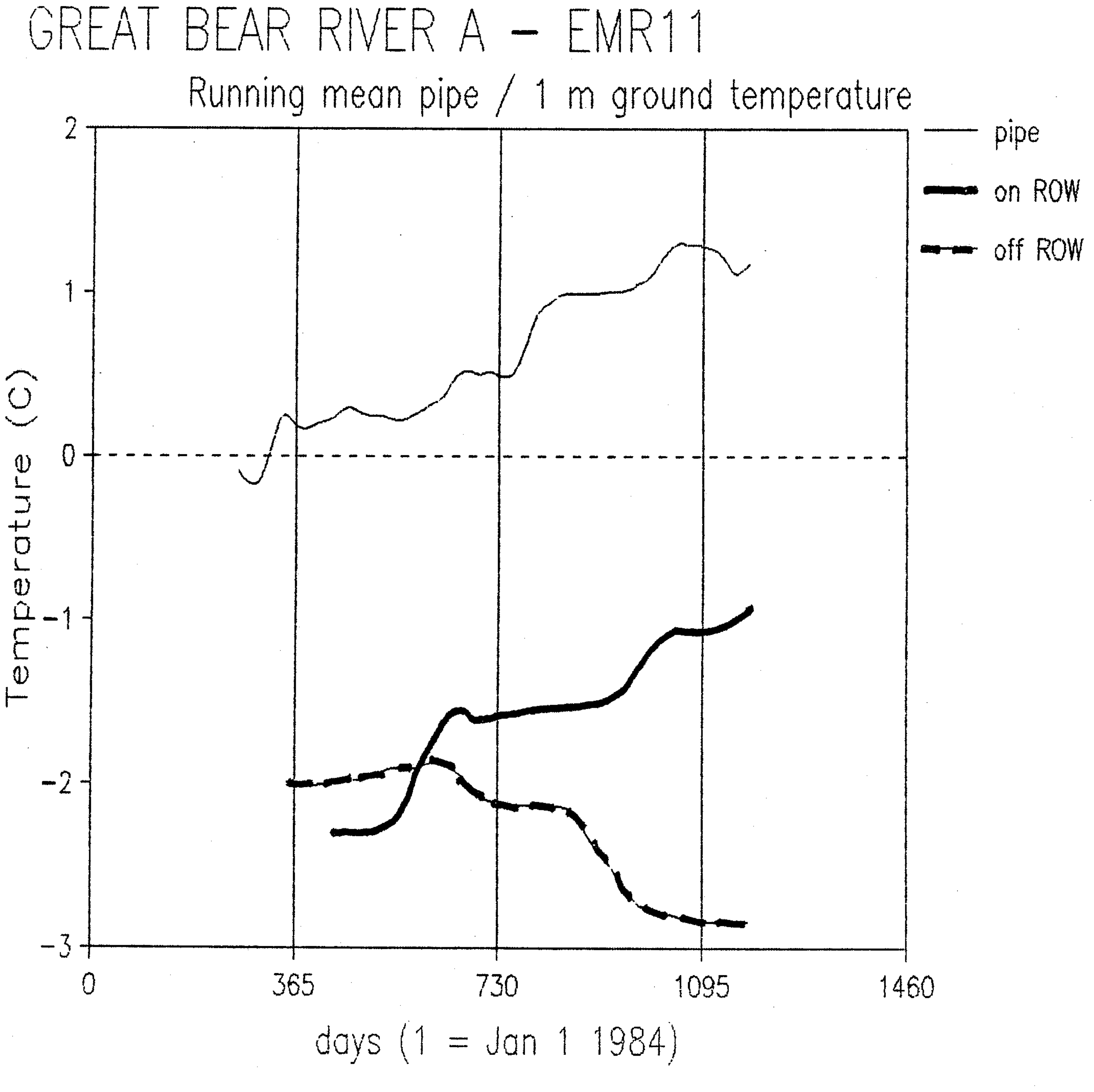

GREAT BEAR RIVER A – EMR11
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
2
1
0
-1
-2
-3
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.11

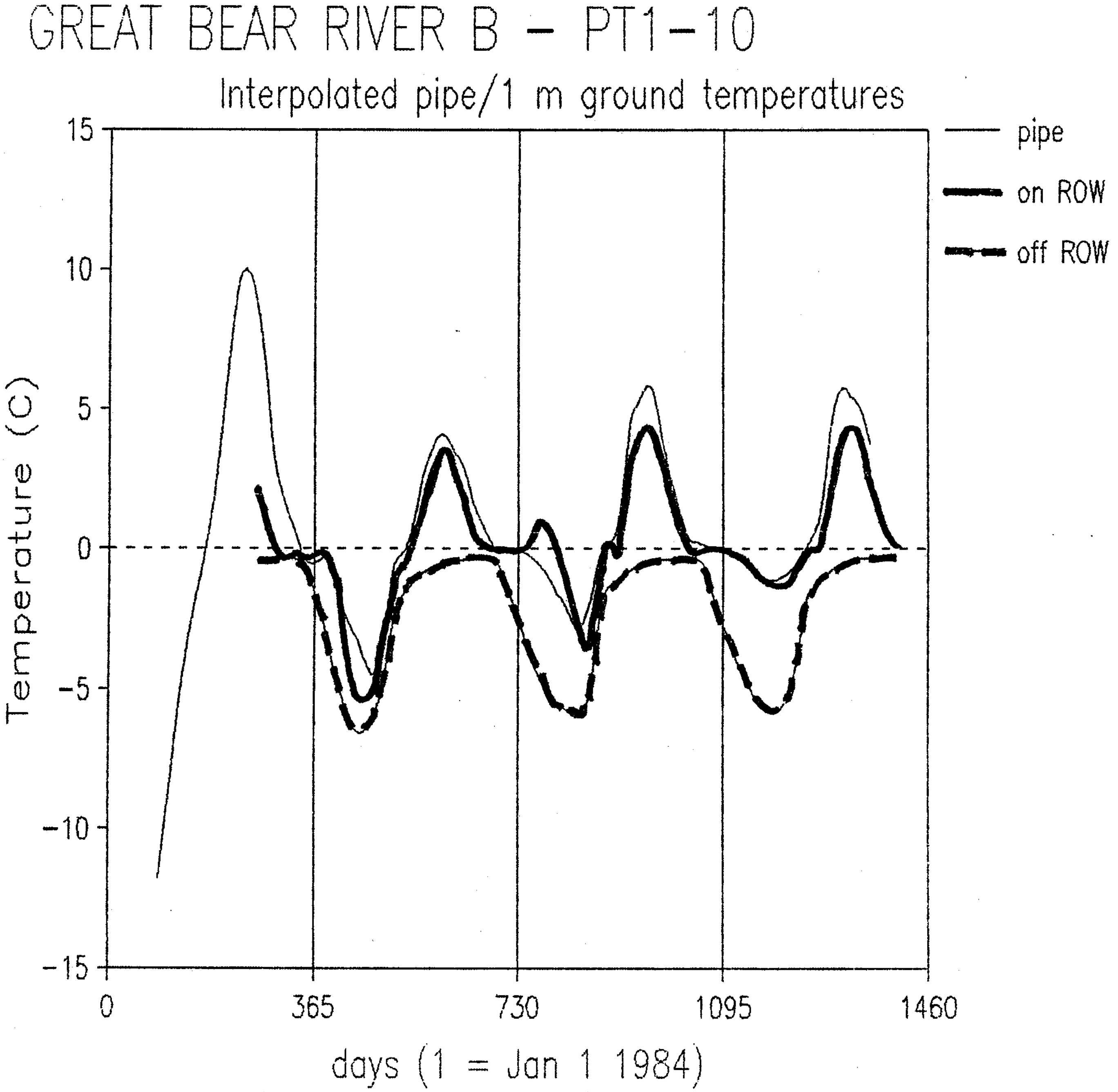
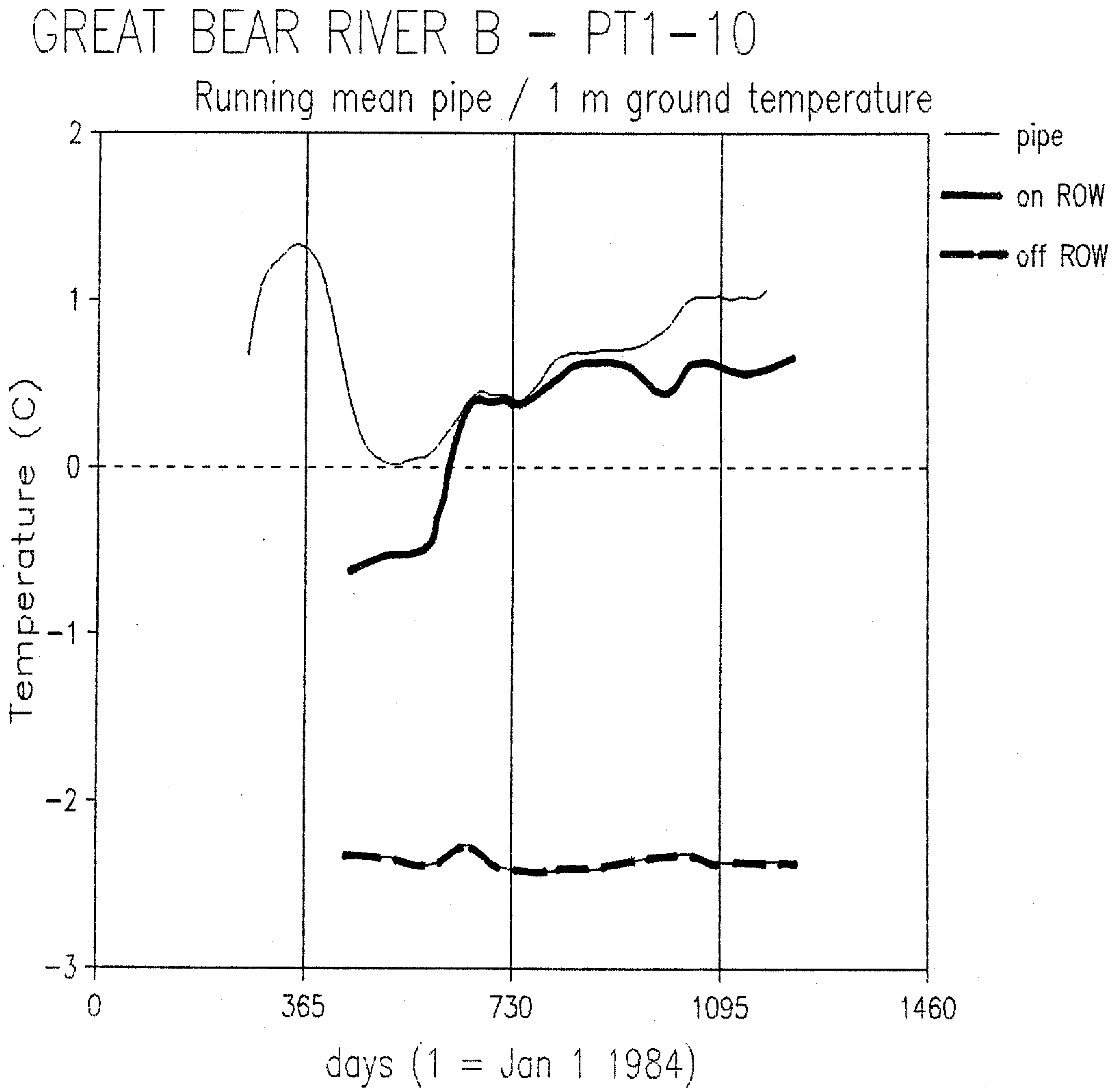

GREAT BEAR RIVER B - PT1-10
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
15
10
5
0
-5
-10
-15
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.12



GREAT BEAR RIVER B - PT1-10
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
2
1
0
-1
-2
-3
Temperature (C)
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.13

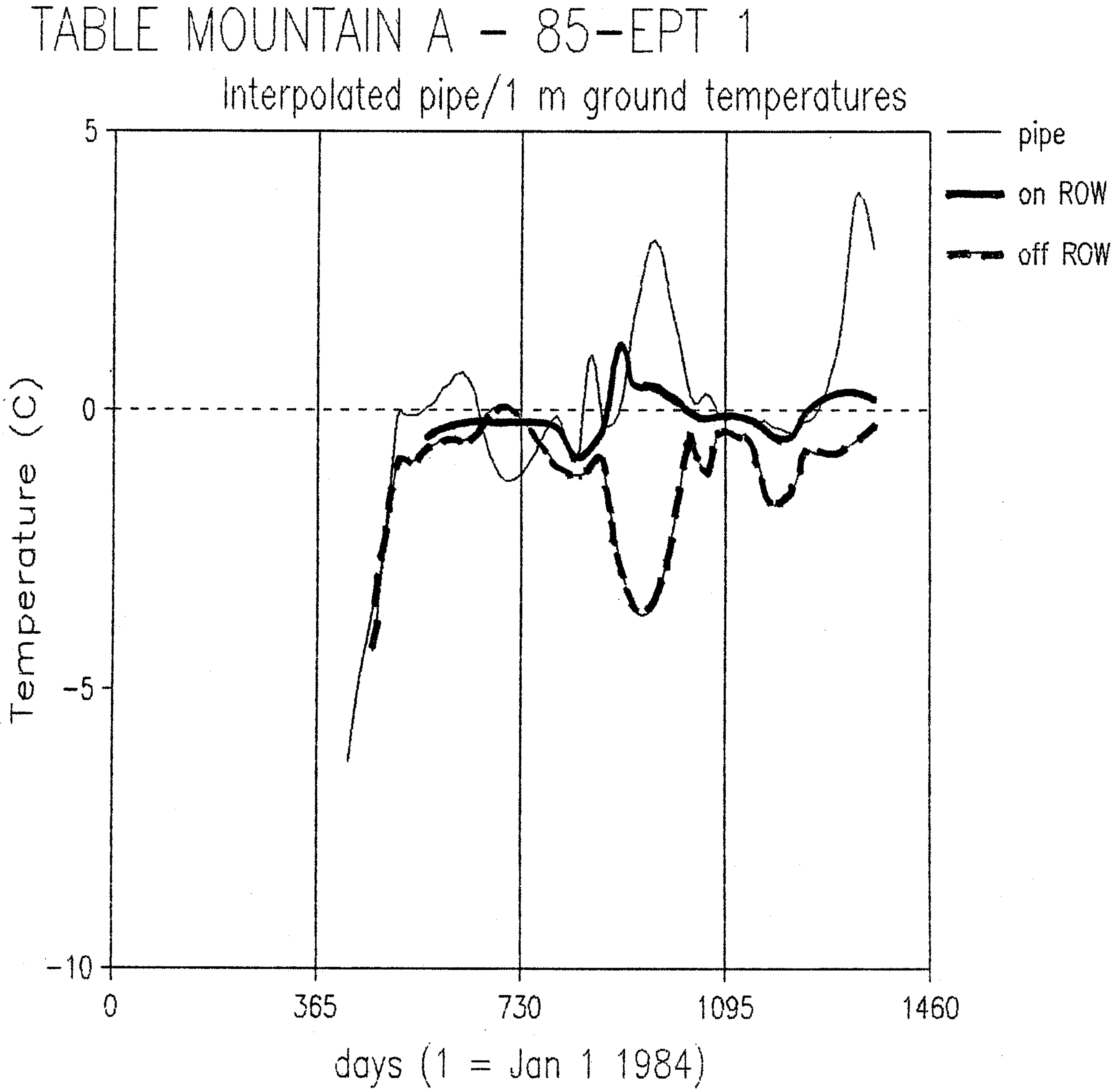


TABLE MOUNTAIN A – 85–EPT 1
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
5
0
-5
-10
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.14

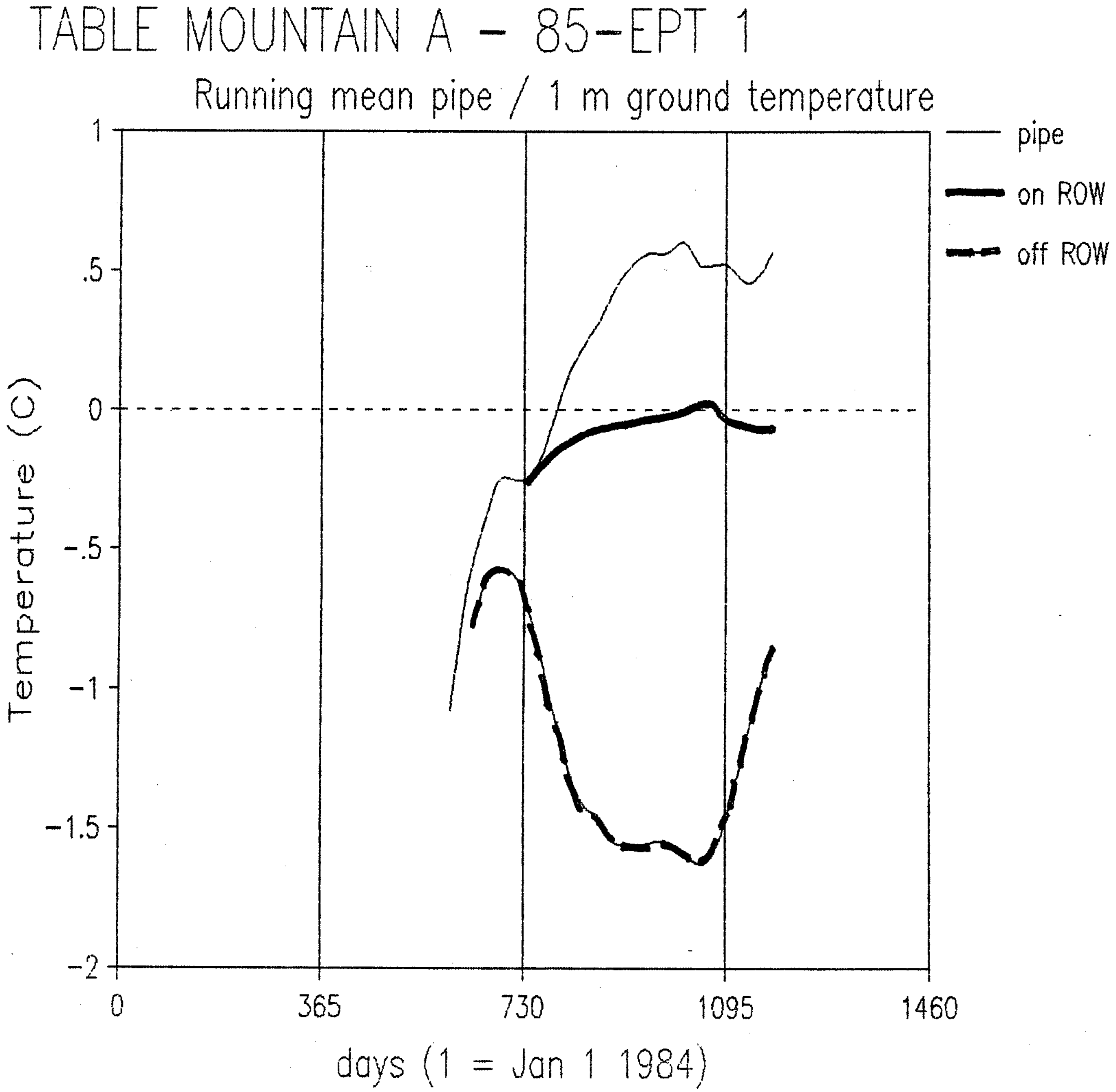


TABLE MOUNTAIN A - 85-EPT 1
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
1
.5
0
-.5
-1
-1.5
-2
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.15

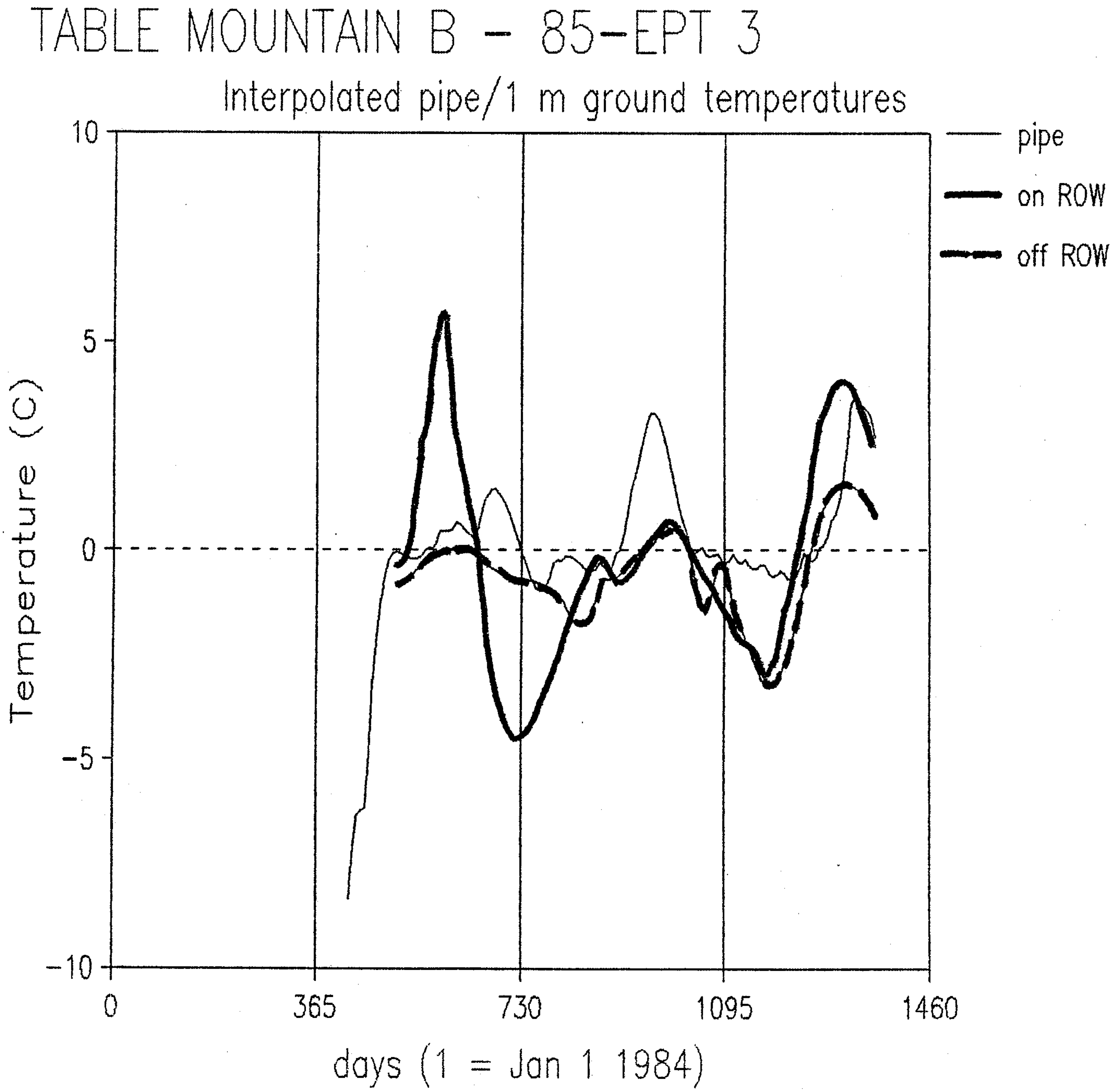


TABLE MOUNTAIN B - 85-EPT 3
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
10
5
0
-5
-10
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.16

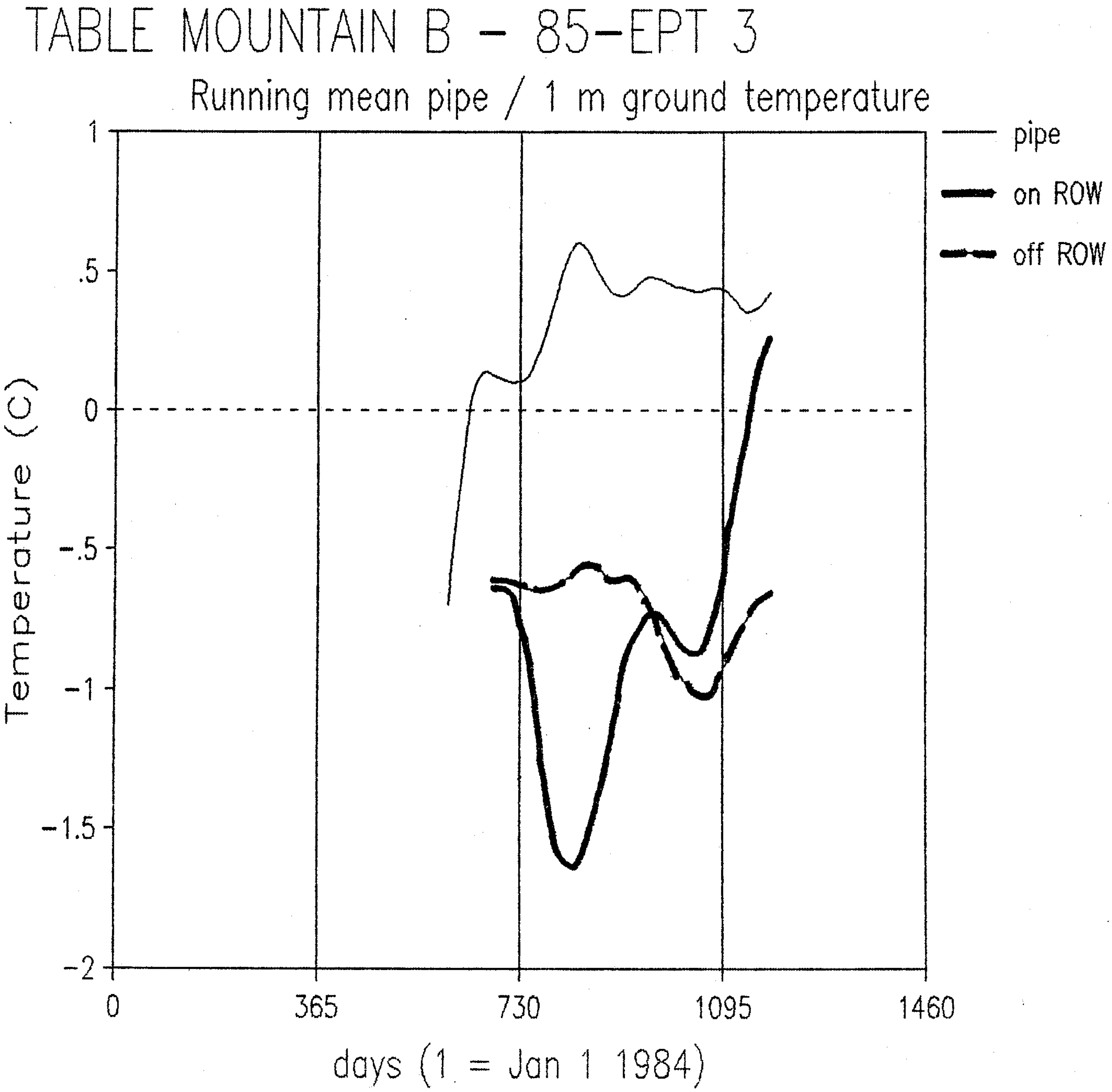


TABLE MOUNTAIN B - 85-EPT 3
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
1
.5
0
-.5
-1
-1.5
-2
Temperature (C)
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.17

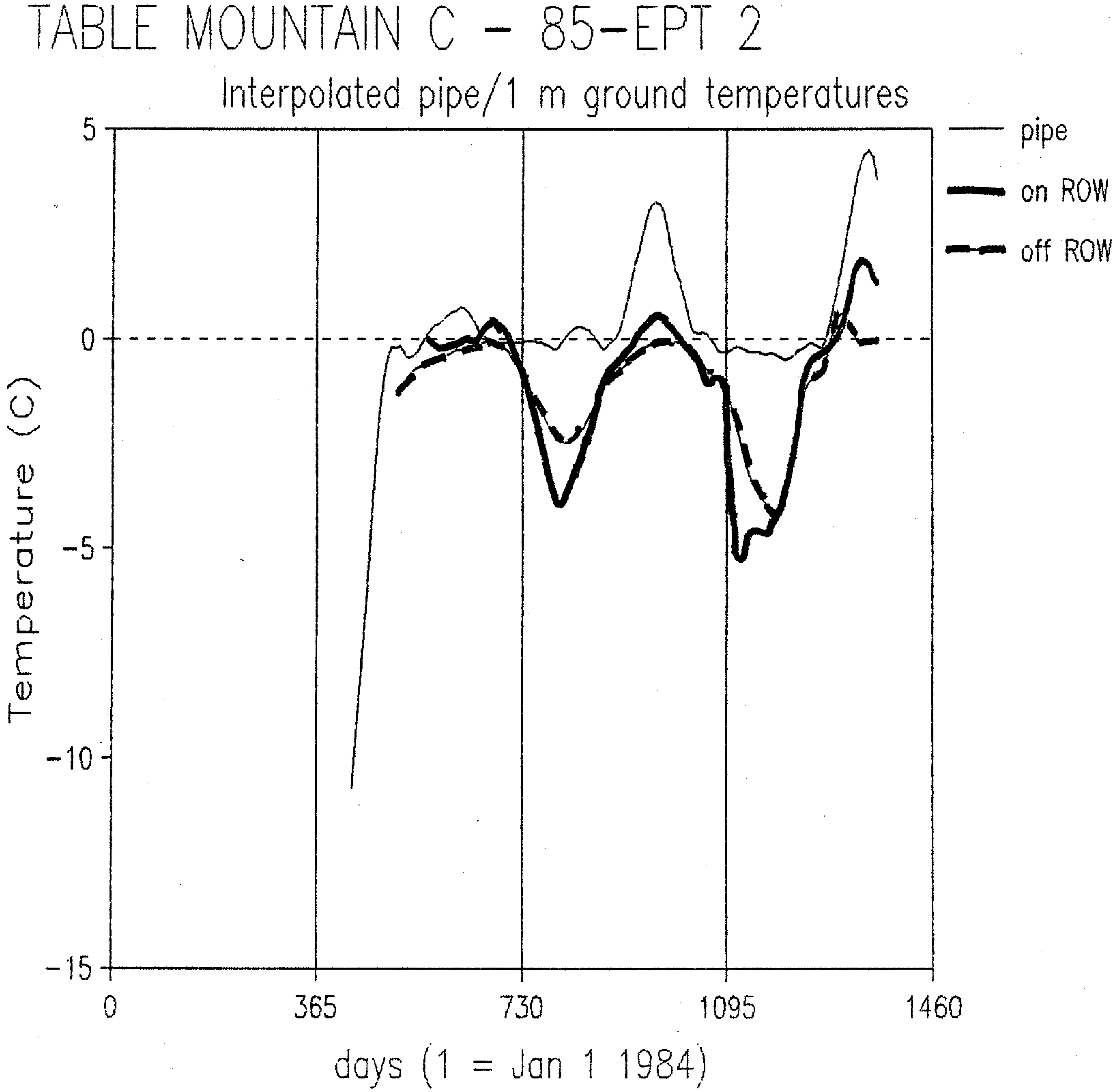


TABLE MOUNTAIN C - 85-EPT 2
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
5
0
-5
-10
-15
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.18

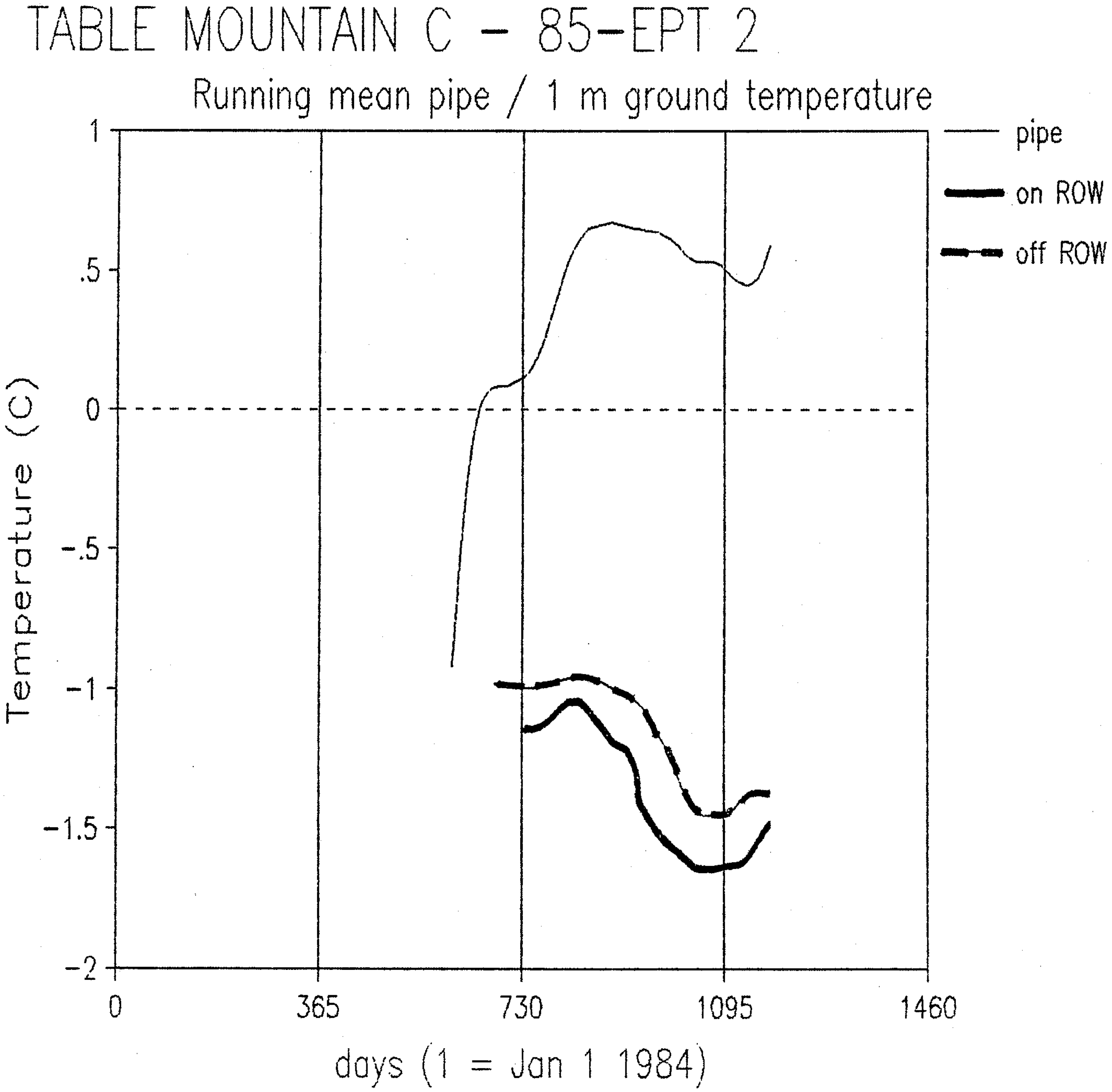


TABLE MOUNTAIN C - 85-EPT 2
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
1
.5
0
-.5
-1
-1.5
-2
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.19

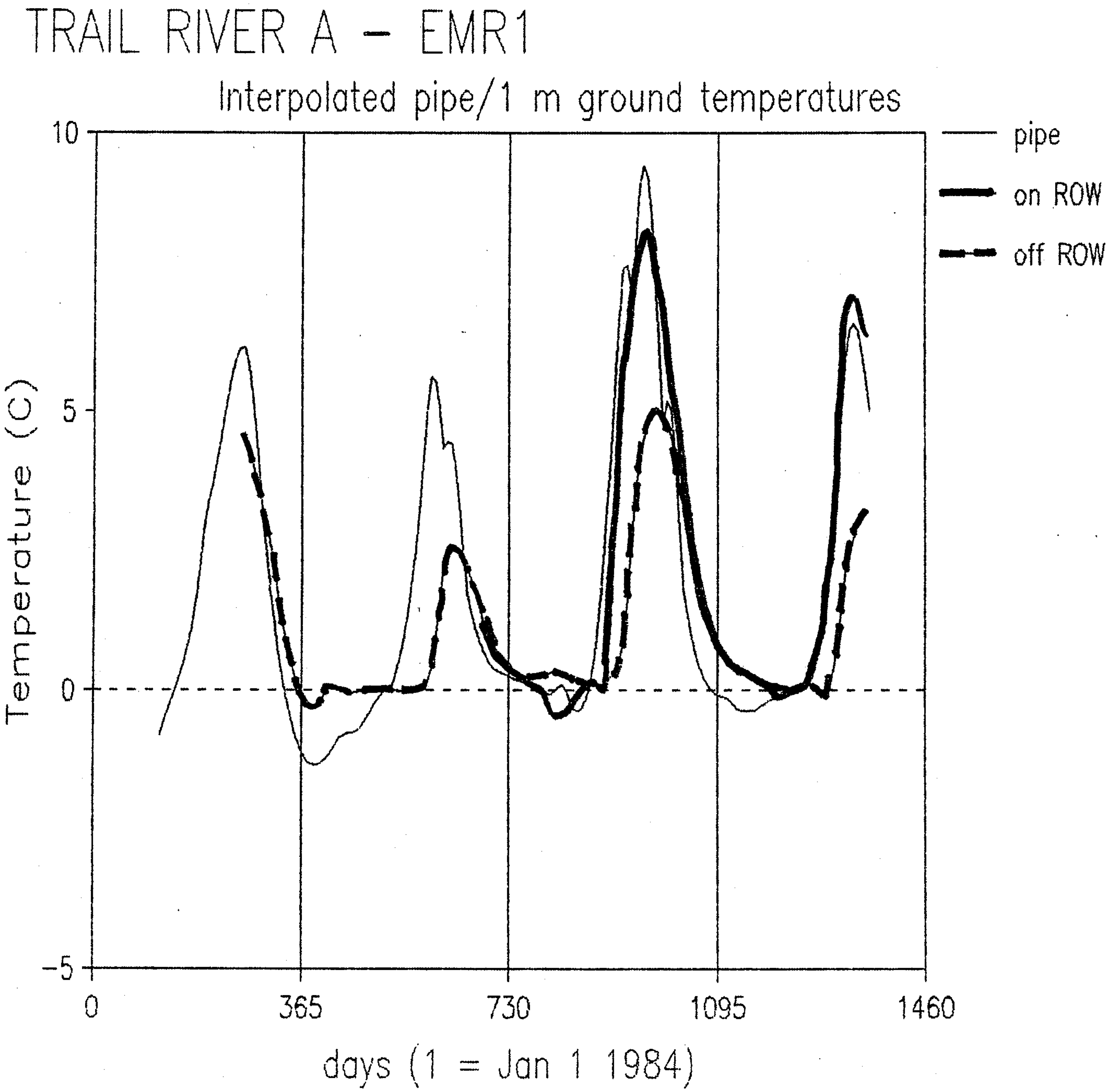

TRAIL RIVER A - EMR1
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
10
5
0
-5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.20

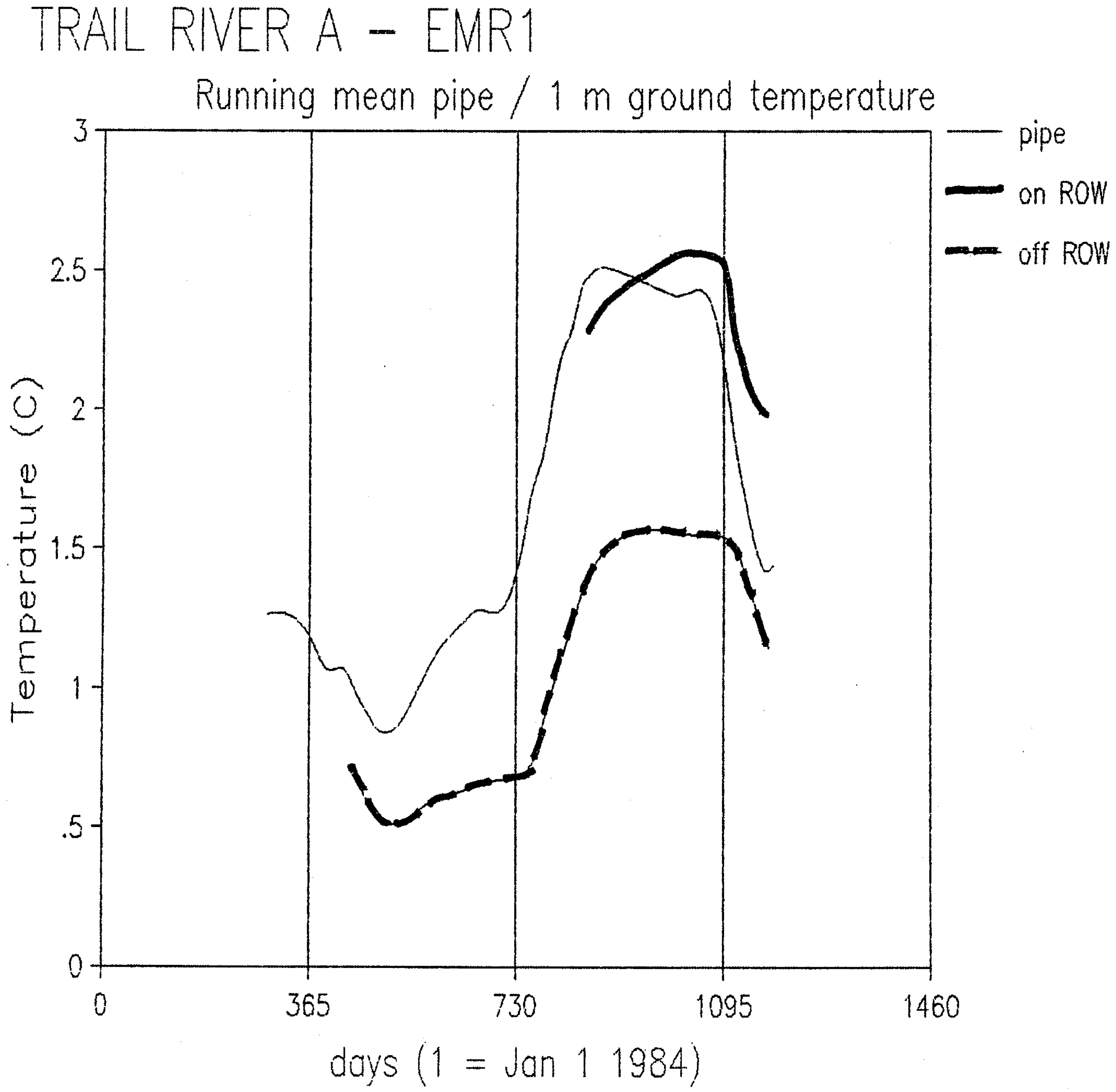

TRAIL RIVER A - EMR1
Running mean pipe / 1 m ground temperature
Temperature (C)
3
2.5
2
1.5
1
.5
0
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.21

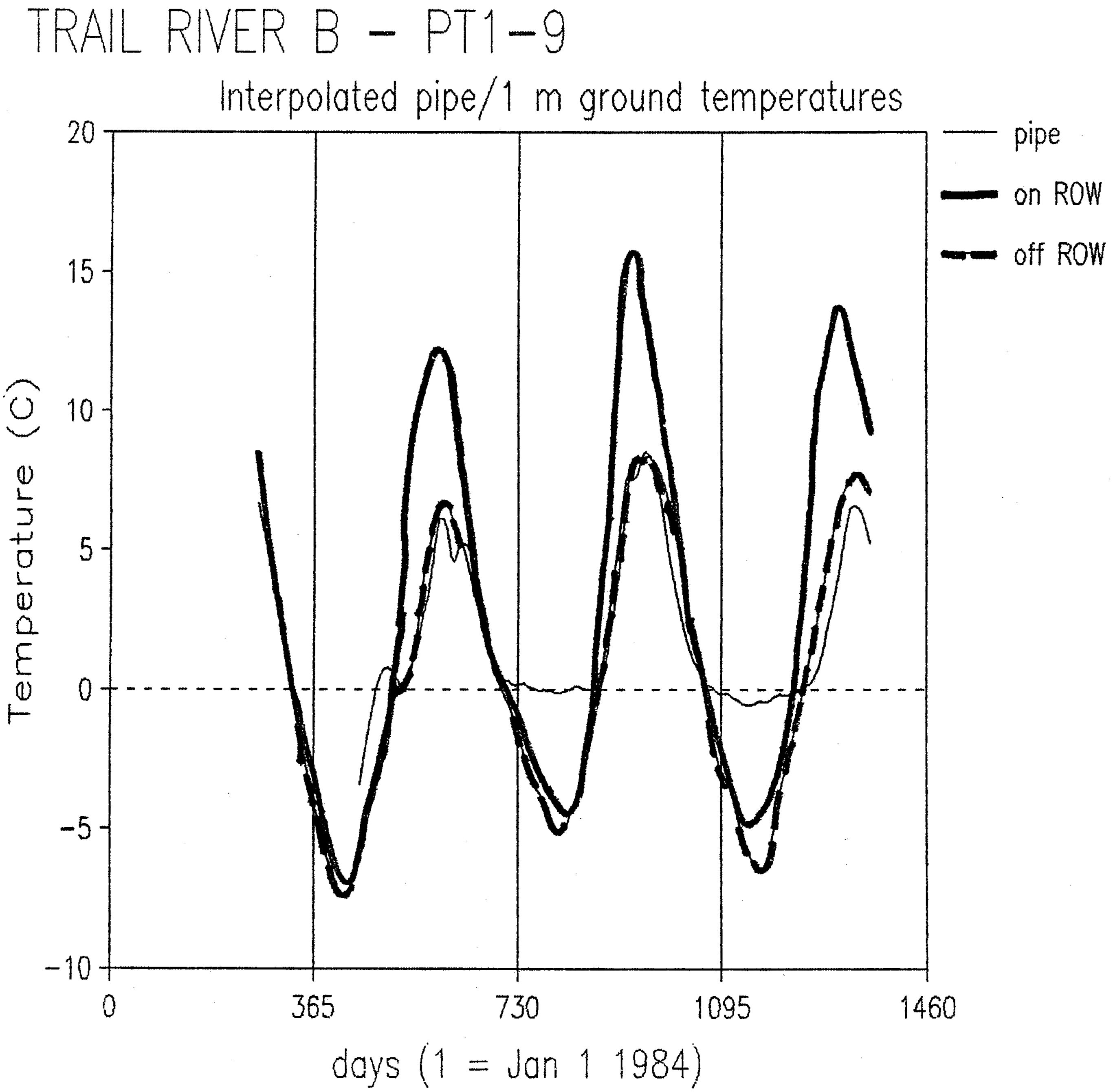

TRAIL RIVER B - PT1-9
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
20
15
10
5
0
-5
-10
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.22

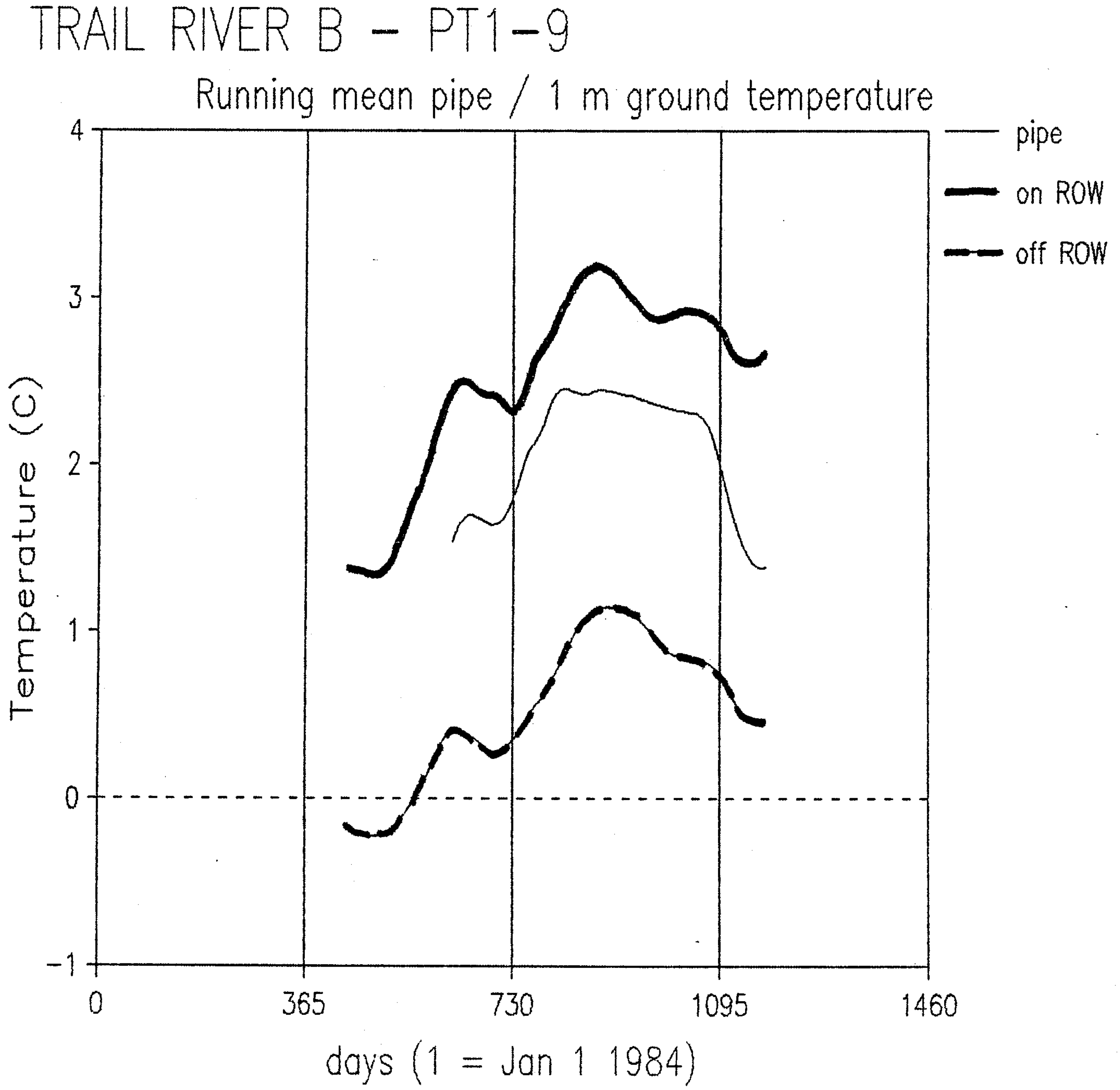
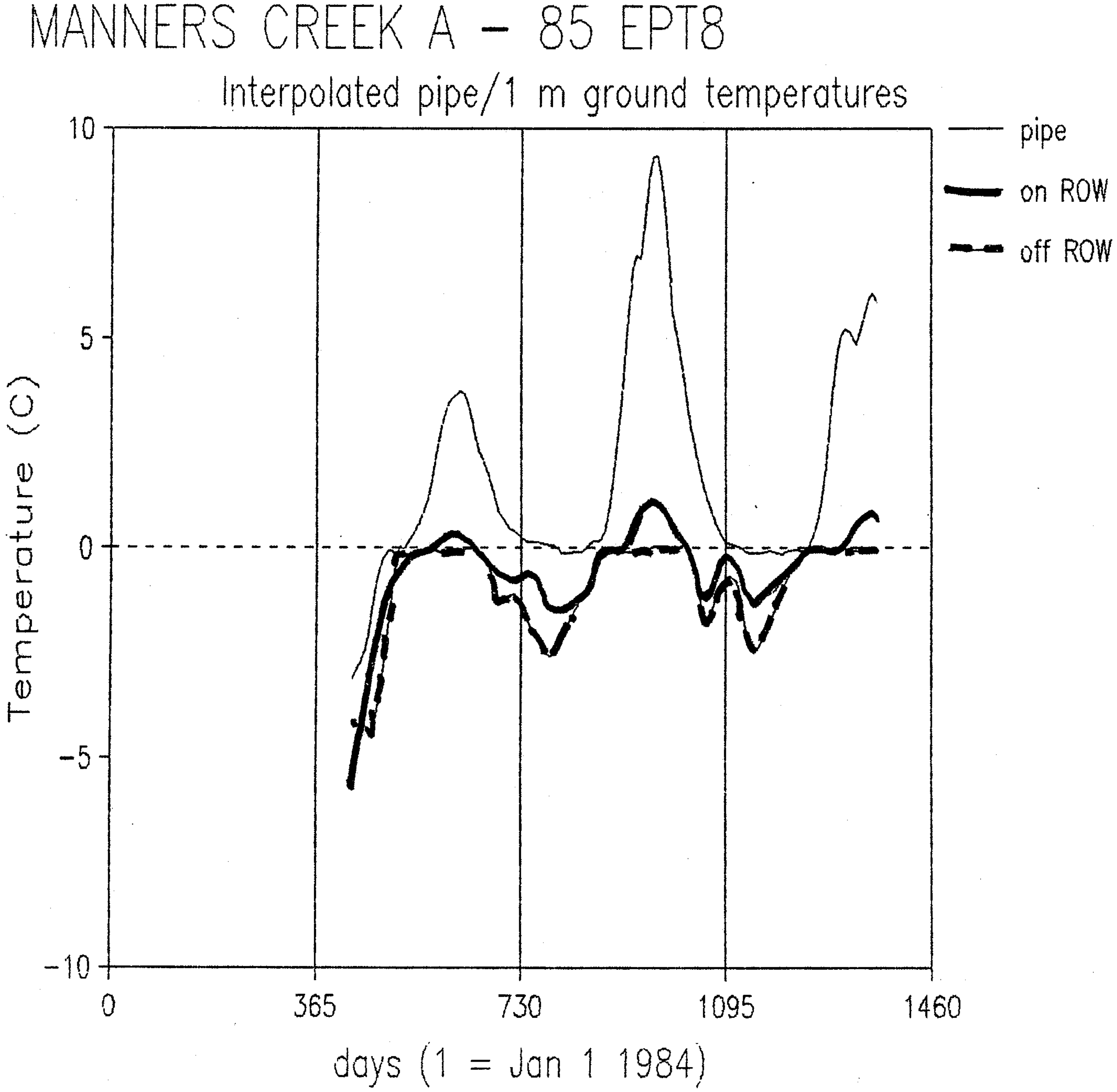

TRAIL RIVER B - PT1-9
Running mean pipe / 1 m ground temperature
Temperature (C)
4
3
2
1
0
-1
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.23



MANNERS CREEK A - 85 EPT8
Interpolated pipe/1 m ground temperatures
10
5
0
-5
-10
Temperature (C)
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.24

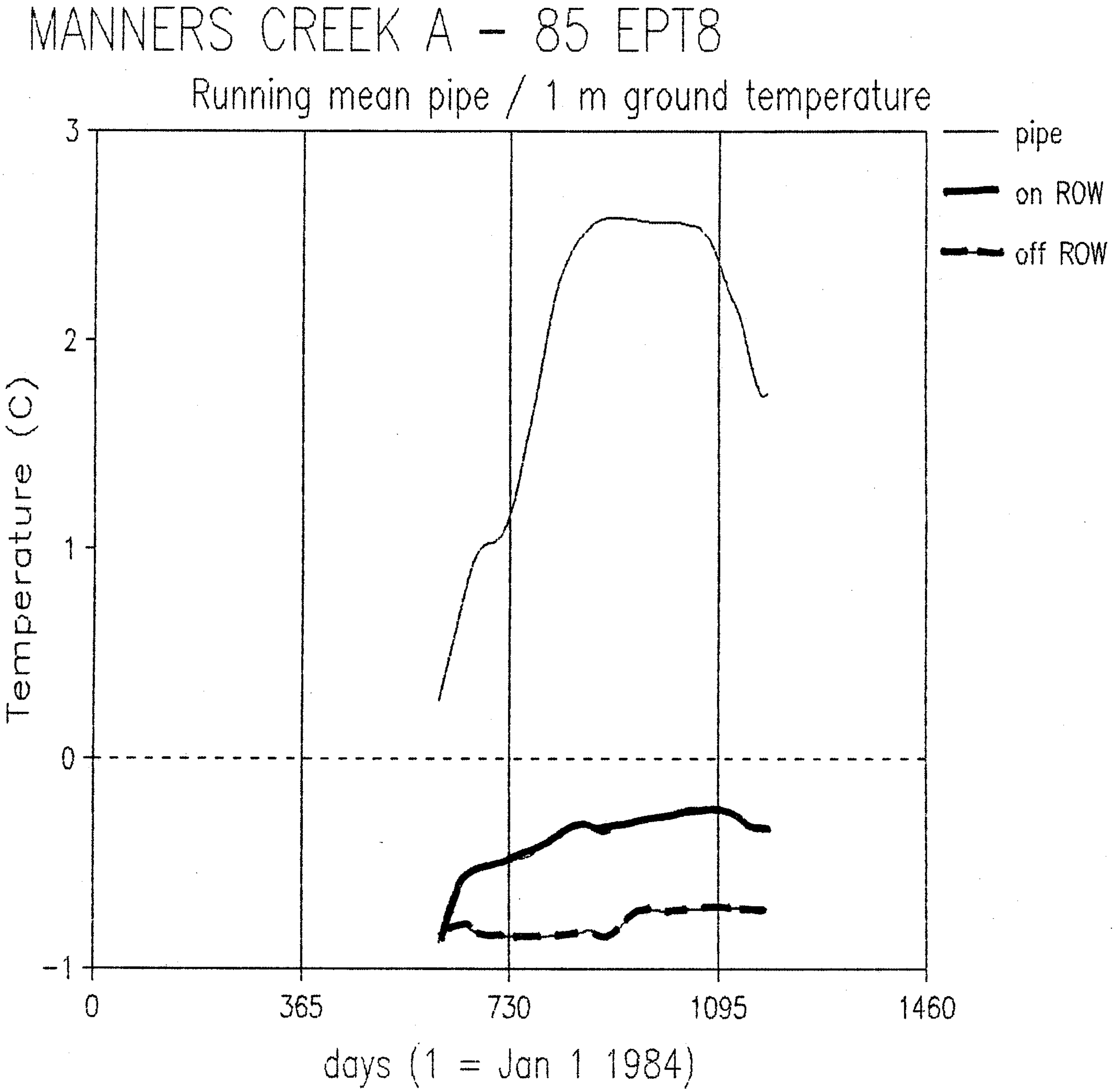

MANNERS CREEK A - 85 EPT8
Running mean pipe / 1 m ground temperature
Temperature (C)
3
2
1
0
-1
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.25

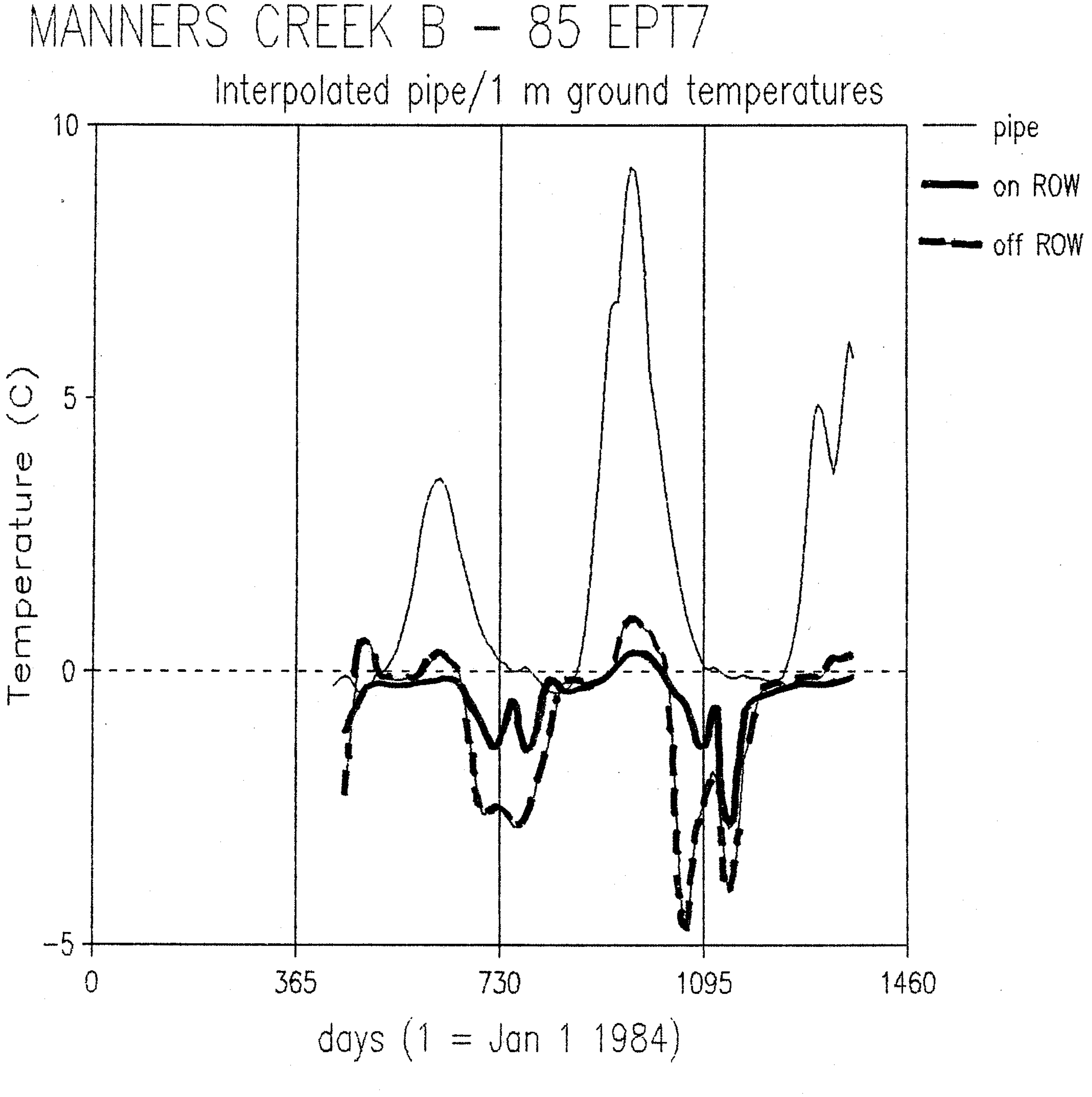

MANNERS CREEK B - 85 EPT7
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
10
5
0
-5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.26

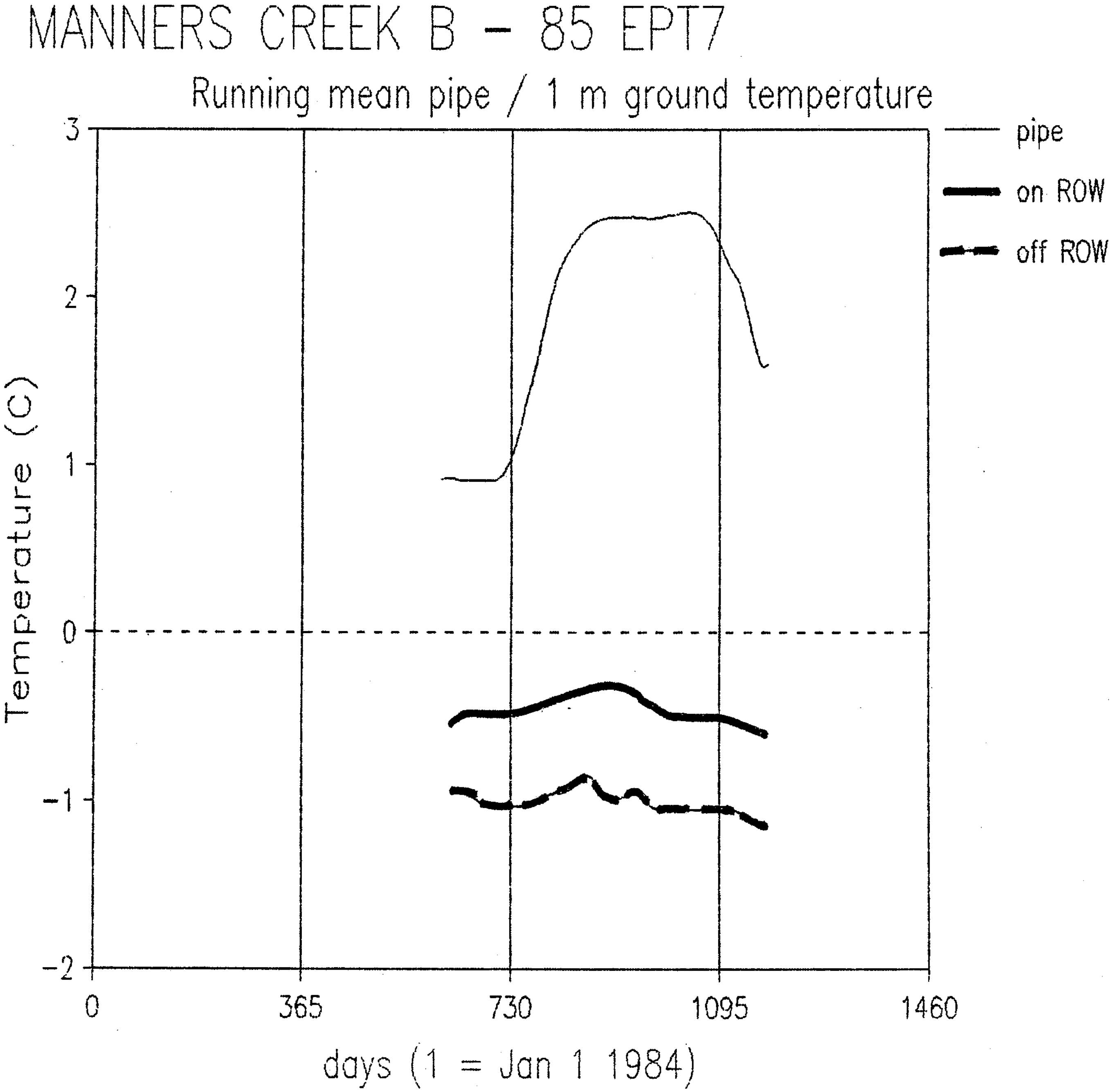

MANNERS CREEK B - 85 EPT7
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
3
2
1
0
-1
-2
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.27

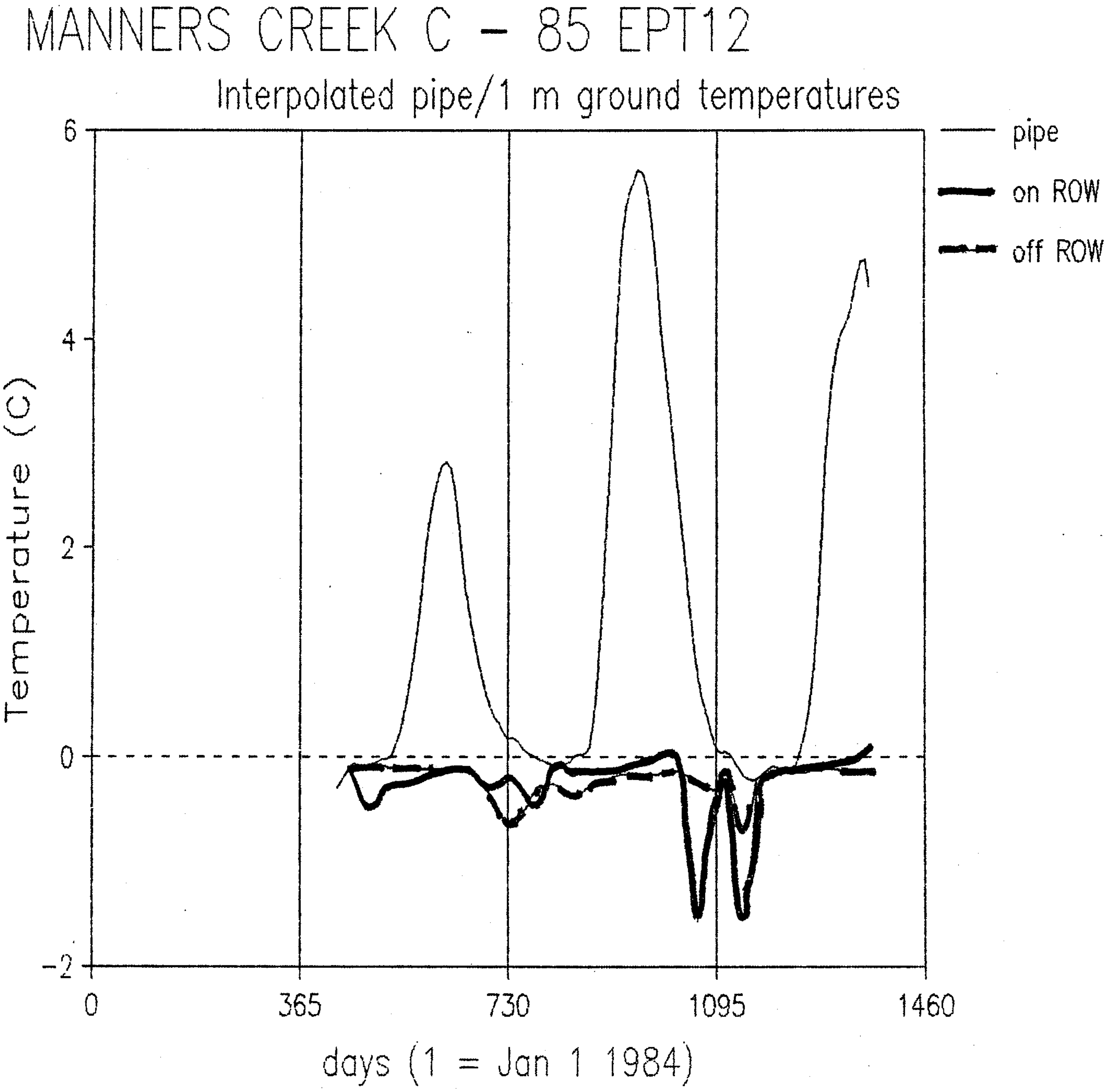

MANNERS CREEK C - 85 EPT12
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
6
4
2
0
-2
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.28

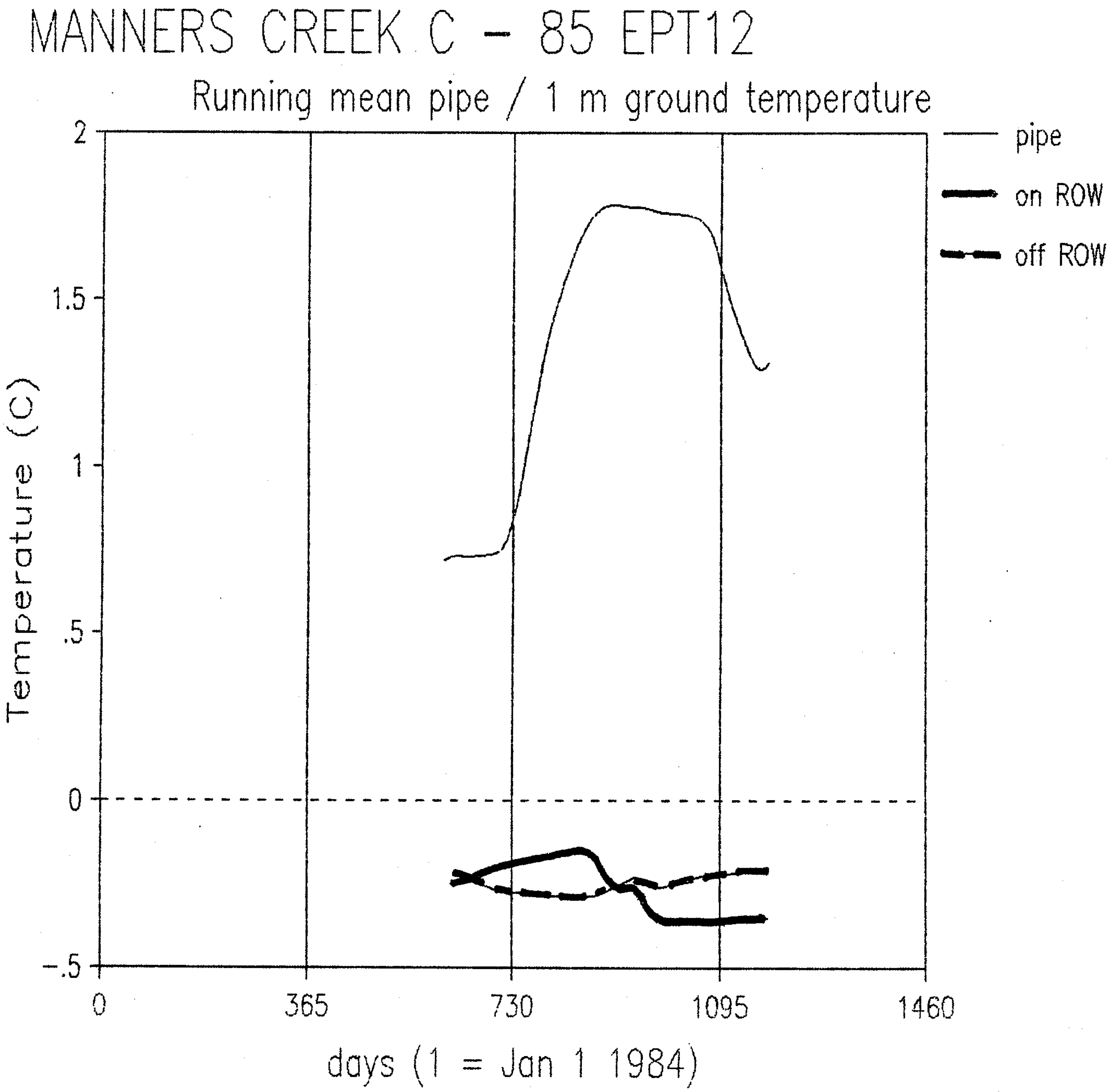

MANNERS CREEK C - 85 EPT12
Running mean pipe / 1 m ground temperature
Temperature (C)
2
1.5
1
.5
0
-.5
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.29

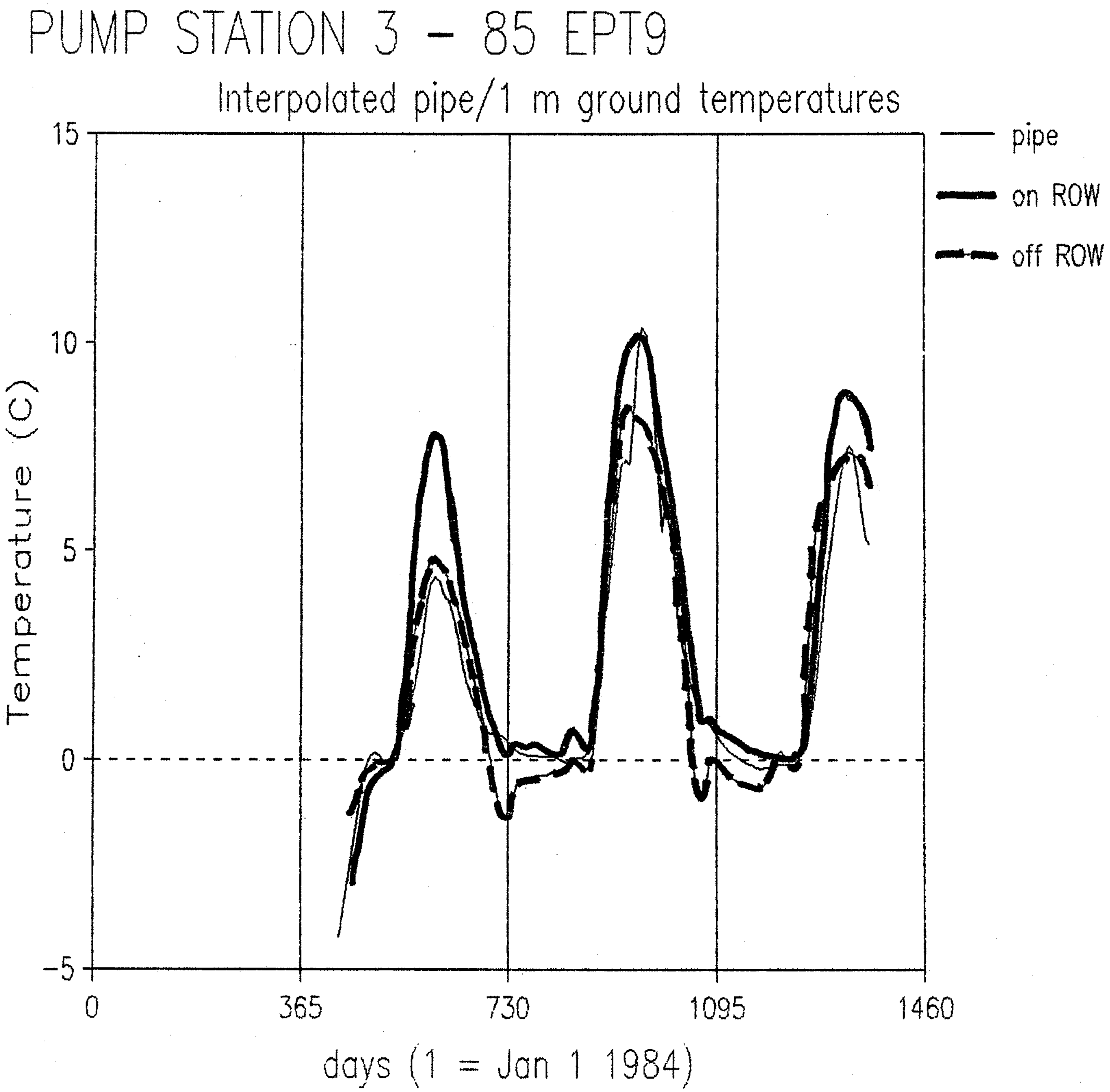

PUMP STATION 3 - 85 EPT9
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
15
10
5
0
-5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.30

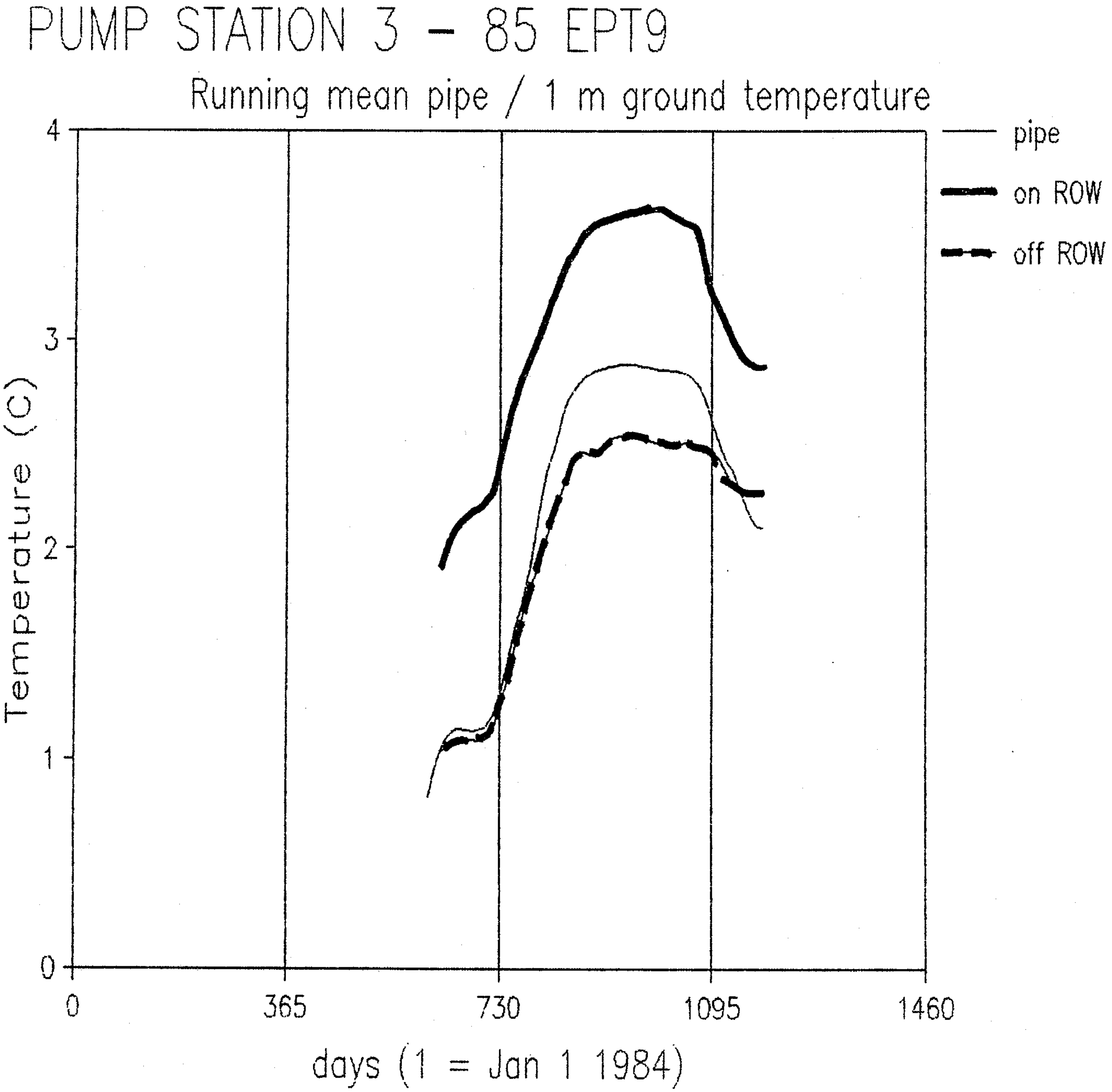

PUMP STATION 3 - 85 EPT9
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
0
1
2
3
4
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.31

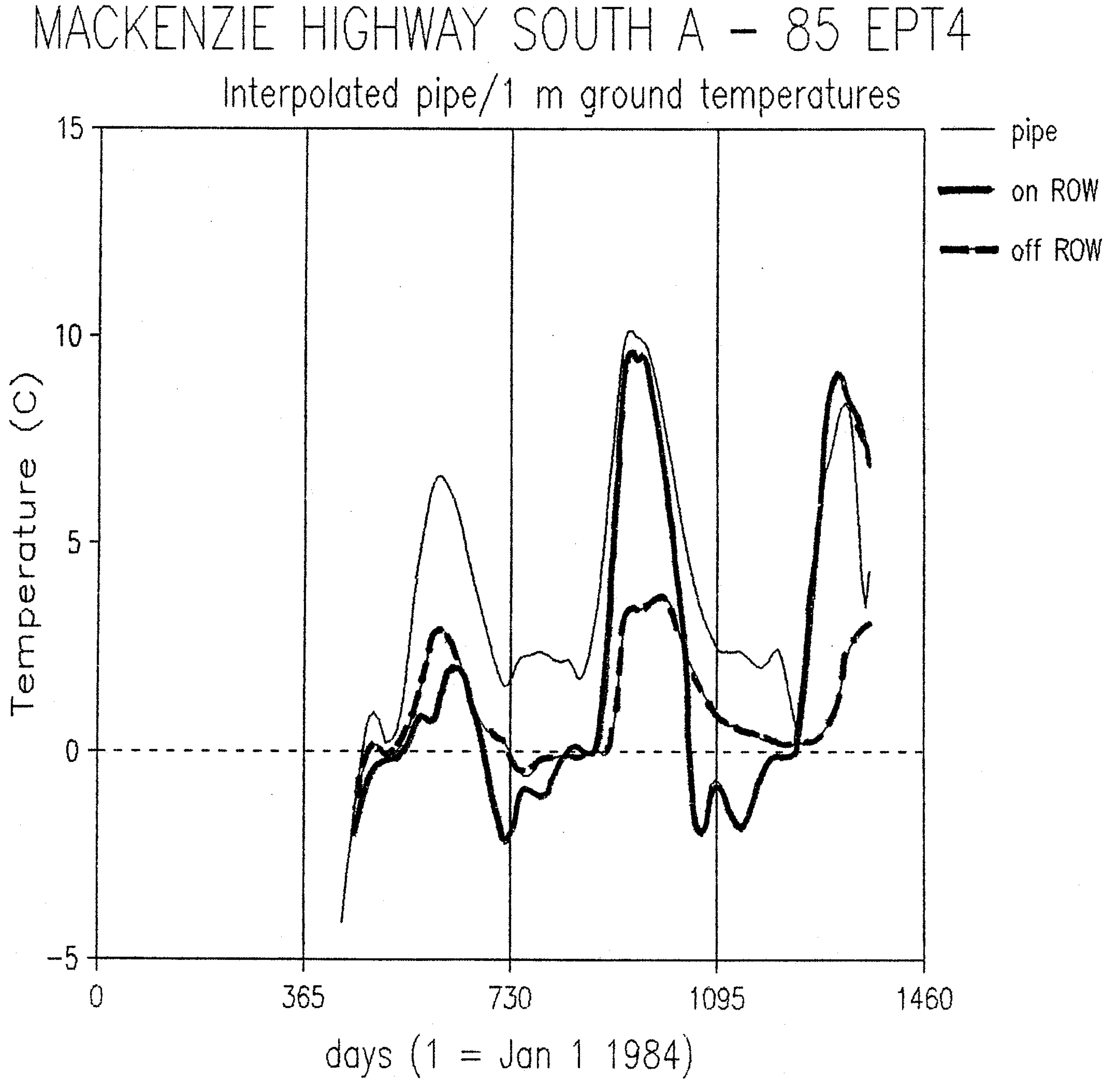
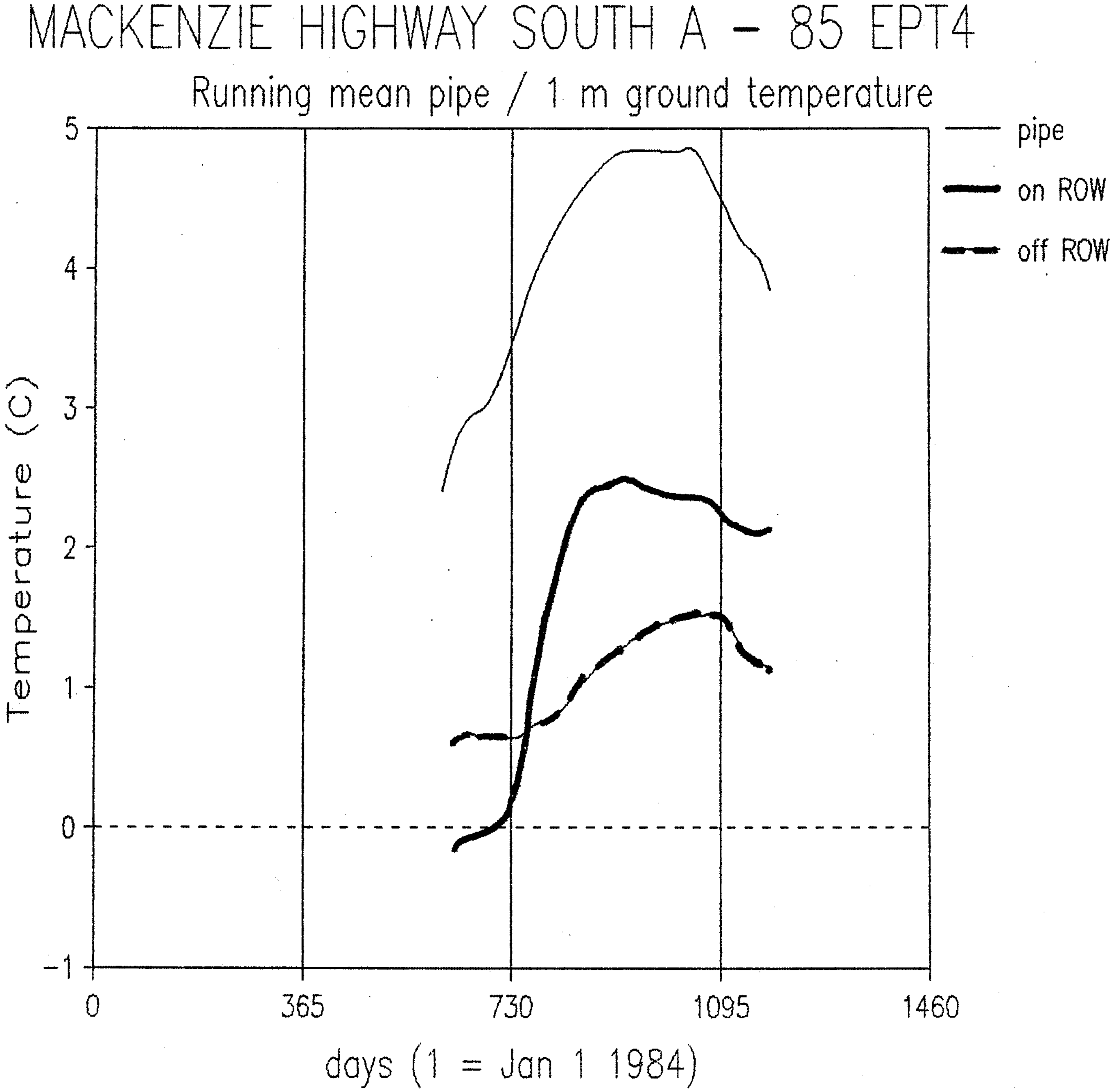

MACKENZIE HIGHWAY SOUTH A - 85 EPT4
Interpolated pipe/1 m ground temperatures
15
10
5
0
-5
Temperature (C)
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.32



MACKENZIE HIGHWAY SOUTH A - 85 EPT4
Running mean pipe / 1 m ground temperature
Temperature (C)
5
4
3
2
1
0
-1
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Figure 3.33

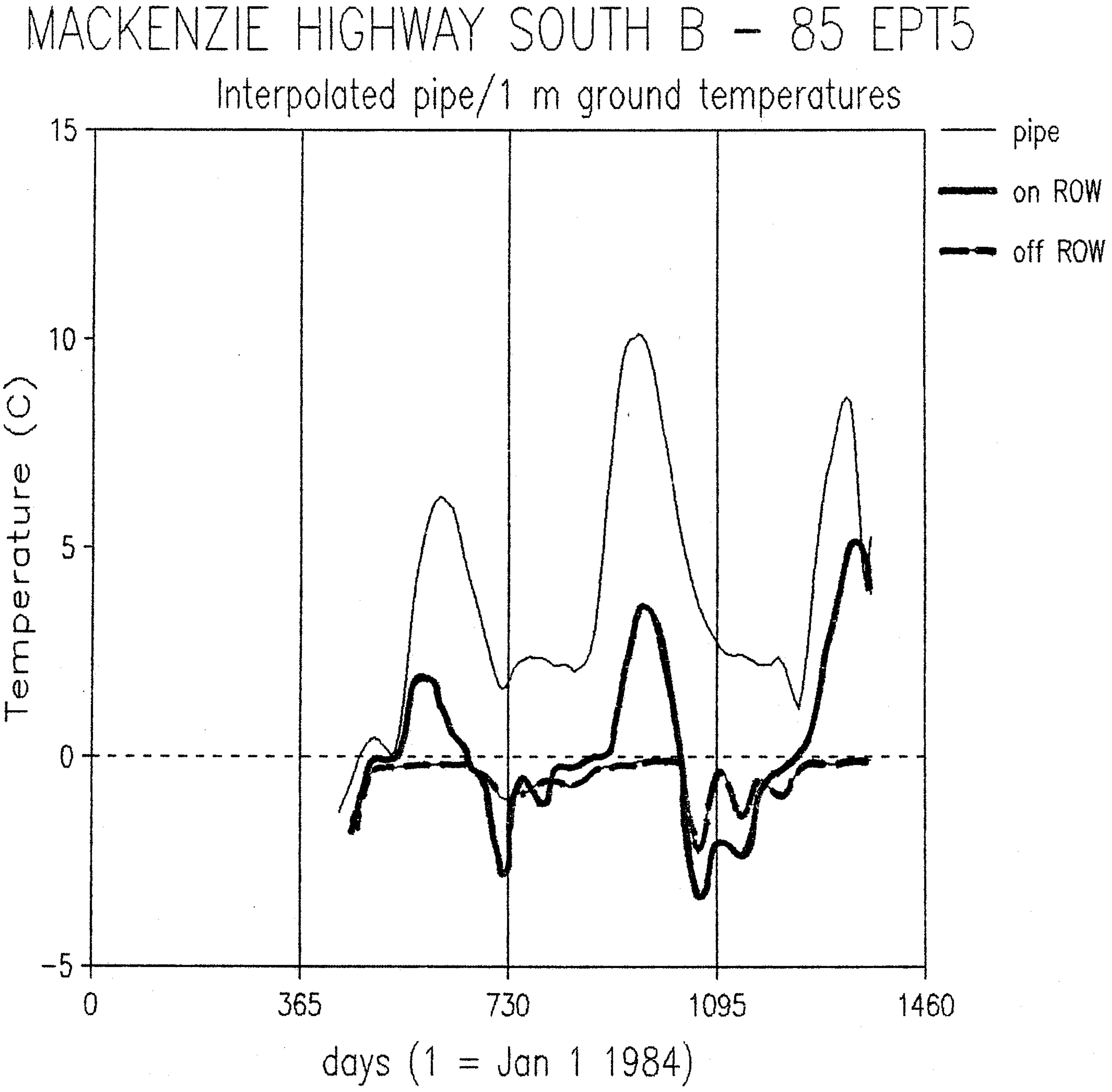

MACKENZIE HIGHWAY SOUTH B - 85 EPT5
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
15
10
5
0
-5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.34

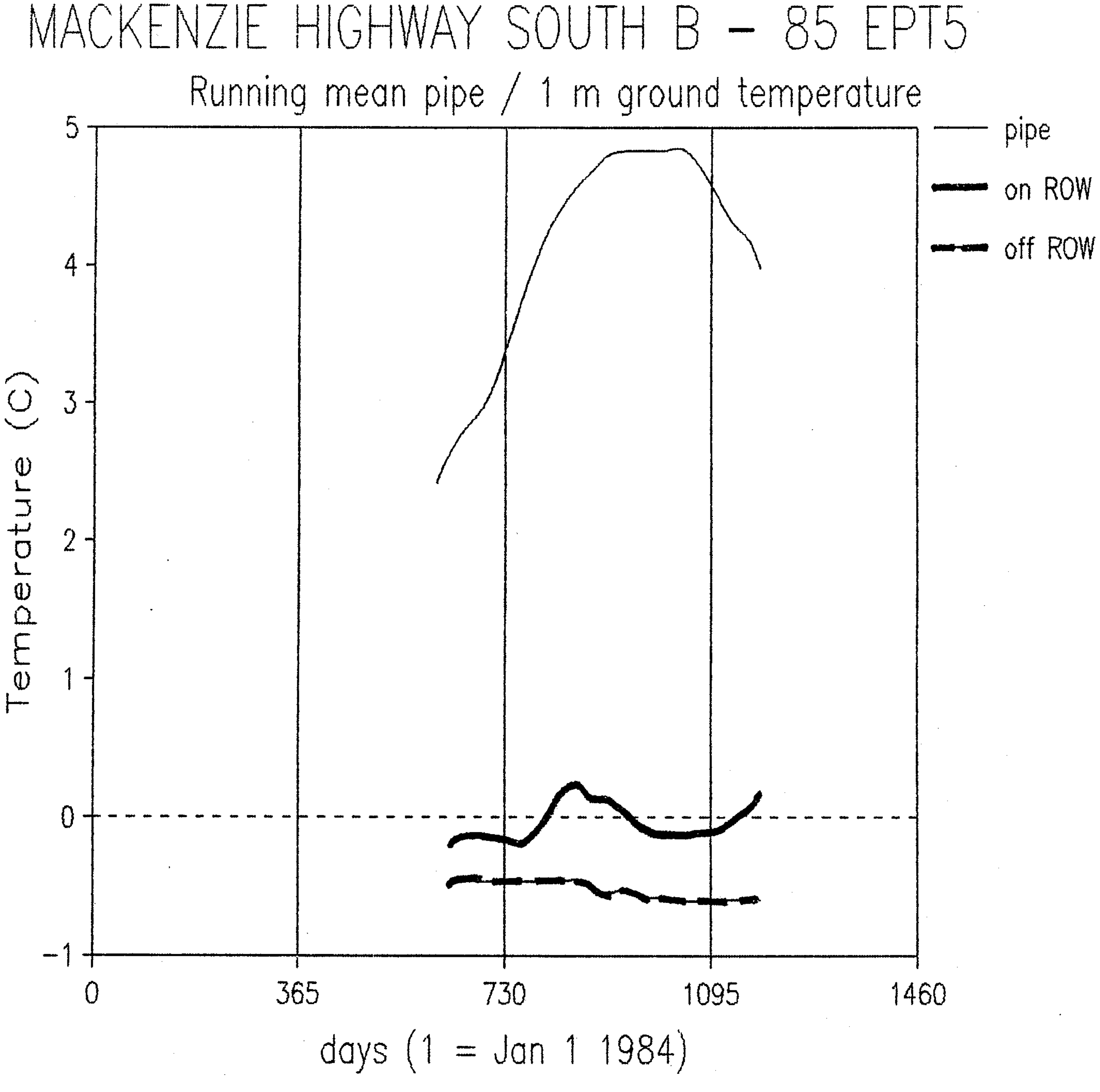

MACKENZIE HIGHWAY SOUTH B - 85 EPT5
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
5
4
3
2
1
0
-1
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.35

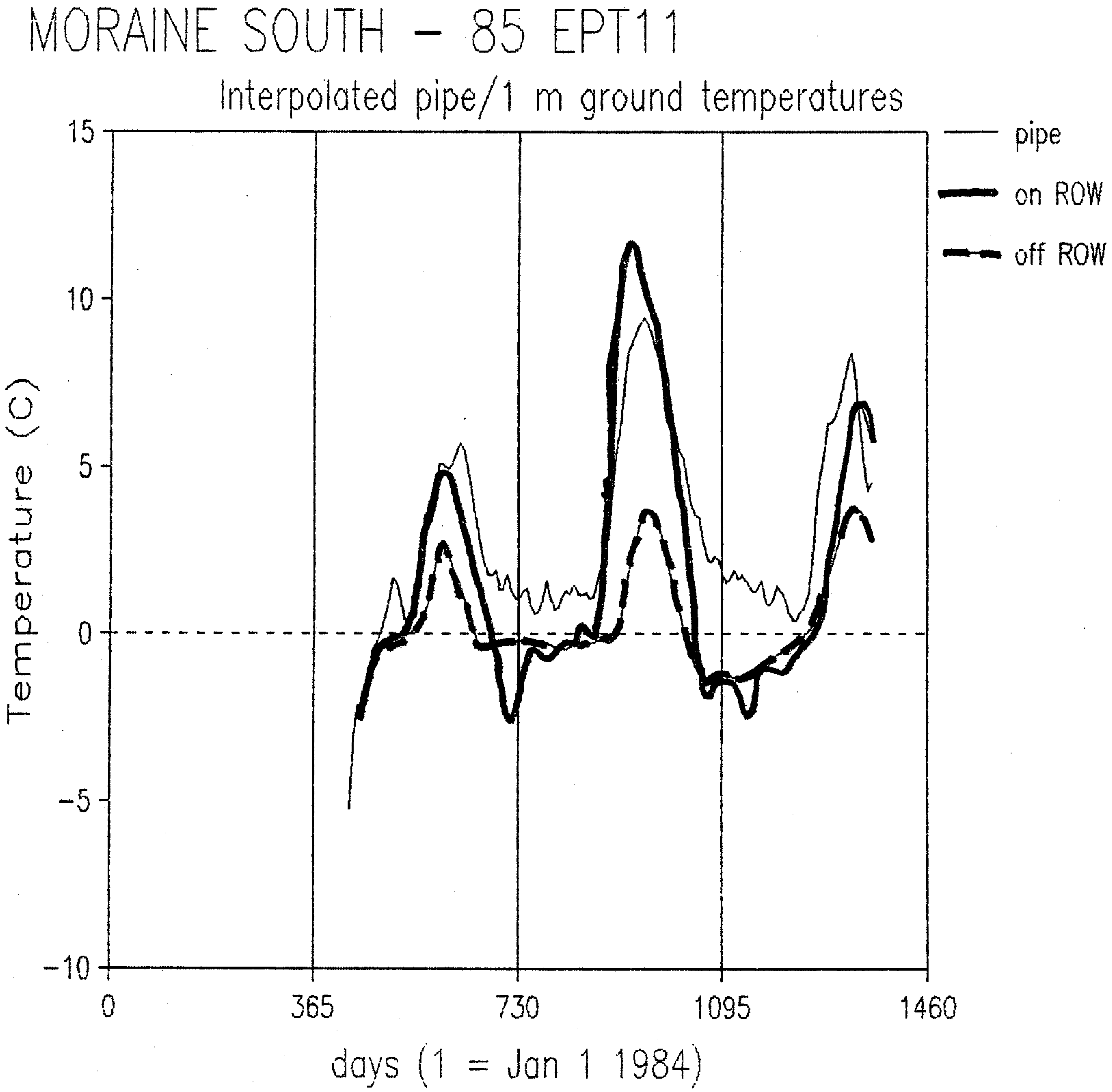
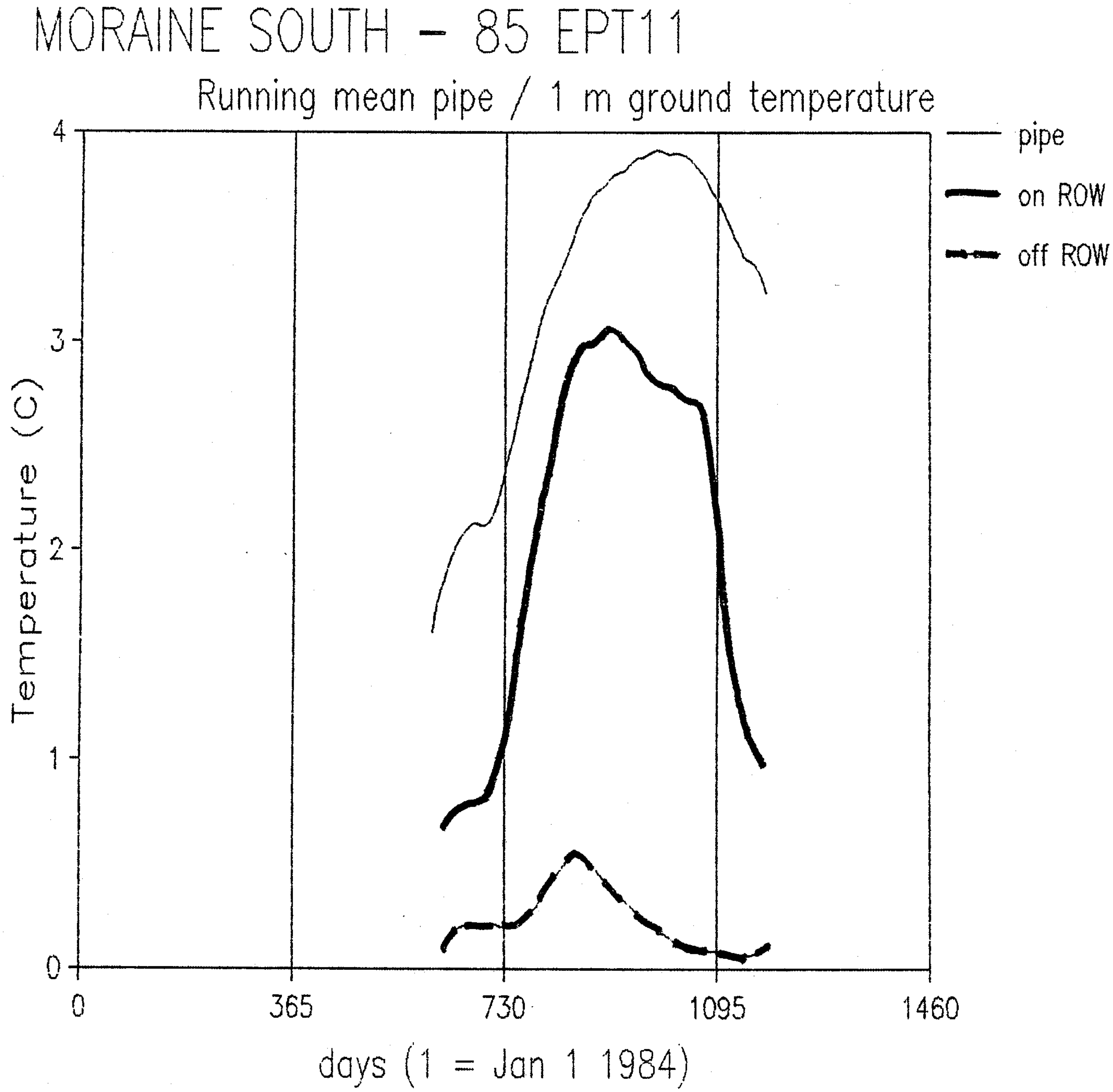

MORAINE SOUTH - 85 EPT11
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
15
10
5
0
-5
-10
Temperature (C)
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.36



MORAINE SOUTH - 85 EPT11
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
0
1
2
3
4
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.37

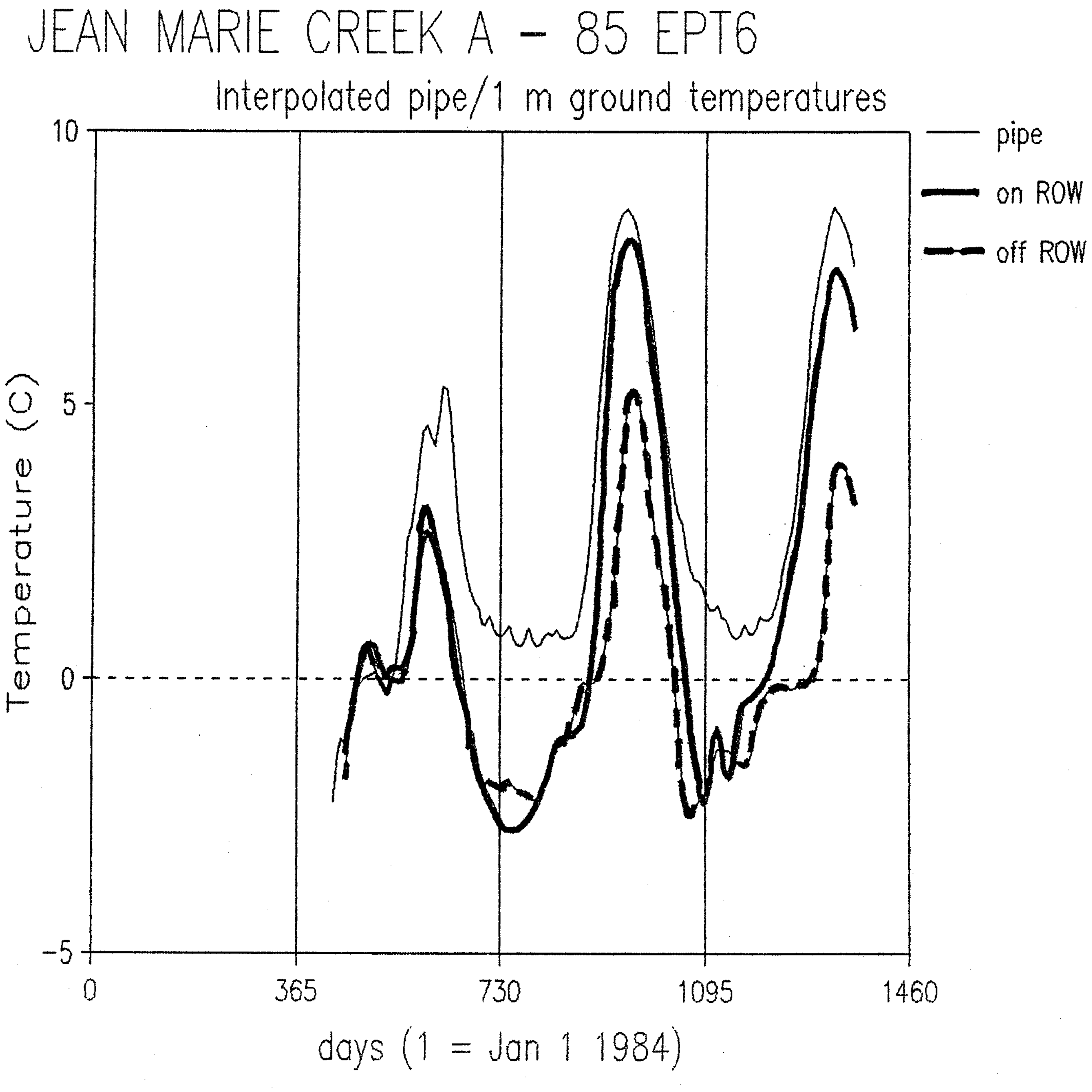
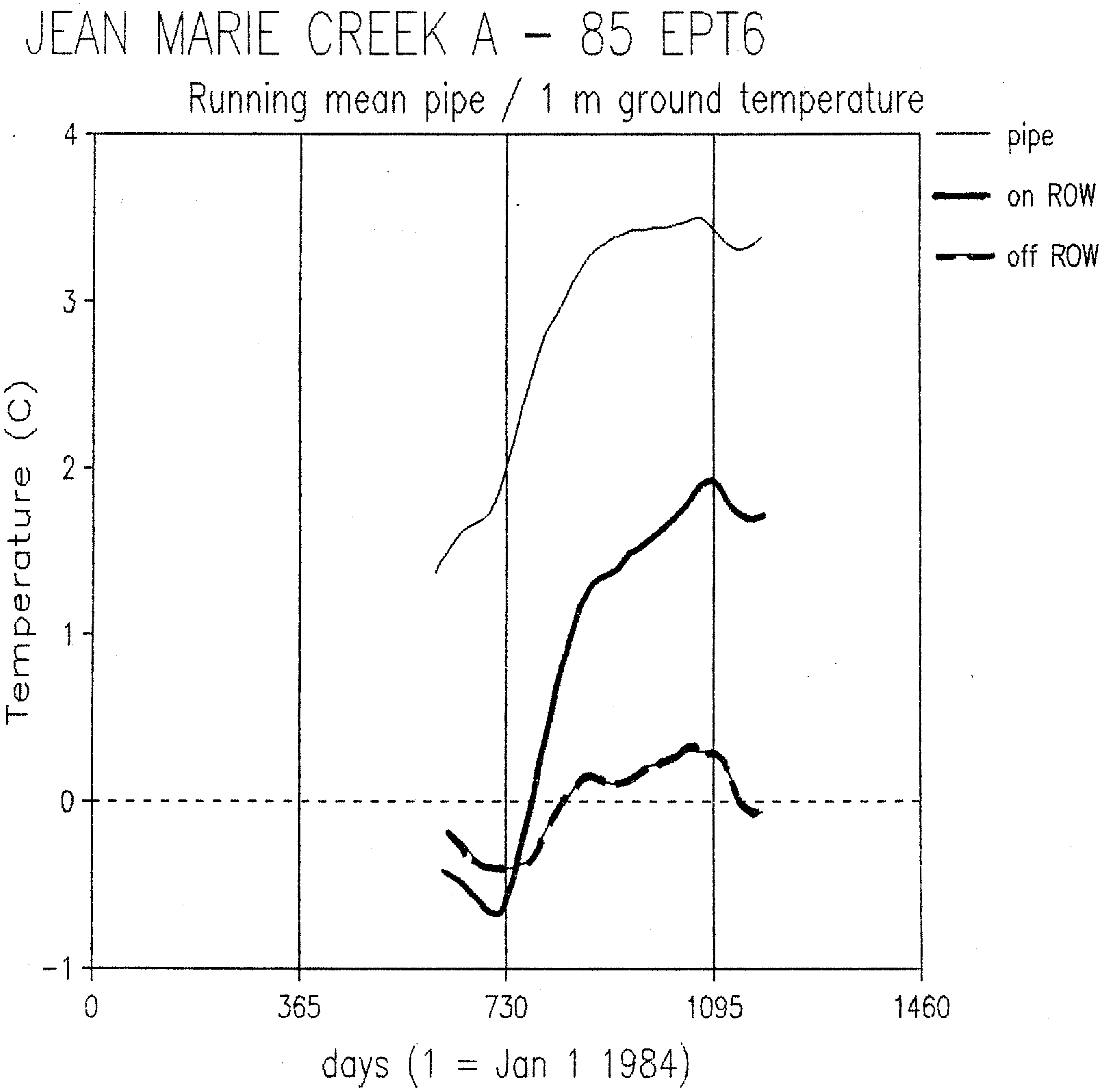

JEAN MARIE CREEK A - 85 EPT6
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
10
5
0
-5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.38



JEAN MARIE CREEK A - 85 EPT6
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
4
3
2
1
0
-1
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.39

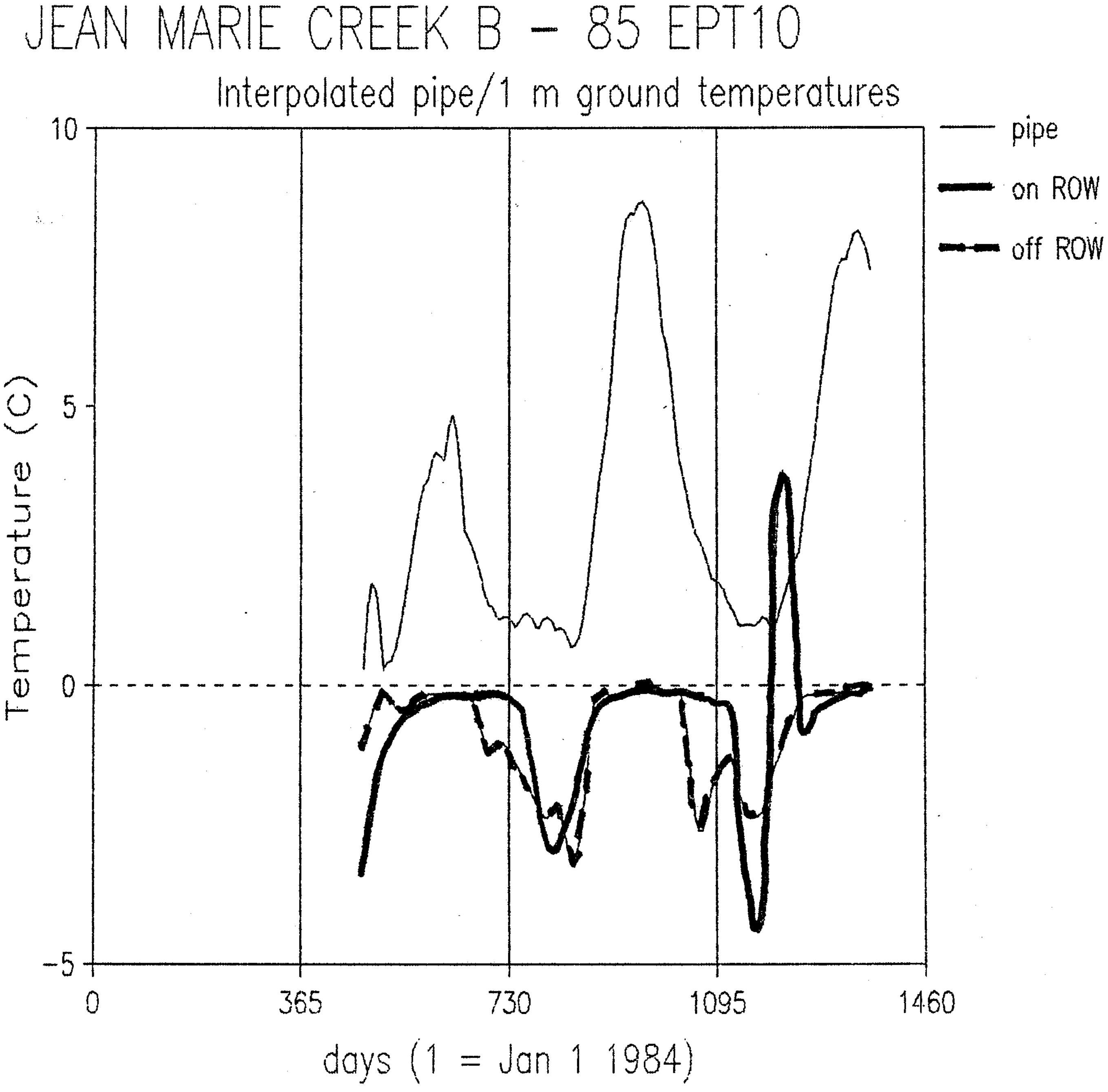

JEAN MARIE CREEK B - 85 EPT10
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
10
5
0
-5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.40

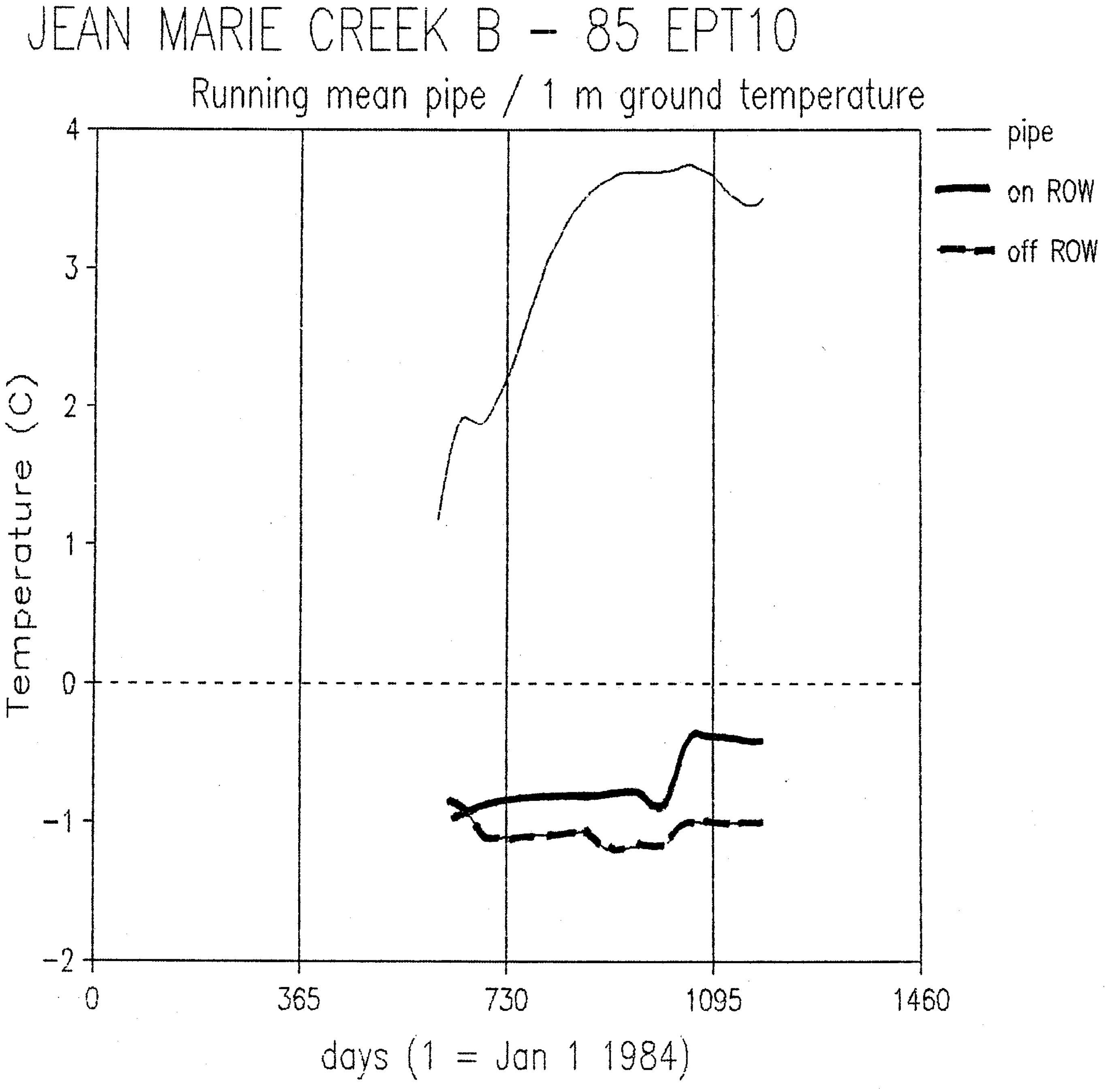

JEAN MARIE CREEK B – 85 EPT10
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
4
3
2
1
0
-1
-2
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.41

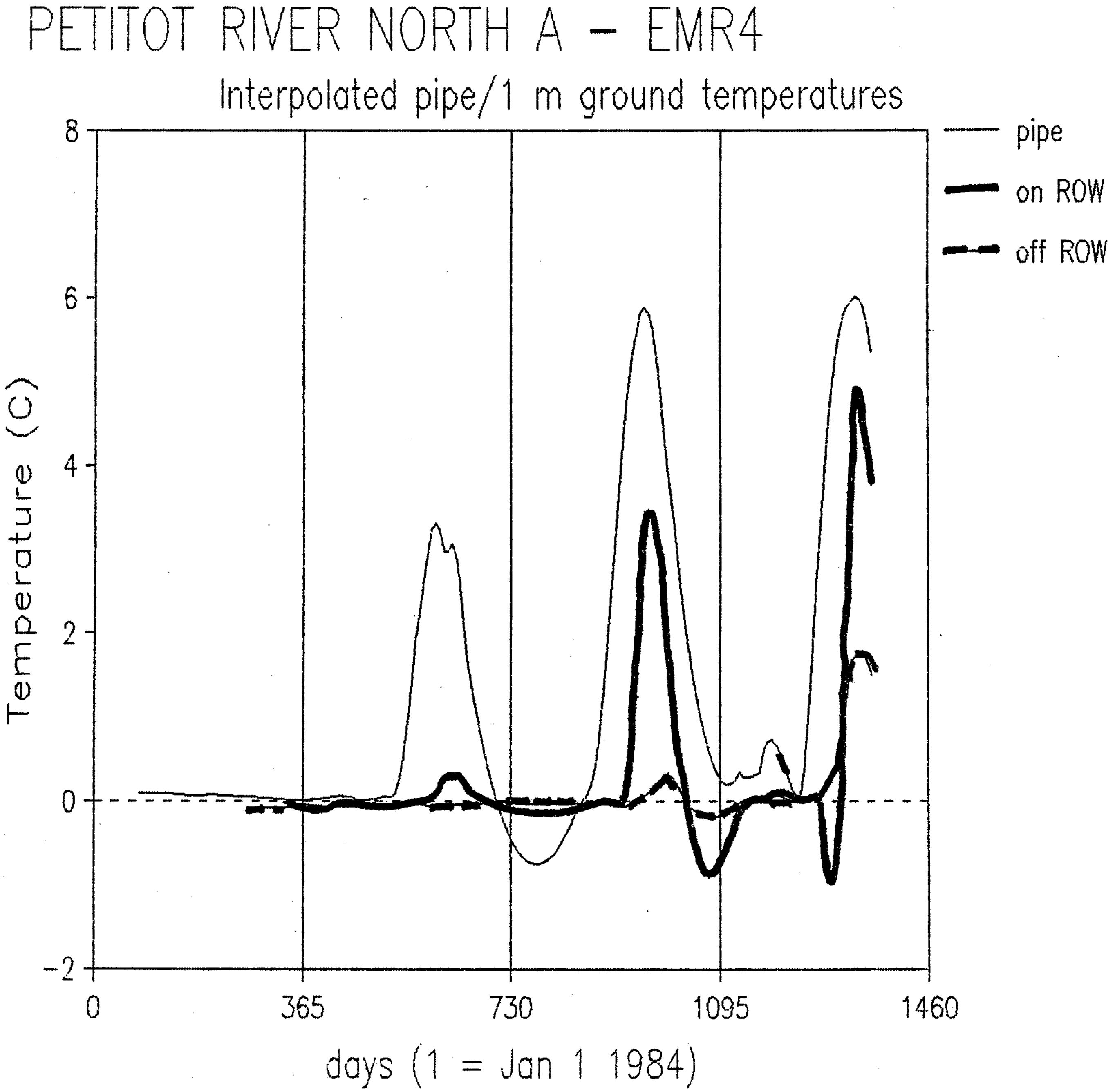

PETITOT RIVER NORTH A – EMR4
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
8
6
4
2
0
–2
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.42

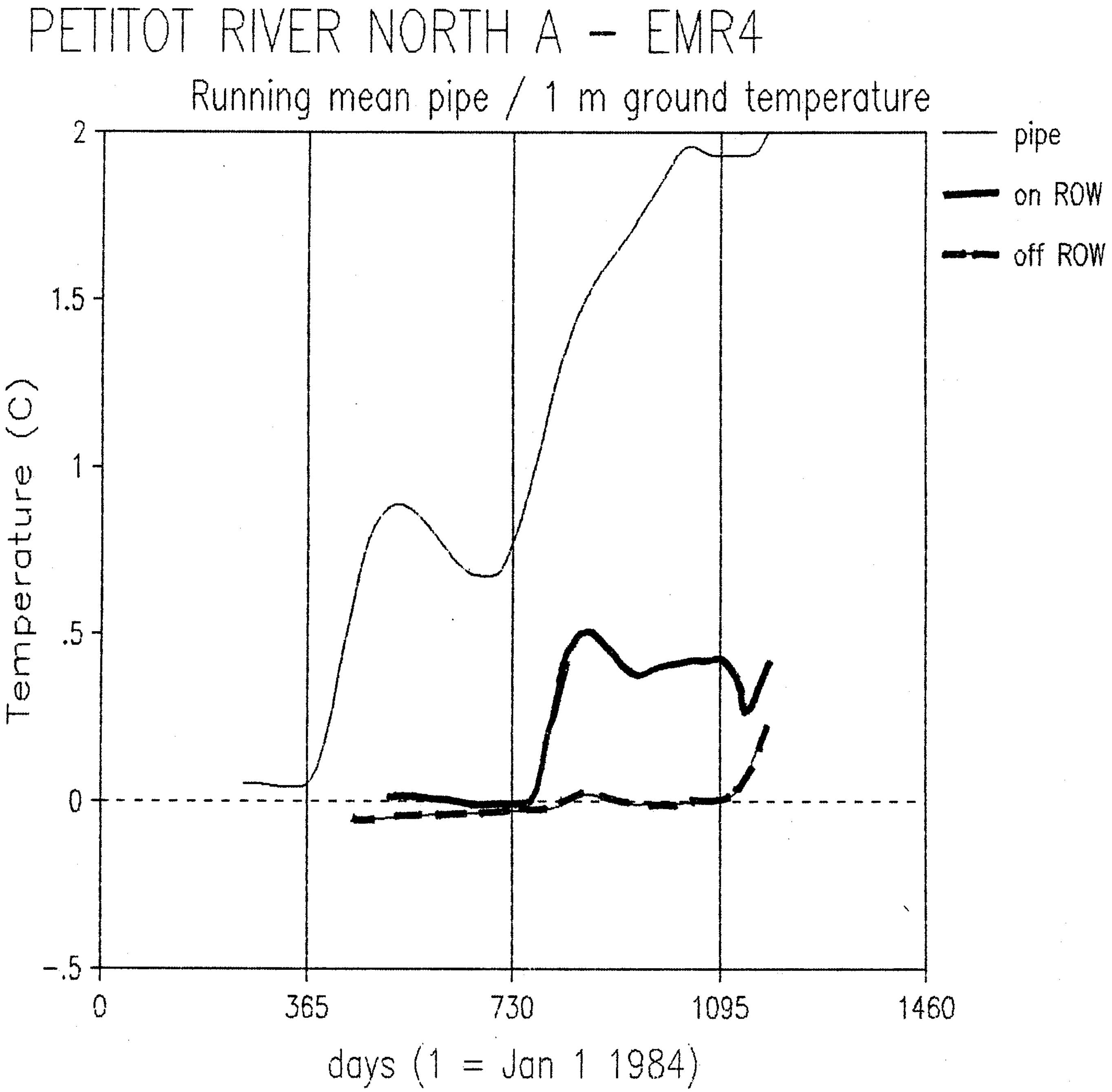

PETITOT RIVER NORTH A - EMR4
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
2
1.5
1
.5
0
-.5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.43

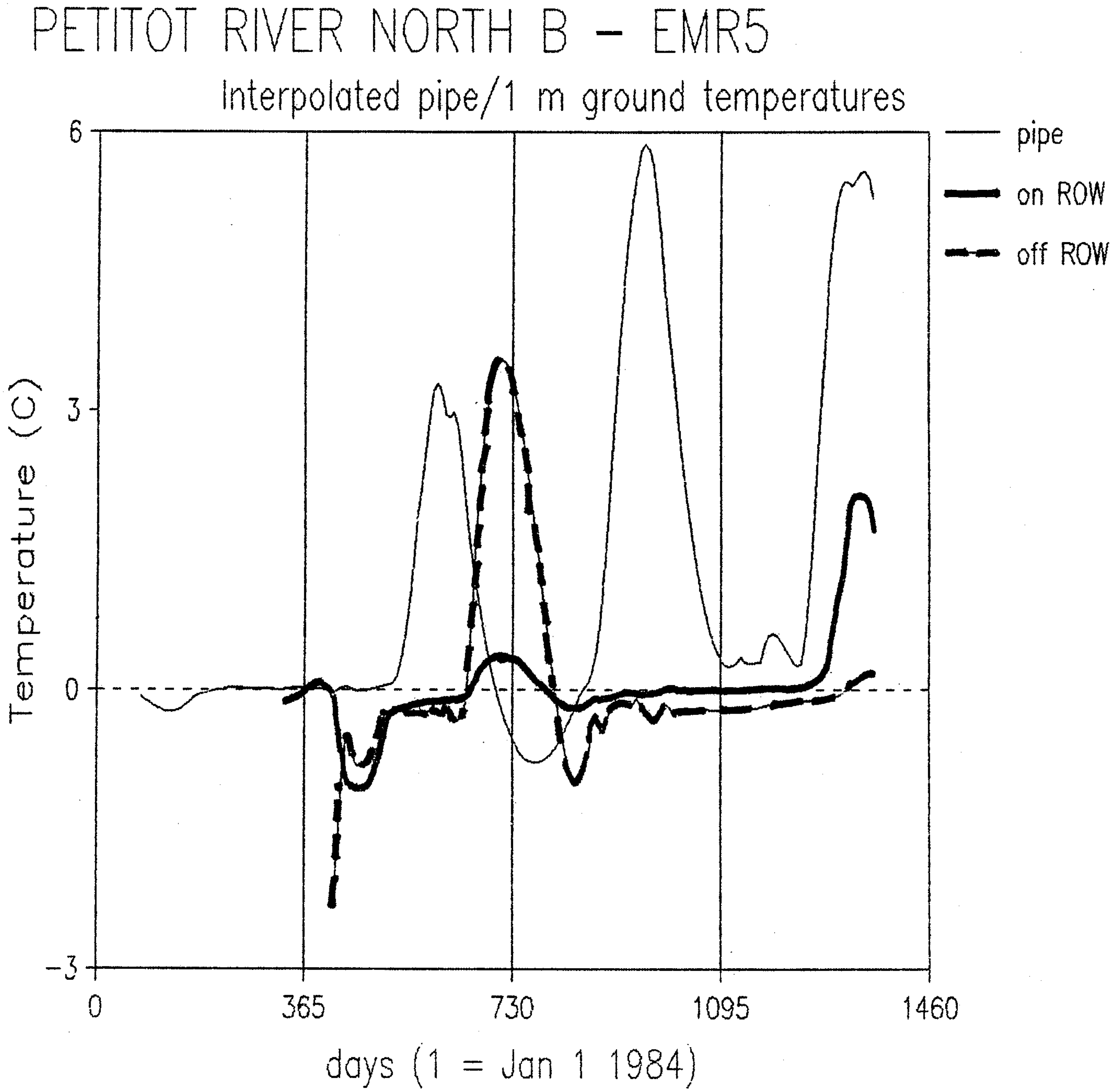

PETITOT RIVER NORTH B - EMR5
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
6
3
0
-3
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.45

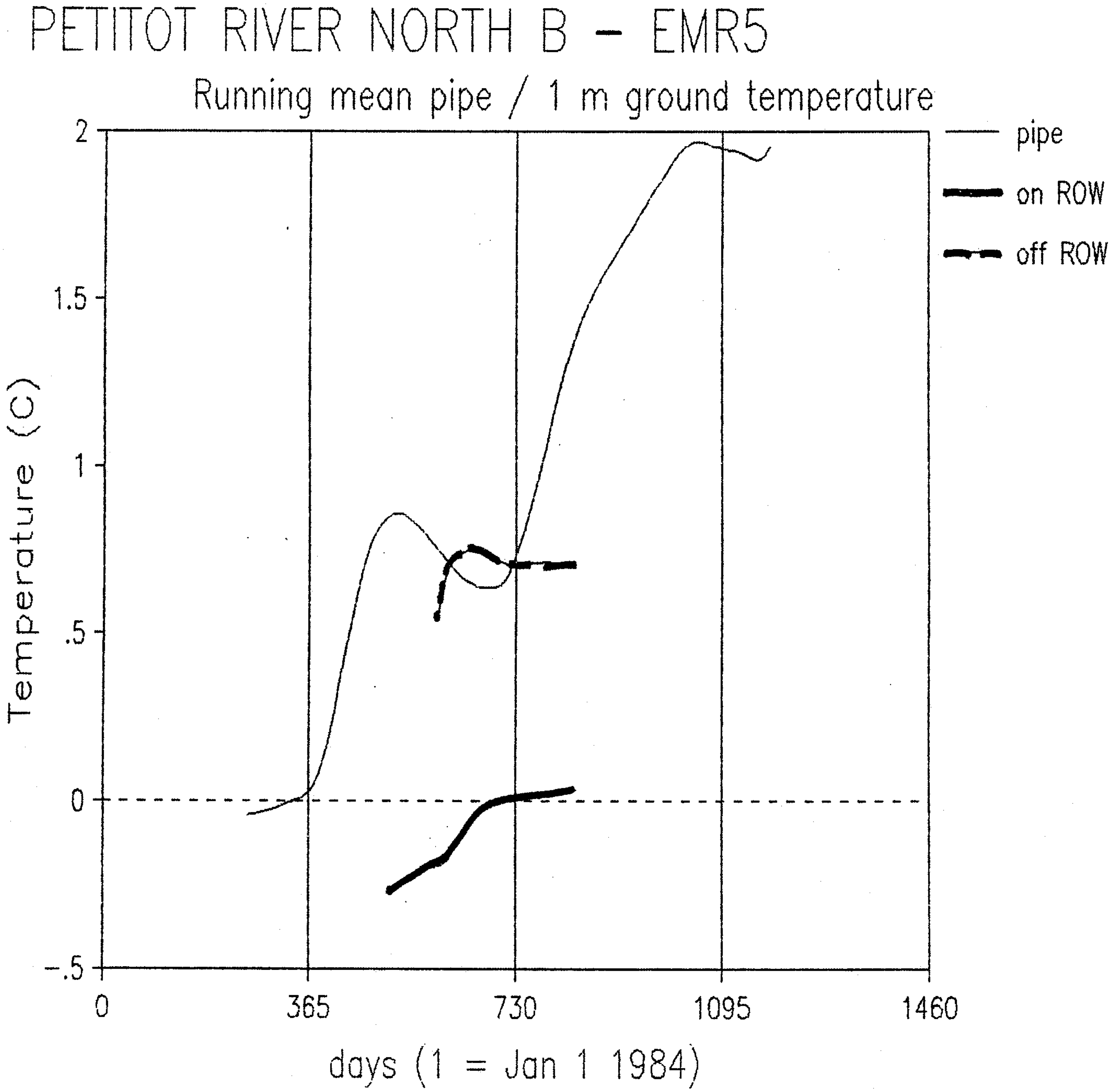
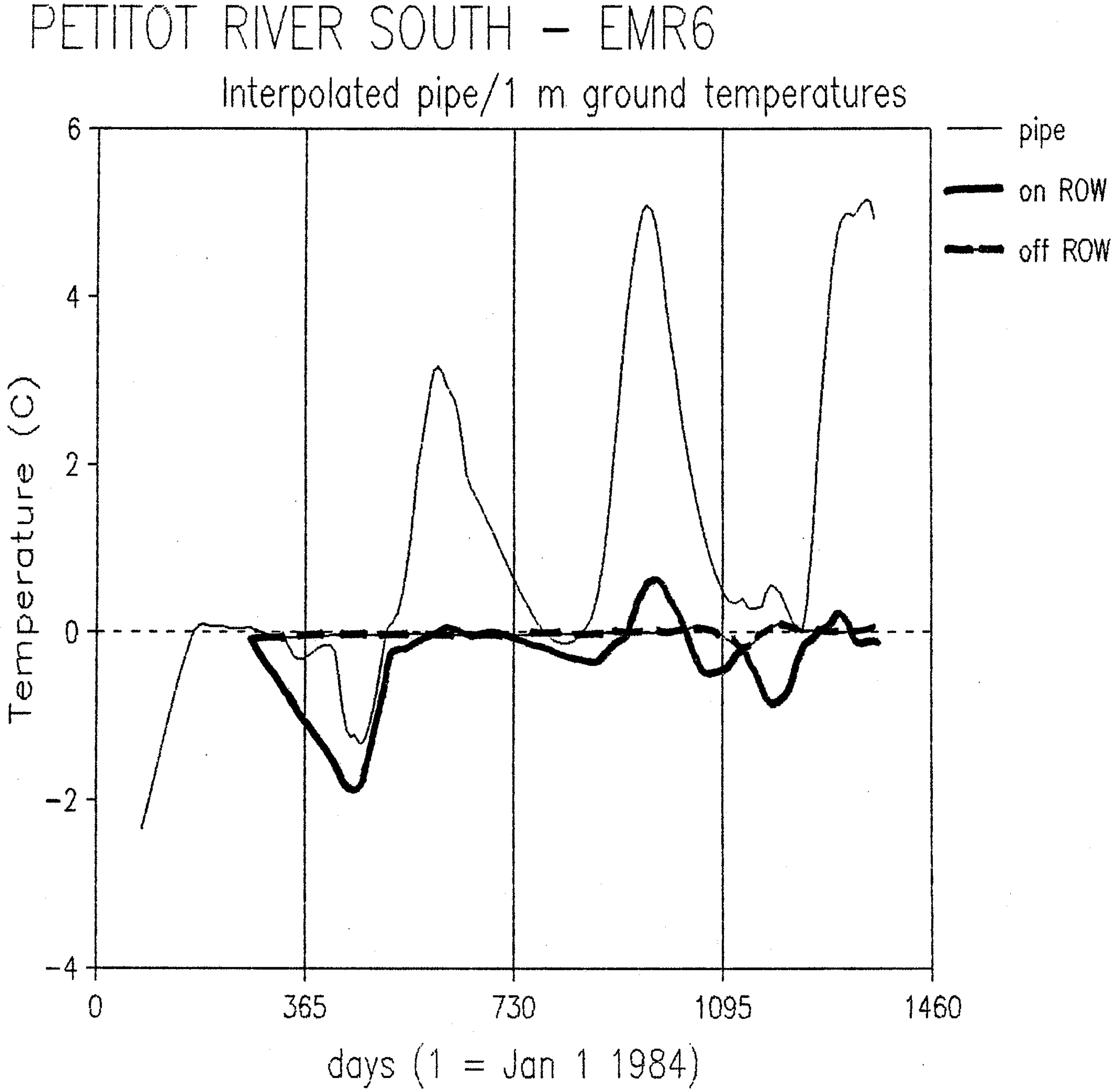

PETITOT RIVER NORTH B - EMR5
Running mean pipe / 1 m ground temperature
pipe
on ROW
off ROW
Temperature (C)
2
1.5
1
.5
0
-.5
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.46



PETITOT RIVER SOUTH - EMR6
Interpolated pipe/1 m ground temperatures
pipe
on ROW
off ROW
Temperature (C)
6
4
2
0
-2
-4
0
365
730
1095
1460
days (1 = Jan 1 1984)

Figure 3.47

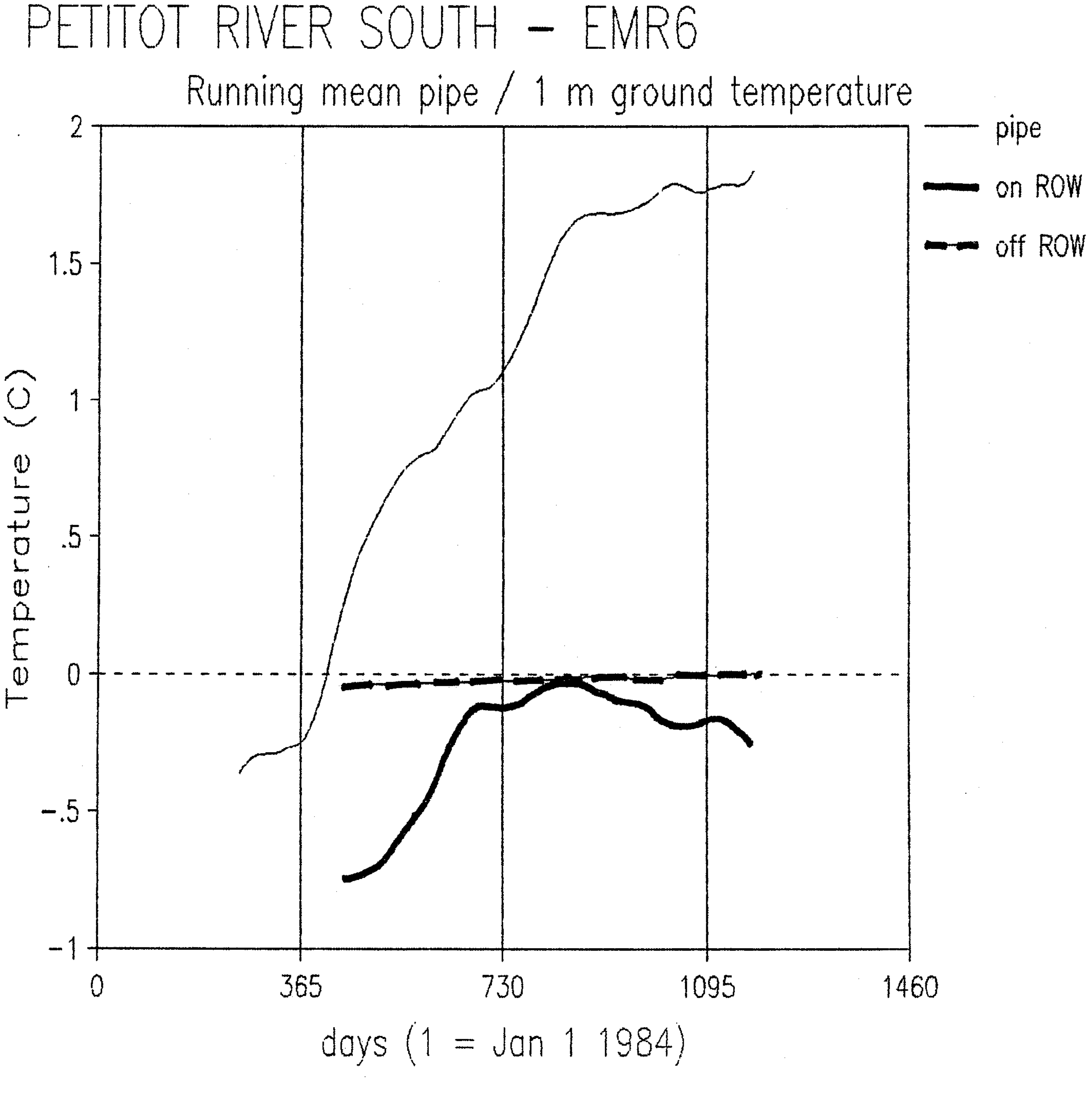

PETITOT RIVER SOUTH - EMR6
Running mean pipe / 1 m ground temperature
Temperature (C)
2
1.5
1
.5
0
-.5
-1
0
365
730
1095
1460
days (1 = Jan 1 1984)
pipe
on ROW
off ROW

Table 3.1

Temperature trends in pipe and ground temperatures

INITIAL PERIOD

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	W	V	W	V	W	W	W	V		W	*								W	W	W
R.O.W.	V	W	*	W	W	W					W	W	*								*		W
Temperature Relationship :																							
PIPE : ROW	W	W	W	C	W	W					C	W	W								W		W

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

Totals:

	W	C	V	*
TRENDS:				
Pipe:	9	2	3	1
R.O.W.	7	0	1	3
RELATIONSHIPS:				
PIPE : ROW	9	2	0	0

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

Table 3.2

Temperature trends in pipe and ground temperatures

MIDDLE PERIOD

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	W	*	*	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
R.O.W.	V	W	*	V	W	V	W	V	C	W	W	W	*	V	W	W	V	W	W	*	W	W	W
Temperature Relationship :																							
PIPE : ROW	W	C	W	C	W	*	W	W	W	V	C	W	W	W	C	W	W	W	W	W	W	V	W

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

Totals:

	W	C	V	*
TRENDS:				
Pipe:	20	1	0	2
R.O.W.	13	1	6	3
RELATIONSHIPS:				
PIPE : ROW	16	4	2	1

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

Table 3.2

Temperature trends in pipe and ground temperatures

FINAL PERIOD

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:	W	V	C	*	W	W	V	V	V	C	C	C	C	C	C	C	C	C	*	C	*	W	W
R.O.W.	V	W	*	V	W	V	*	W	V	C	C	*	*	*	C	C	W	C	V	W	V		C
Temperature Relationship :																							
PIPE : ROW	W	W	W	C	W	W	W	W	W	C	C	W	W	W	C	W	W	W	W	W	W		W

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

Totals:

	W	C	V	*
TRENDS:				
Pipe:	5	11	4	2
R.O.W.	5	6	6	5
RELATIONSHIPS:				
PIPE : ROW	18	4	0	0

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

were warmer or cooler than mean ground temperatures in each of these periods.

Running mean air temperatures recorded at Fort Simpson and Norman Wells weather stations can also be characterized in the same way for the same intervals. Both stations show the same overall pattern: variable in the first interval, then warming in the middle and final intervals.

In all three intervals, the mean annual pipe temperature is higher than the mean annual temperature on the right-of-way at most sites. Since the pipe is not a net heat source over its whole length, it may be inferred that the ground thermal regime adjacent to the pipe is different from that of the rest of the right-of-way.

In addition to the effect of any heat supplied by oil flowing in the pipe, higher mean annual temperatures observed in the pipe could be due to changes to the ground immediately around the pipe. Where subsidence in the pipe ditch contributes to ponding, the increased latent heat content of the soil around the pipe can raise the mean annual temperature (Goodrich, 1982). Such subsidence could also increase snow depth immediatly over the pipe, again increasing the mean annual temperature by raising winter ground temperatures. Both of these hypotheses are supported by the fact that, at many sites, the pipe temperature hovers near the freezing point for the entire winter (eg. see Figures 3.15,3.17,3.19,3.21,3.23). However, this cannot be the sole explanation of the discrepancy, since the greatest temperature difference between pipe and ground temperatures is often experienced during the summer.

From the start of the first interval to the end of the middle interval the trend is clear: at most sites, both the pipe and the right of way experienced a warming trend which tended to decelerate toward the end of this period. The warming trend (at most sites) in the first period reflects the cooling of the ground due to snow removal during right-of-way clearing and pipeline installation. In general, the magnitude of the warming trend in the initial period increases somewhat as one moves south: this may be because the length of time between the installation of the pipe and the commencement of oil flow was shorter in the south.

The rate of pipe and ground temperature increase slowed down at most sites in the middle interval. This is most striking with the pipe temperature trends, where it is apparent for all sites which show a temperature increase. The deceleration is not so clearcut on the right-of-way, but it is still apparent for the majority of sites which experienceed a warming trend. The sites which experienced this deceleration are evenly divided between those without permafrost (or thin permafrost) and those which have warmed to within 1 degree of 0°.

In the final period, half of the sites show a cooling trend in the pipe, compared to cooling trends in only six of twenty-two T3 cables. This cooling trend occured in spite of the rising mean annual air temperature trend apparent in the weather station records. From the interpolated temperature curves, the cooling appears to be concentrated in the summer months. The exceptionally dry conditions experienced during this summer could provide a possible mechanism for this cooling trend. If the water content of the active layer declined, this would reduce the diffusivity of this layer, pushing the sensors at the 1 meter depth further down the "thermal offset" profile. This would lower the mean annual temperature, in the manner discussed in section 1.1. This could offset a slight warming trend due to higher air temperatures.

3.2 Ground temperature influence on pipe temperature

The design philosophy for the Norman Wells - Zama pipeline is that pipe temperatures be determined by ambient ground temperatures. To examine this approach , ground and pipeline temperatures were examined at two sites (Canyon Creek and Table Mountain) having three sets of monitoring fences spaced along the pipeline. Examining changes in pipe and ground temperature along the pipeline gives an indication of the spatial scale over which pipe temperature comes into equilibrium with ambient conditions. This approach is necessarily crude, since :

a) pipe temperatures are a function of conditions "upstream", and

b) the spatial extent of the thermal regimes represented by each site is not known.

As with the comparisons in the previous section, the fence thermistor cables designated as T3 were used to compare to pipe temperatures. Actual (rather than interpolated) ground and pipe temperatures were used for this analysis. In the discussion which follows, all ground temperatures are for the 1 meter sensor. Pipe temperatures are the mean value for all pipe temperature sensors at a given site.

Canyon Creek

At Canyon Creek, the three fences are spaced at approximately 300 meter intervals. The pipeline passes from level frozen till at A, to an east-facing permafrost slope covered with wood chips at B, to a west-facing permafrost slope with erosion control berms. One meter ground temperatures at the three sites (cable T3) are shown in Figure 3.47. Site B is nearly isothermal just below 0^{o} C through the year, while the other two go through an annual freeze-thaw cycle.

Figures 3.48 and 3.49 show the effect of oil flow on pipe temperature differences along the pipeline at Canyon Creek. Prior to the commencement of oil flow in the pipe, the difference in pipe temperature between sites A and B was as much as 8^{o} (5^{o} between A and C). Figure 3.50 shows the same data as Figure 3.49 but only for the period for which oil was flowing in the pipe. Once oil began to flow, the pipe temperature difference from A to C was never more than $.8^{o}$. In comparison, differences in ground temperature (at the T3 sites) along the pipeline were as much as 5^{o} between A and B, and as much as 8^{o} between A and C through the measurement period.

Figure 3.47

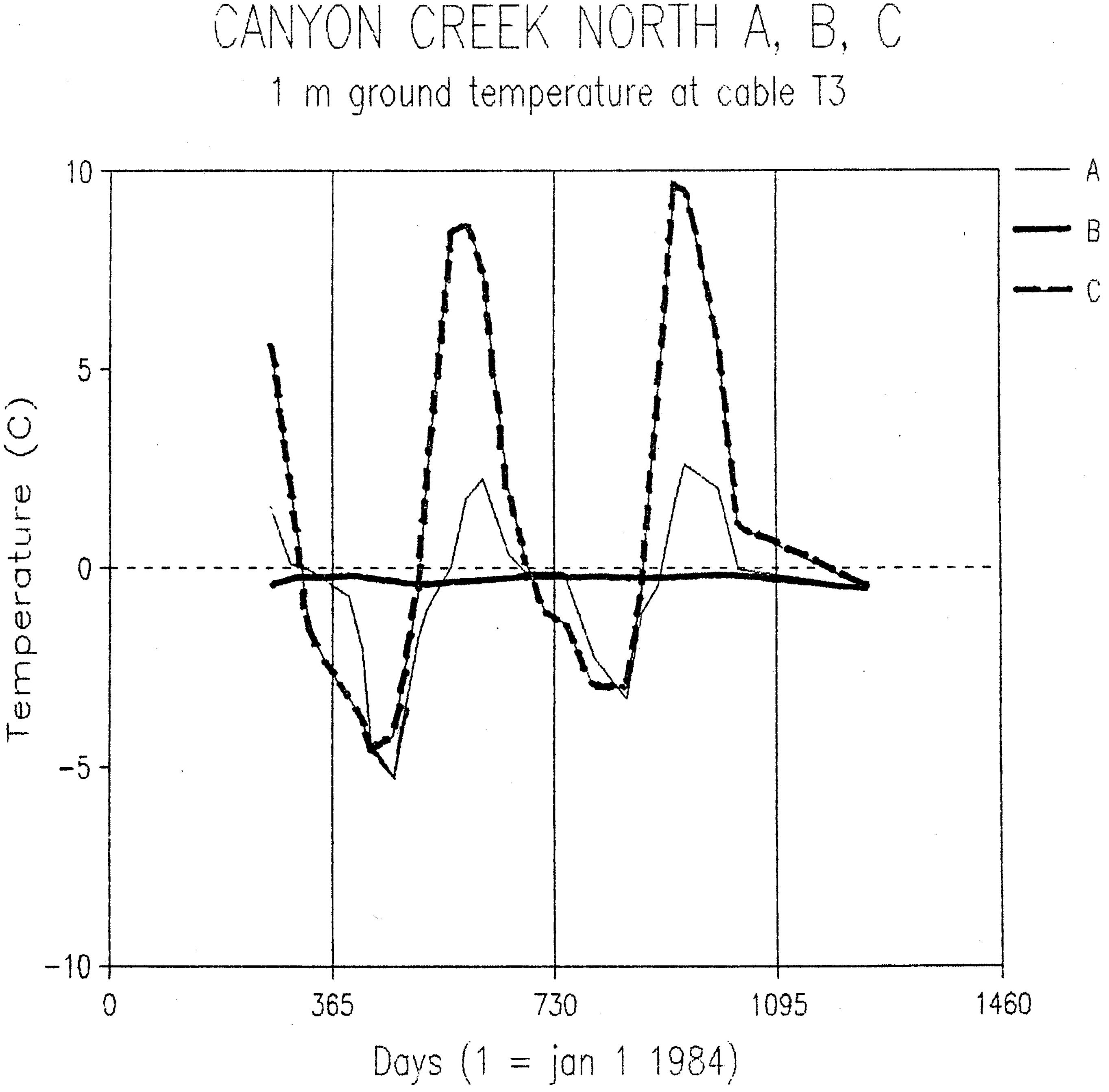

CANYON CREEK NORTH A, B, C
1 m ground temperature at cable T3
10
5
0
-5
-10
Temperature (C)
0
365
730
1095
1460
Days (1 = jan 1 1984)
A
B
C

Figure 3.48

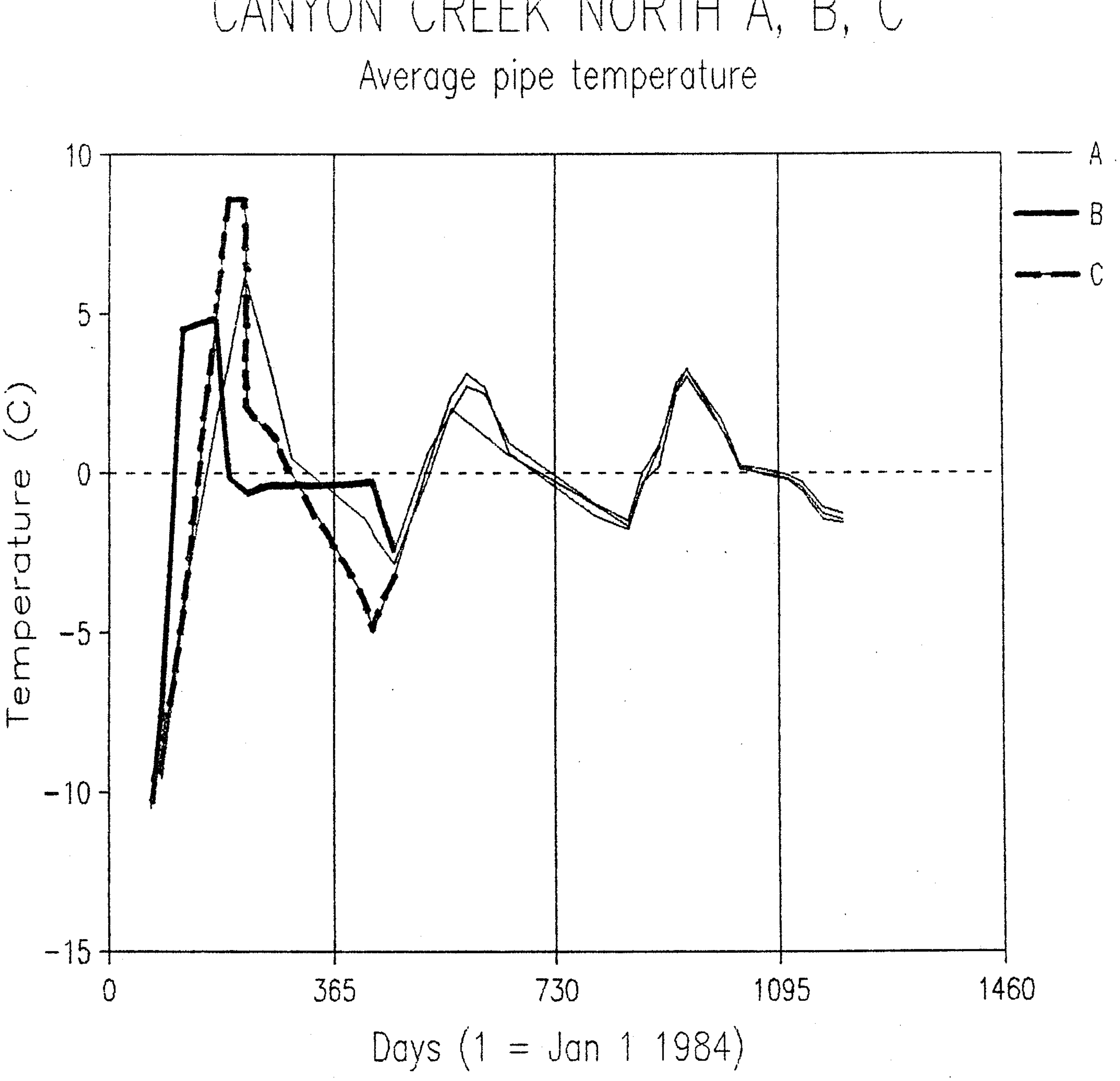
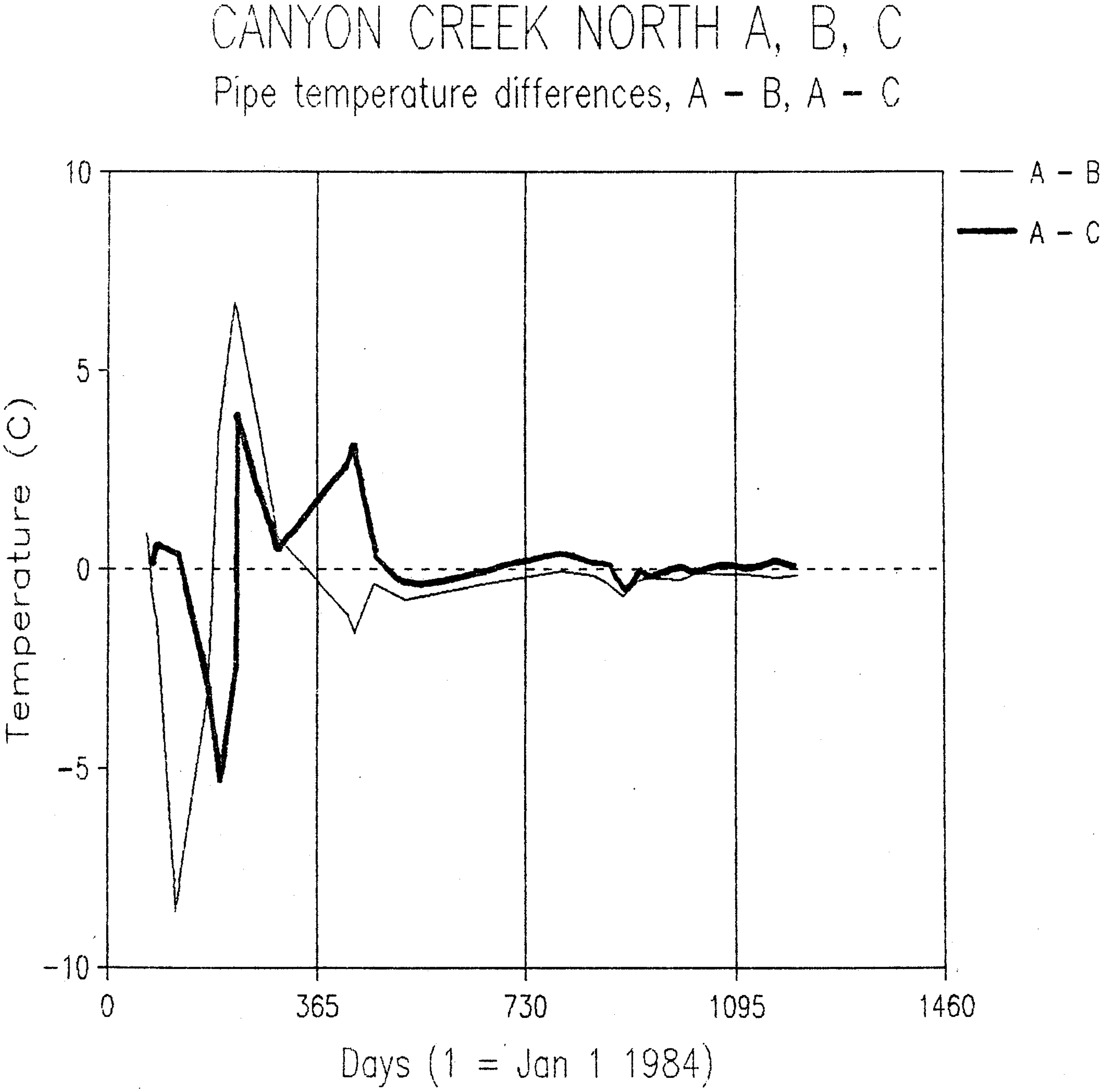

CANYON CREEK NORTH A, B, C
Average pipe temperature
Temperature (C)
10
5
0
-5
-10
-15
0
365
730
1095
1460
Days (1 = Jan 1 1984)
A
B
C

Figure 3.49



3 7

Figure 3.50

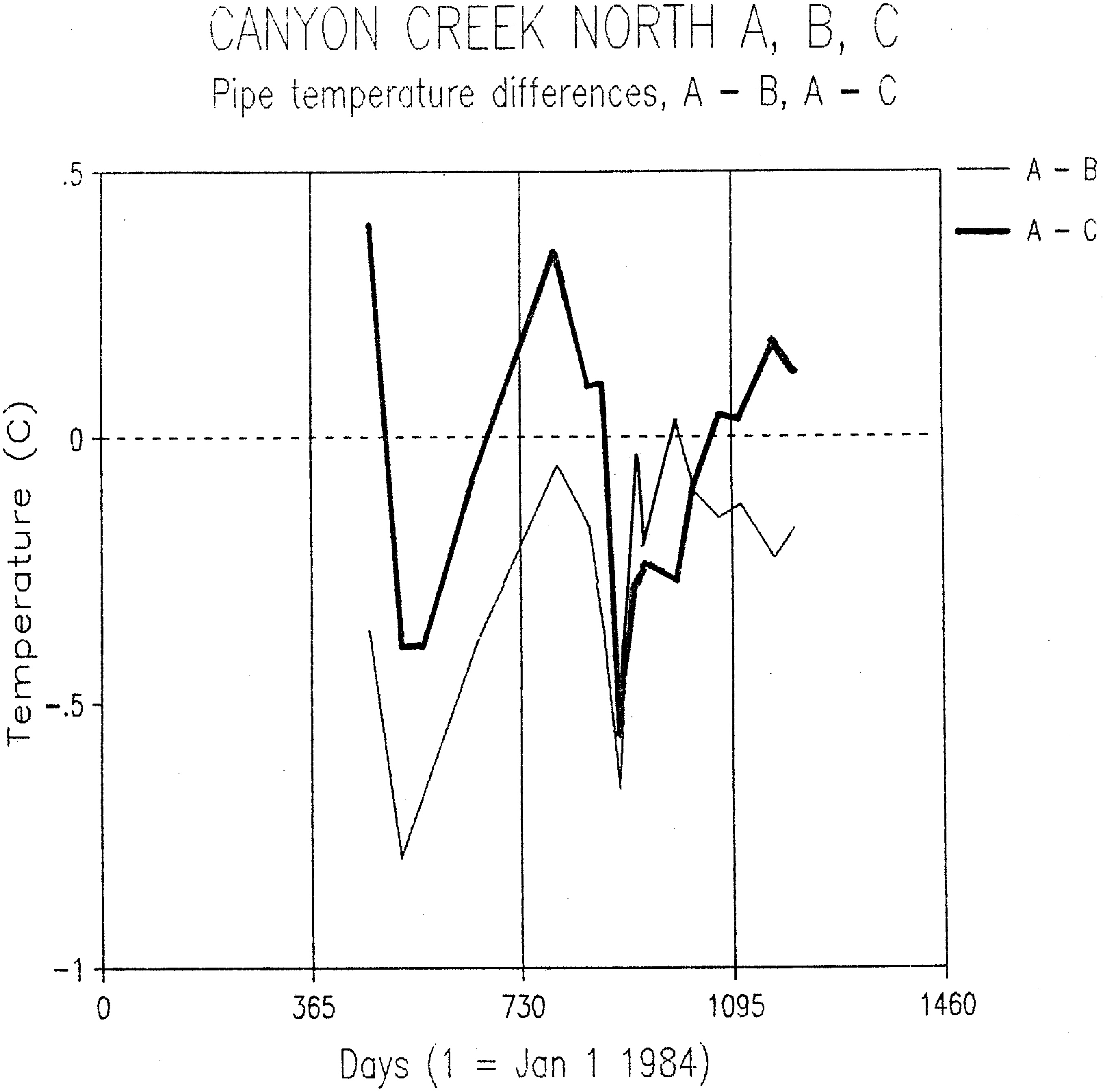
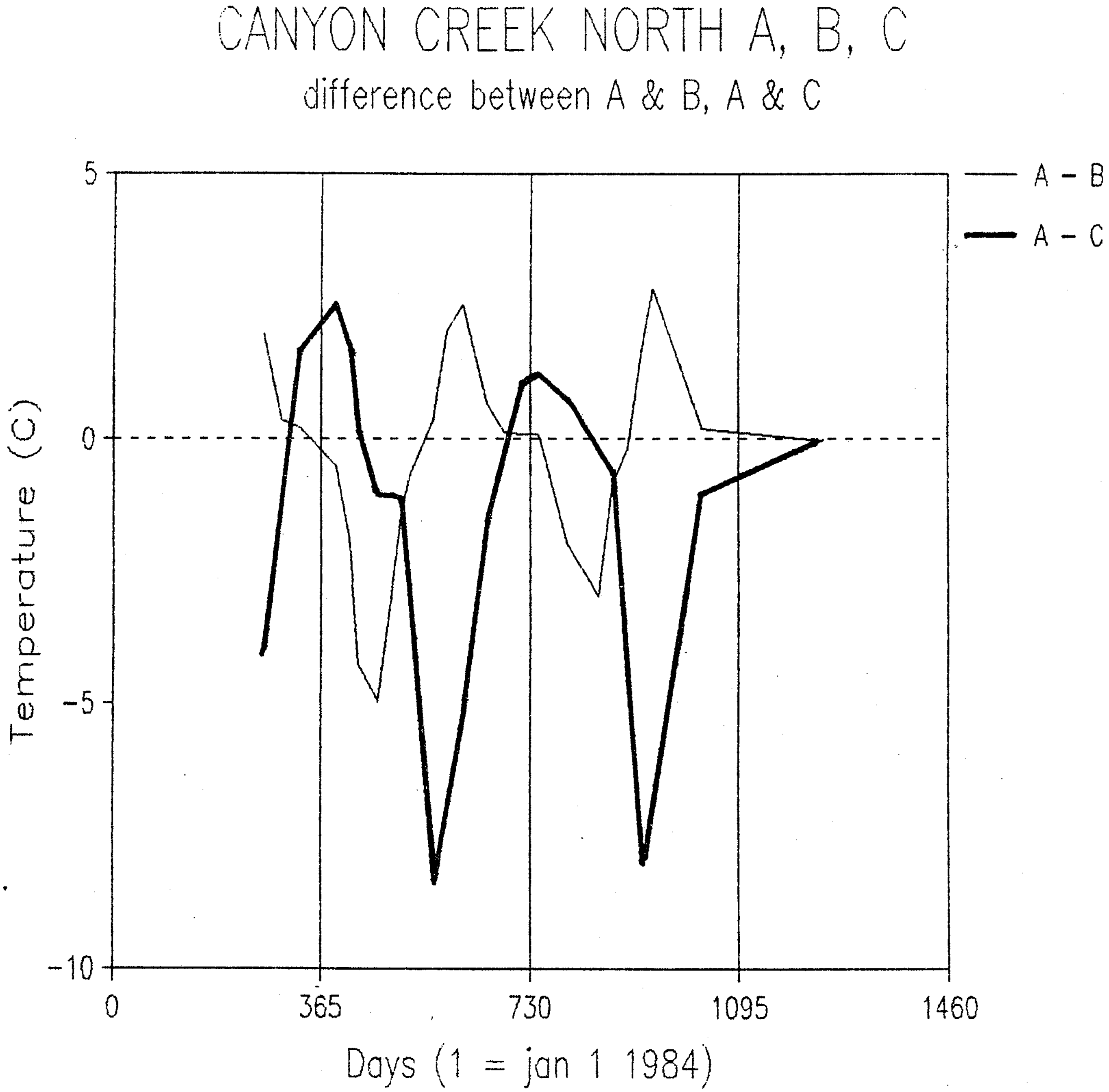

CANYON CREEK NORTH A, B, C
Pipe temperature differences, A − B, A − C
A − B
A − C
.5
0
−.5
−1
Temperature (C)
0
365
730
1095
1460
Days (1 = Jan 1 1984)

Figure 3.51



3.51

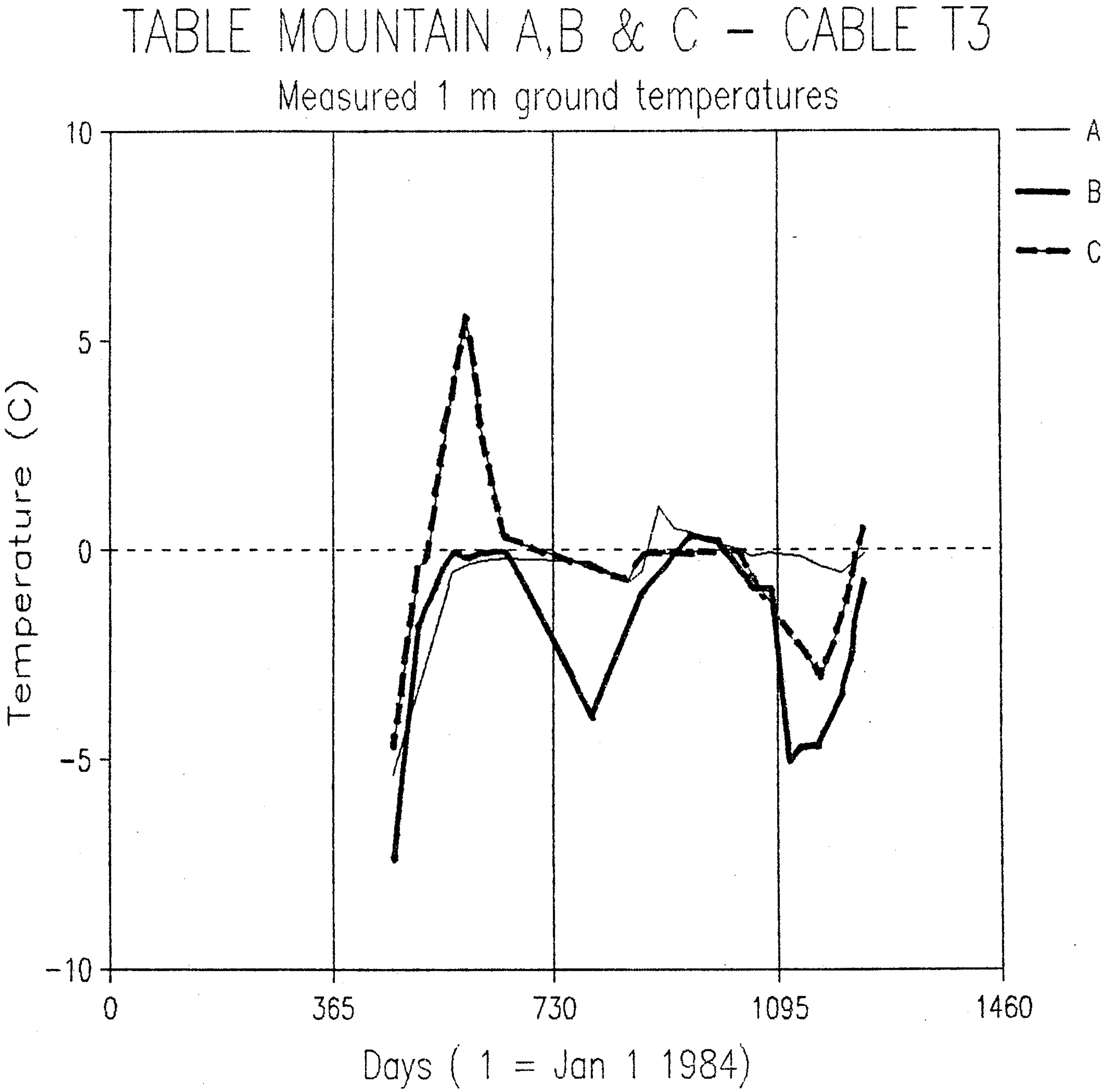
Table Mountain

At Table Mountain, fences A and B are 600 meters apart, while B and C are 300 meters apart. Here, the pipeline passes through an ice rich lacustrine plain : along an old seismic line at A, at a helipad clearing at B, and through a new clearing at C. With the exception of site C in 1985, ground temperatures at all three sites hover close to 0° in summer, but experience differing degrees of cooling in winter.

Results (Figures 3.52-3.55) are similar to those obtained for Canyon Creek, though data are not available prior to the commencement of oil flow. The pipe temperature difference (Figure 3.54) between site A and the others was never more than $.4^{\circ}$, while differences in 1 m ground temperature (in the T3 cables - Figure 3.55) along the pipeline were as much as 6° between A and B, and as much as 5° between A and C through the measurement period.

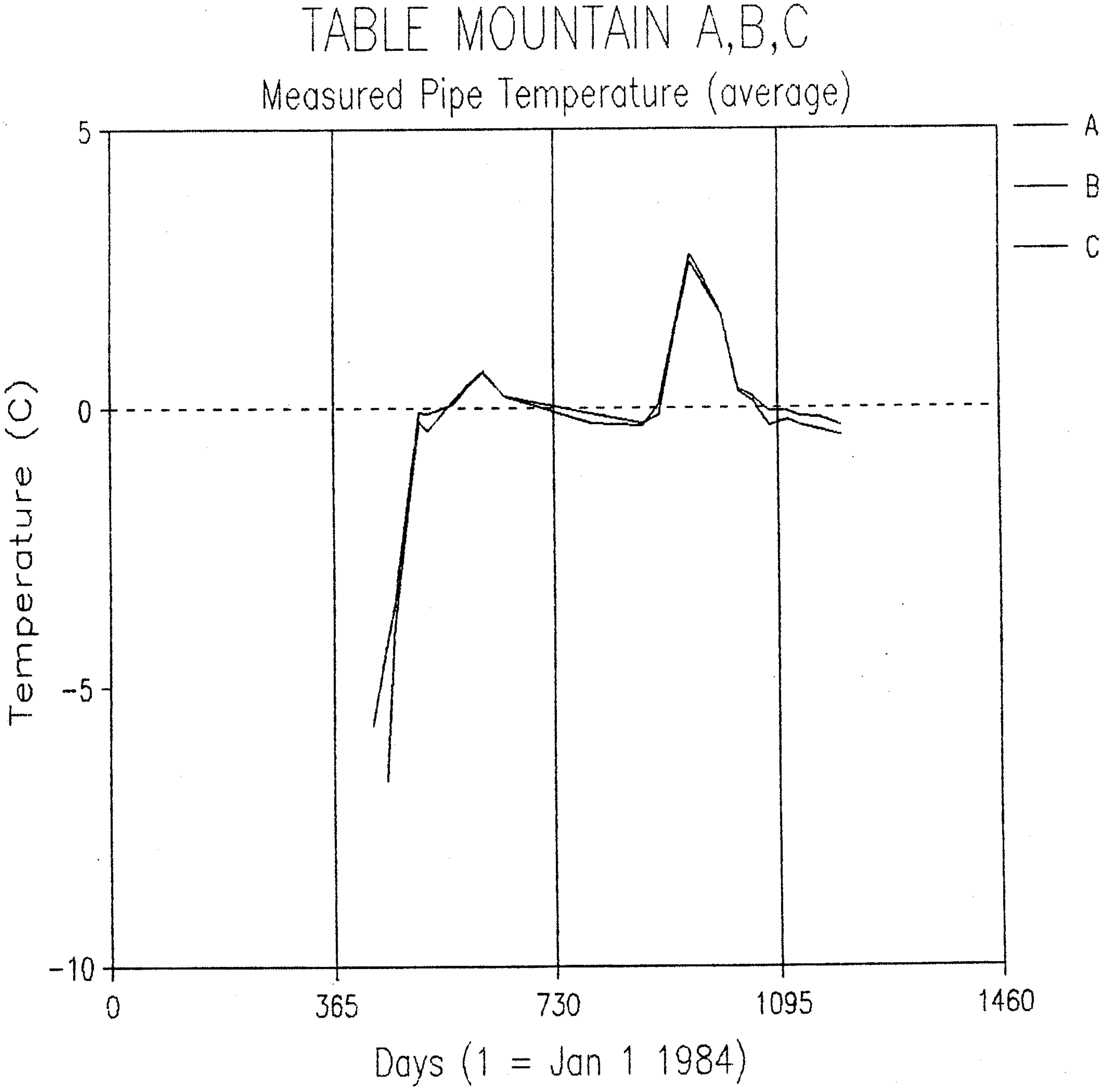
These results indicate that the length scale required for the pipe temperature to come into equilibrium with ambient ground temperatures is much greater than the scale of spatial variation of ground thermal regimes.

Figure 3.52



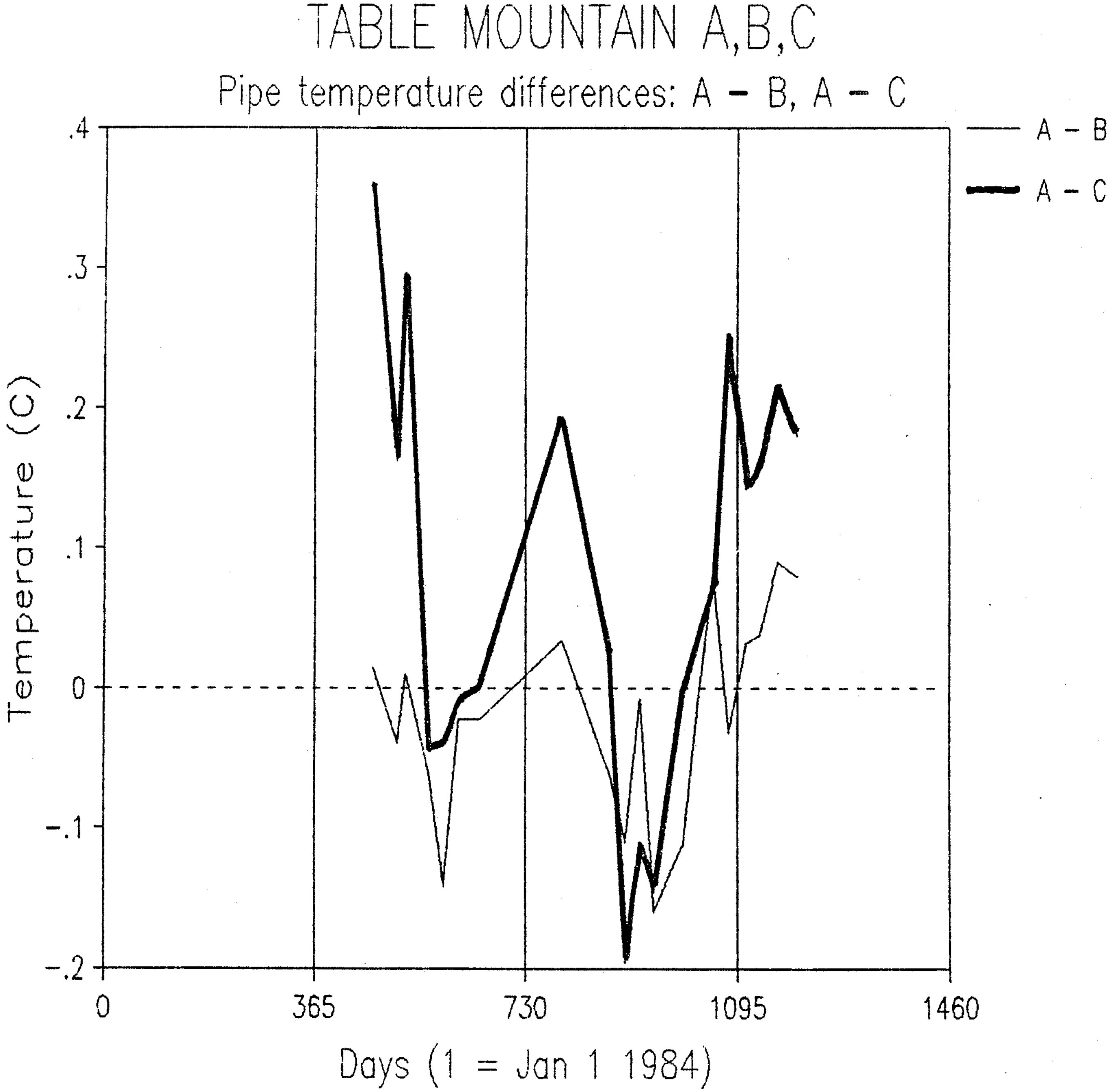
3.52

Figure 3.53



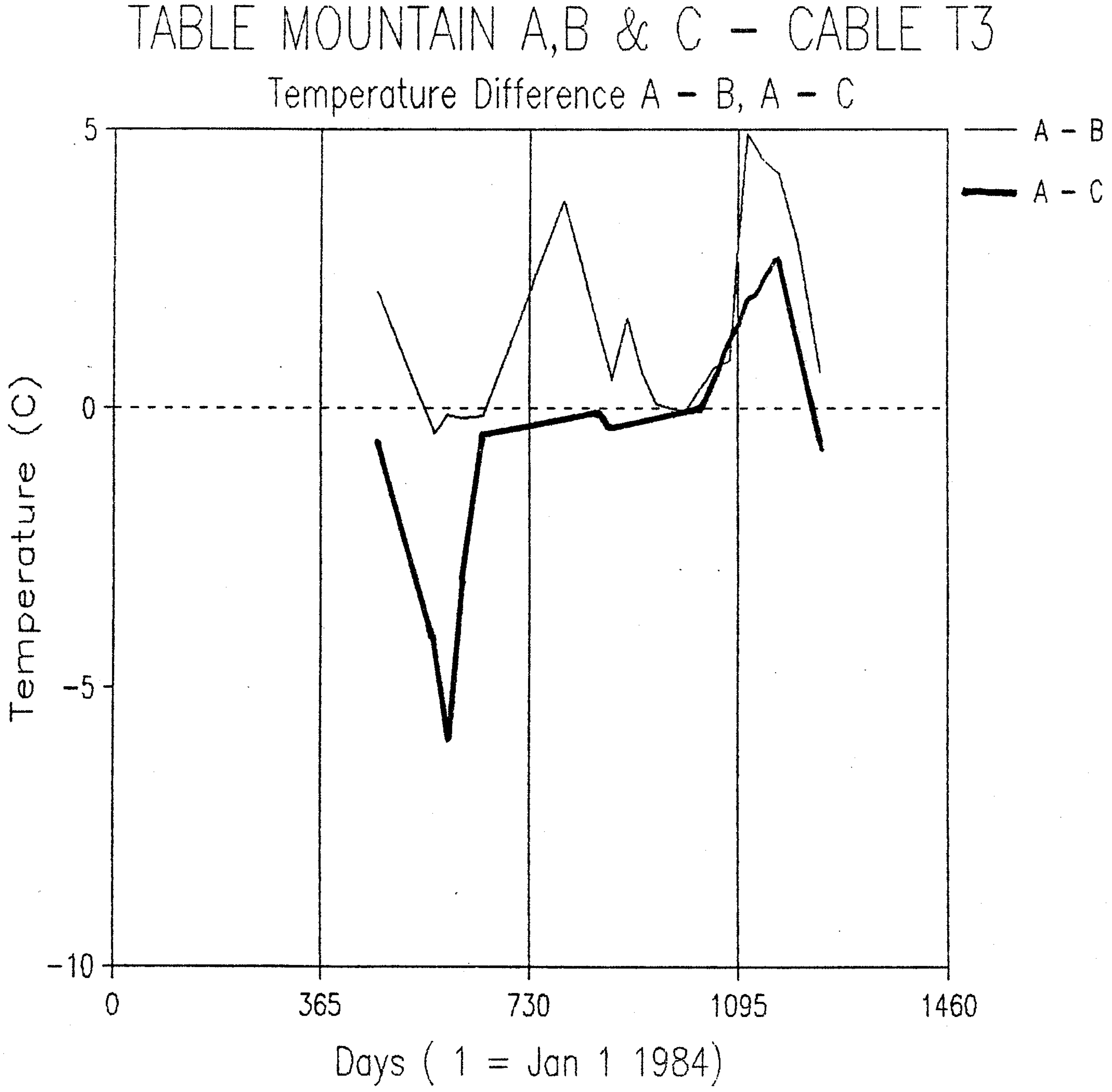
3.53

Figure 3.54



3.54

Figure 3.55



3.55

SECTION 4

RIGHT-OF-WAY PERFORMANCE

4.1 Comparison of ground temperatures on and off the pipeline Right-of-way

Tables 4.1-4.3 summarise the running mean data in the same manner as in the previous section: The running means in three periods (April 1985-February 1986, March 1986 - December 1986, and January 1987-October 1987) were examined and characterised as showing either stable temperatures, a warming trend, a cooling trend, or a variable pattern of change. The tables also indicate whether mean 1 meter ground temperatures on the right-of-way were warmer or cooler than mean ground temperatures off of the right-of-way in each of these periods.

For all periods, at most sites the mean annual temperature at 1 meter is higher in the T3 cable than in the T4 cable.

The observed warming trend in air temperatures (Figure 1.3b) is not evident in the ground temperature trends in the "undisturbed" off-right-of-way sites. Similarly, the cooling trend in some T3 cables is not apparent: for the first two periods, a significant minority of the T4 sensors had stable temperatures. In the final period, temperature trends were almost evenly divided between the four categories. In this period, more T4 sensors experienced a either warming or cooling trends than previously.

In all periods, trends in the T3 and T4 cables are are not matched at most sites. By the final period, however,

Table 4.1

Temperature trends on and off right-of-way

INITIAL PERIOD

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.	V	W	*	W	W	W					W	W	*								*		W
Off R.O.W.	W	W	*	W	*	*					W	*	*								*		*
Temperature Relationship :																							
ON: OFF	W	*	W	W	*	W					W	W	W								*		C

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

Totals:

	W	C	V	*
TRENDS:				
On R.O.W.	7	0	1	3
Off R.O.W.	4	0	0	7
RELATIONSHIPS:				
ON: OFF	7	1	0	3

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

Table 4.2

Temperature trends on and off right-of-way

MIDDLE PERIOD

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.	V	W	*	V	W	V	W	V	C	W	W	W	*	V	W	W	V	W	W	*	W	W	W
Off R.O.W.	C	V	*	V	C	*	C	C	C	W	V	*	*	*	W	W	*	V	V	*	*	W	*
Temperature Relationship : ON : OFF	W	V	W	W	C	W	W	C	C	W	W	W	W	W	W	W	W	W	W	W	W	W	C

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

Totals:

	W	C	V	*
TRENDS:				
On R.O.W.	13	1	6	3
Off R.O.W.	4	5	5	9
RELATIONSHIPS:				
ON : OFF	18	4	1	0

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

Table 4.3

Temperature trends on and off right-of-way

FINAL PERIOD

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.	V	W	*	V	W	V	*	W	V	C	C	*	*	*	C	C	W	C	V	W	V		C
Off R.O.W.	V	C	*	V	C	*	W	V	V	C	C	*	*	*	C	W	W	W	W	W	W		C
Temperature Relationship : ON : OFF	W	W	W	C	W	W	W	W	W	C	C	W	W	W	C	W	W	W	W	W	W		W

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

Totals:

	W	C	V	*
TRENDS:				
On R.O.W.	5	6	6	5
Off R.O.W.	7	6	4	5
RELATIONSHIPS:				
ON : OFF	18	4	0	0

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

one half of the sites have the 1 meter sensors in these cables are responding in the same way to the thermal environment.

The thermal behavior of the three sites at Table mountain (Figures 3.14-3.18) provide some insight into the the way in which right-of way sections of different age can respond to the changes imposed by the pipeline. Site 7a is situated in a previously cleared section; 7b is in a helipad at a bend in the pipeline; and 7c is on a new section of the right-of-way. Comparison of 1 meter ground temperatures on and off of the right-of-way at the three sites 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 up to the melting point since pipeline operation began. The early data suggest that the active layer did not reach 1 m in 1985, while it did in 1986 and 1987. The data for the T4 cable are not sufficiently complete to compare with the data for T3. At site 7b, the T3 data before mid 1986 is unreliable. However, the trends are similar in T3 and T4 after this, although the trend in the T3 sensor is toward a much more rapid temperature rise. Site 7c, the newest right-of-way section, shows the best agreement between trends on and off of the right-of-way.

SECTION 5

LONG TERM THAW AND THAW SETTLEMENT

5.1 Thaw Settlement.

The amount of thaw settlement which can occur at a given site is dependent upon the depth of thaw which it has experienced, and upon the reduction in volume which the thawed soil undergoes.

Thaw settlement is defined as:

> "The generally differential downward movement of the ground surface resulting from the escape of water on melting of excess ice in the soil and the thaw consolidation of the soil mass."
> (Johnston,1981)

"Excess" ice may be defined as ice which is not held within the soil pores, but exists between layers of soil as ice lenses or similar inclusions. If the pores in the frozen soil are saturated, water from the melting of excess ice will be expelled, with the rate of expulsion governed by the thaw consolidation process. An additional component of the volume change is due to the 9% volume reduction of ice upon thawing. The loss of volume due to the loss of excess ice will be the same for saturated and unsaturated soils, with a difference only in the amount of water expelled. In unsaturated soils, some water from excess ice will enter the soil pores. Similarly, some water from excess ice will be reabsorbed into the matrix of over-consolidated compressible soils, again without the loss of water

Thaw settlement is usually parmeterized as having two components :

$$S = A_0 + A_1p$$

where S = thaw strain (dimensionless)

A_n = thaw settlement parameters

p = overburden pressure.

Here, A_0 can be considered the settlement due solely to thawing and the subsequent loss of excess ice, while A_1 is the additional settlement due to consolidation by the weight of the overlying soil. This approach has lead to two thaw settlement test methods: tests may be performed at different overburden pressures to determine A_0 and A_1 (eg. McRoberts et al. 1983), or an average overburden pressure may be applied during tests to obtain a value for A_0 which contains some component due to A_1 (eg. Speer et al. 1973).

The problem with parameterizing thaw settlement is to establish a relationship between the settlement parameter(s) and some known physical property of the soil. Lucher and Afifi (1973) established a relationship between settlement and the frozen (i.e. initial) dry density of the soil. Nelson et al. (1983) developed a relationship between settlement and five factors derived from three properties : porosity, frozen moisture content, and degree of saturation. These approaches could not be applied in the present case, since these quantities are not known for the soil materials recovered (see Patterson et al. 1987).

Instead, the approach of Speer et al.(1973) and McRoberts et al.(1978) was adopted. Here, thaw settlement is related to the frozen wet bulk density of the soil. Bulk density is used as a surrogate for the excess ice content of the soil. The reliability of a relationship between thaw settlement and wet bulk density will be affected most by the saturation and dry bulk density of the frozen material. Lesser variables include the degree of saturation of the soil pores (i.e. between excess ice layers) and the density of soil particles. These factors increase the variability of the relationship from soil to soil. Nelson et al. (1983) (using five compound variables as detailed above) found that the standard error of their estimates of thaw settlement was greatest for silty materials.

Figure 5.1 compares the relationships developed by both Speer et al.(1973) and McRoberts et al.(1978): given the close agreement between the curves, the scatter in the original data, and the crude estimates of bulk density from Patterson et al. (1987), choice among these curves is somewhat arbitrary. The equation developed by Speer et al.(1973) was adopted for its simplicity.

The relationship of Speer et al. (1973) was used to estimate thaw settlement at those monitoring sites for which sufficient bulk density data were available (sites 7A,7B,7C,8A, and 12B). The bulk densities of individual core fragments were used to obtain the predicted thaw strain using :

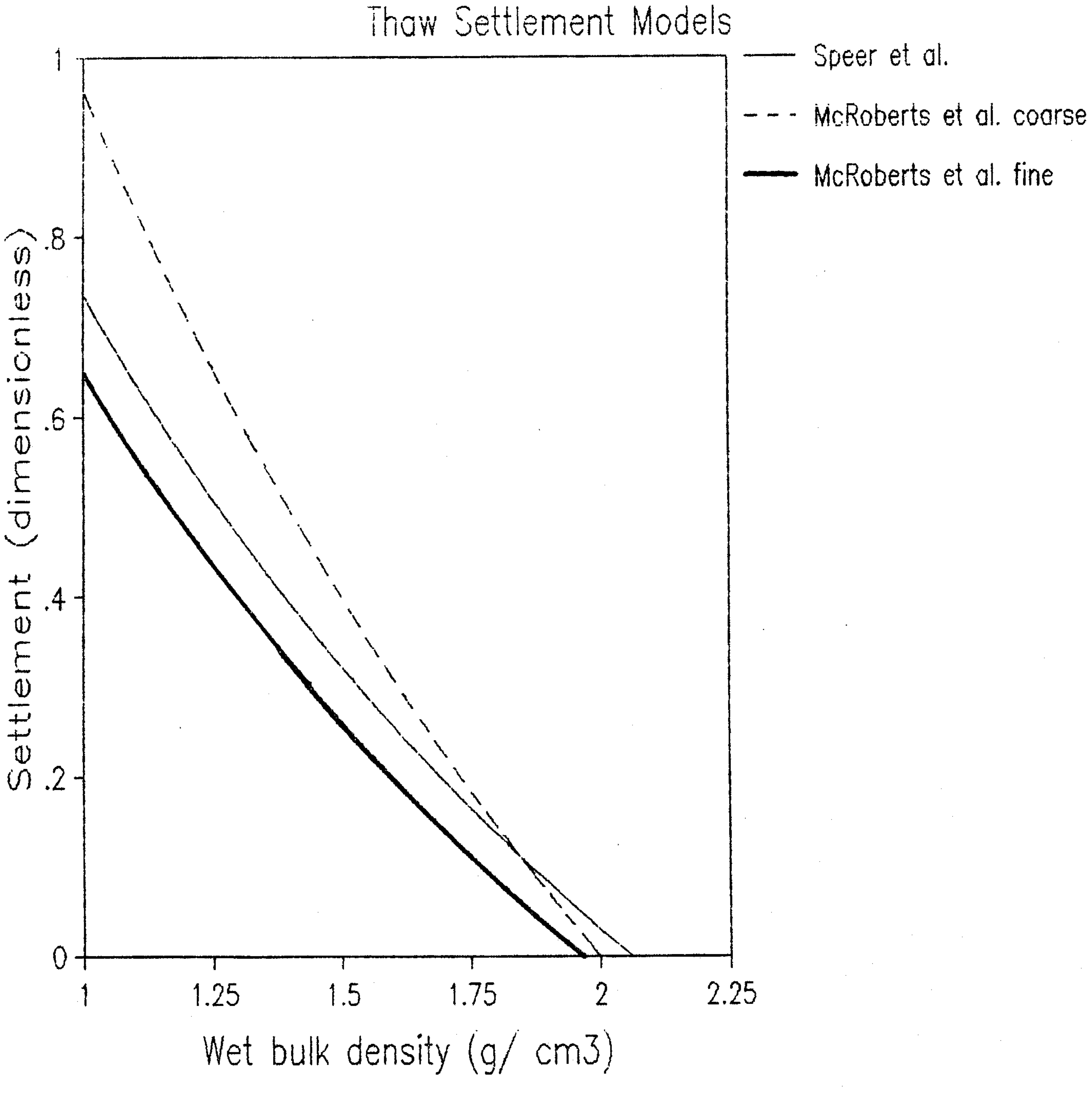
$$S = .736 - 1.018 \ln (d_w)$$

where S = dimensionless settlement factor

d_w = frozen wet bulk density ($g\ cm^{-3}$)

which is the relationship developed by Speer et al.(1973)

Figure 5.1


Thaw Settlement Models
Speer et al.
McRoberts et al. coarse
McRoberts et al. fine
Settlement (dimensionless)
1
.8
.6
.4
.2
0
1
1.25
1.5
1.75
2
2.25
Wet bulk density (g/ cm3)

(modified to give dimensionless settlement). Results are presented in Figures 5.2 to 5.6. Negative thaw settlement values were assumed to be zero.

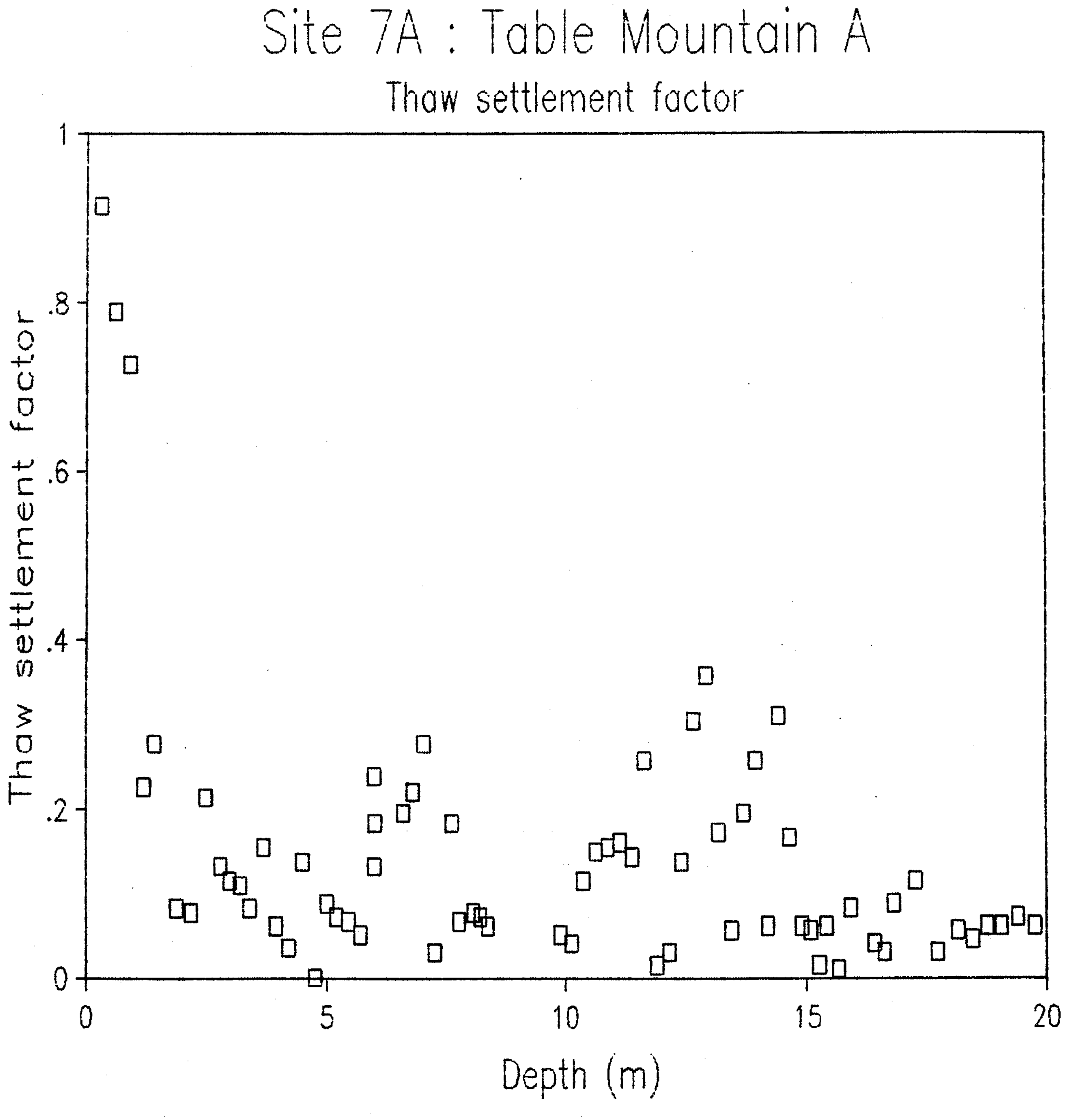
For all sites, the settlement factor is higher at the surface than below it, reflecting the effect of the lower overburden pressure on density, as well as the effect of seasonal frost on the soil structure of the active layer.

Results for the Table Mountain sites indicate that the material at site 7A is much more ice rich than at the other two sites. At 7A, the thaw settlement factor is high to a depth of 15 meters , below which the material changes from "silty clay with gravel inclusions" to "silty clay and clay". At the other sites, the upper mineral soil material is of a higher density, and the change of material below it is to a sand material. The settlement factor is low throughout except for a high ice content layer at about 10 meters at site 7B: core material was not recovered for site 7C at this depth.

The soil at Site 8A is sand down to a depth of 5m , and has a low settlement factor down to this depth. Below this, the settlement factor increases significantly. Of the sites examined here, site 8A has the highest settlement factor values at this depth.

The high thaw settlement factor for surface organic layer at site 12B is due to the use of a model developed for mineral soils. Unfortunately, none of the thaw settlement models investigated applies to organic soils. Intuitivly, one would

Figure 5.2



5.2 - 5.6

Figure 5.3

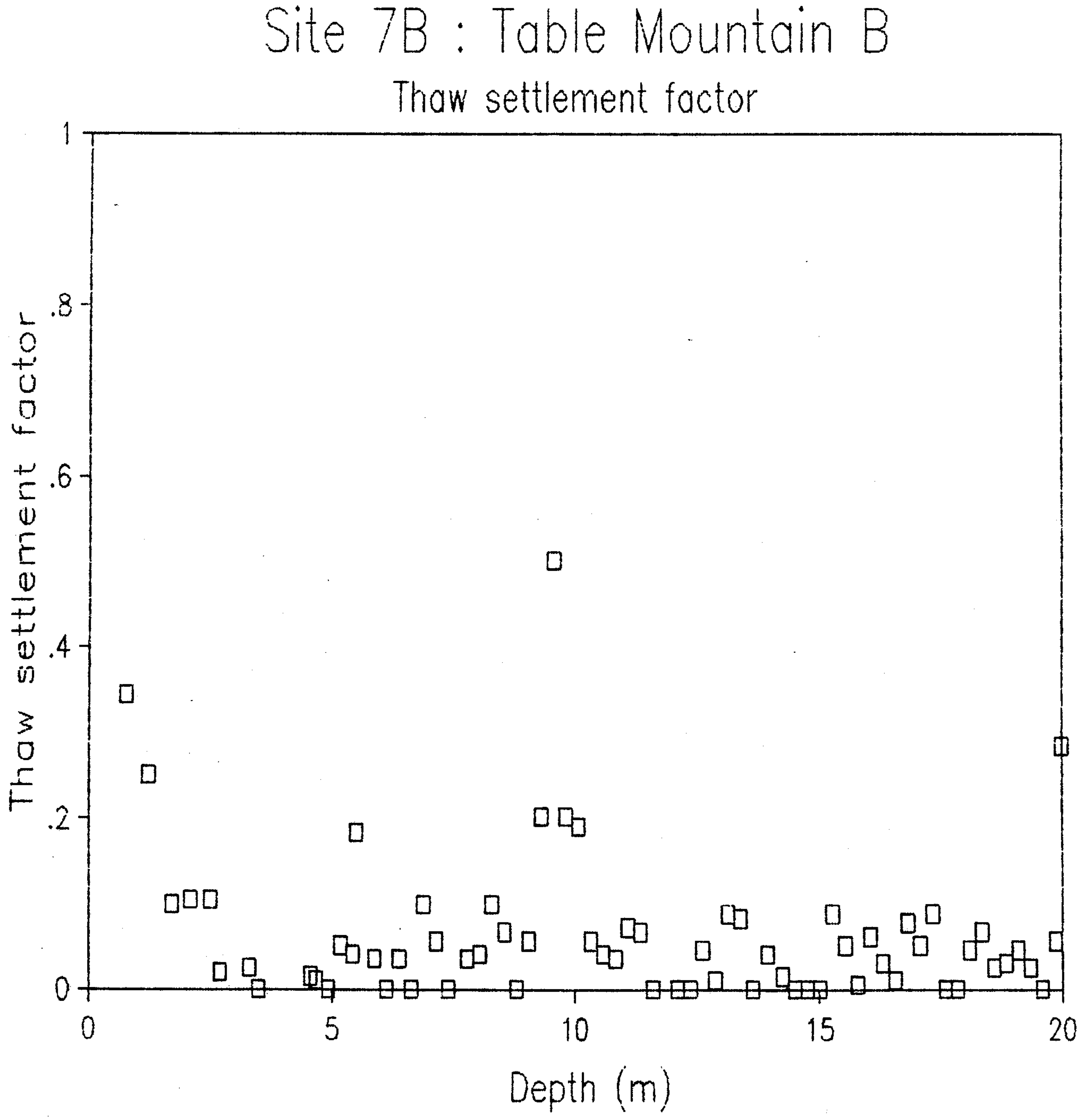

Site 7B : Table Mountain B
Thaw settlement factor
Thaw settlement factor
1
.8
.6
.4
.2
0
0
5
10
15
20
Depth (m)

Figure 5.4

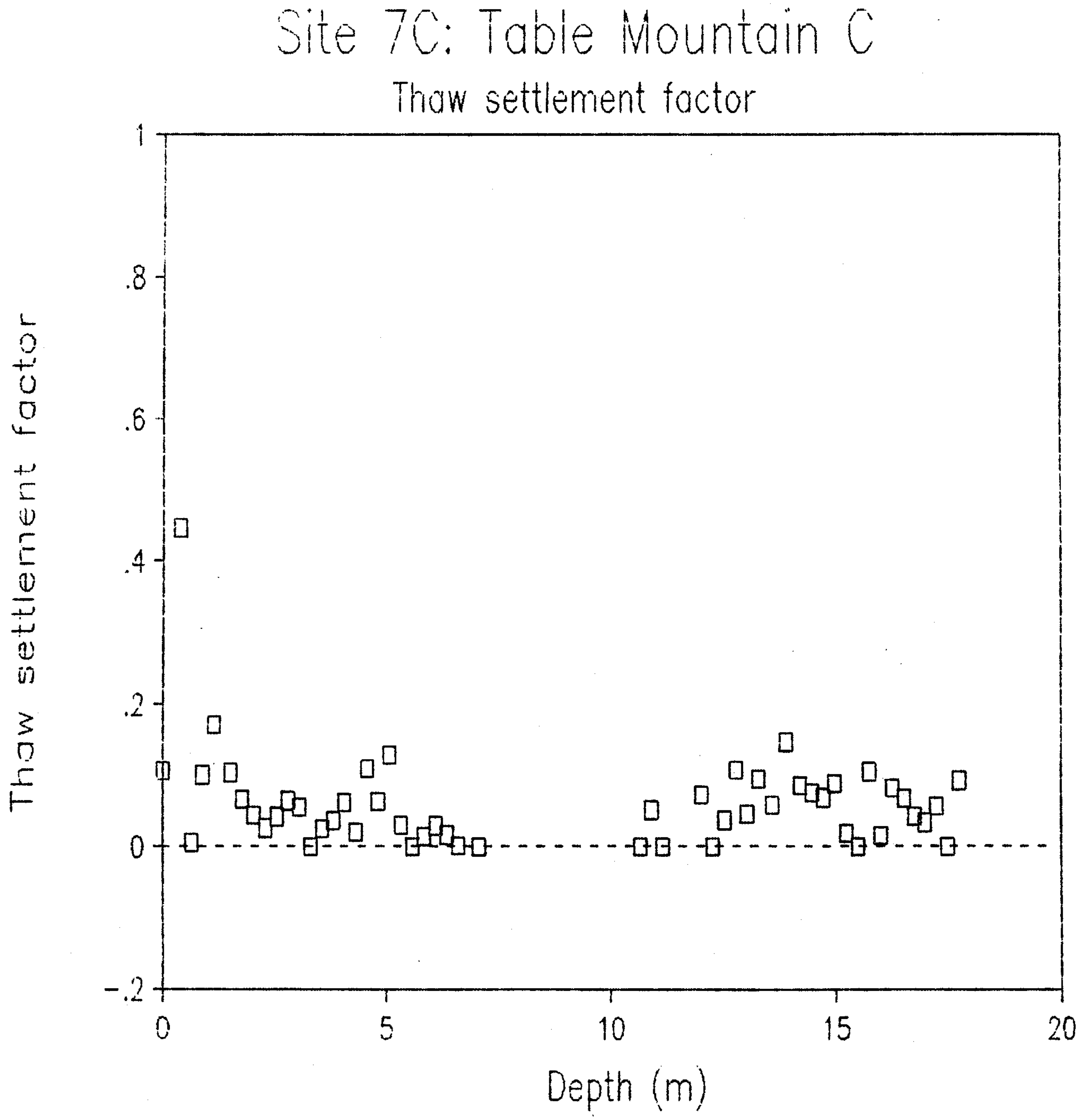

Site 7C: Table Mountain C
Thaw settlement factor
Thaw settlement factor
1
.8
.6
.4
.2
0
-.2
0
5
10
15
20
Depth (m)

Figure 5.5

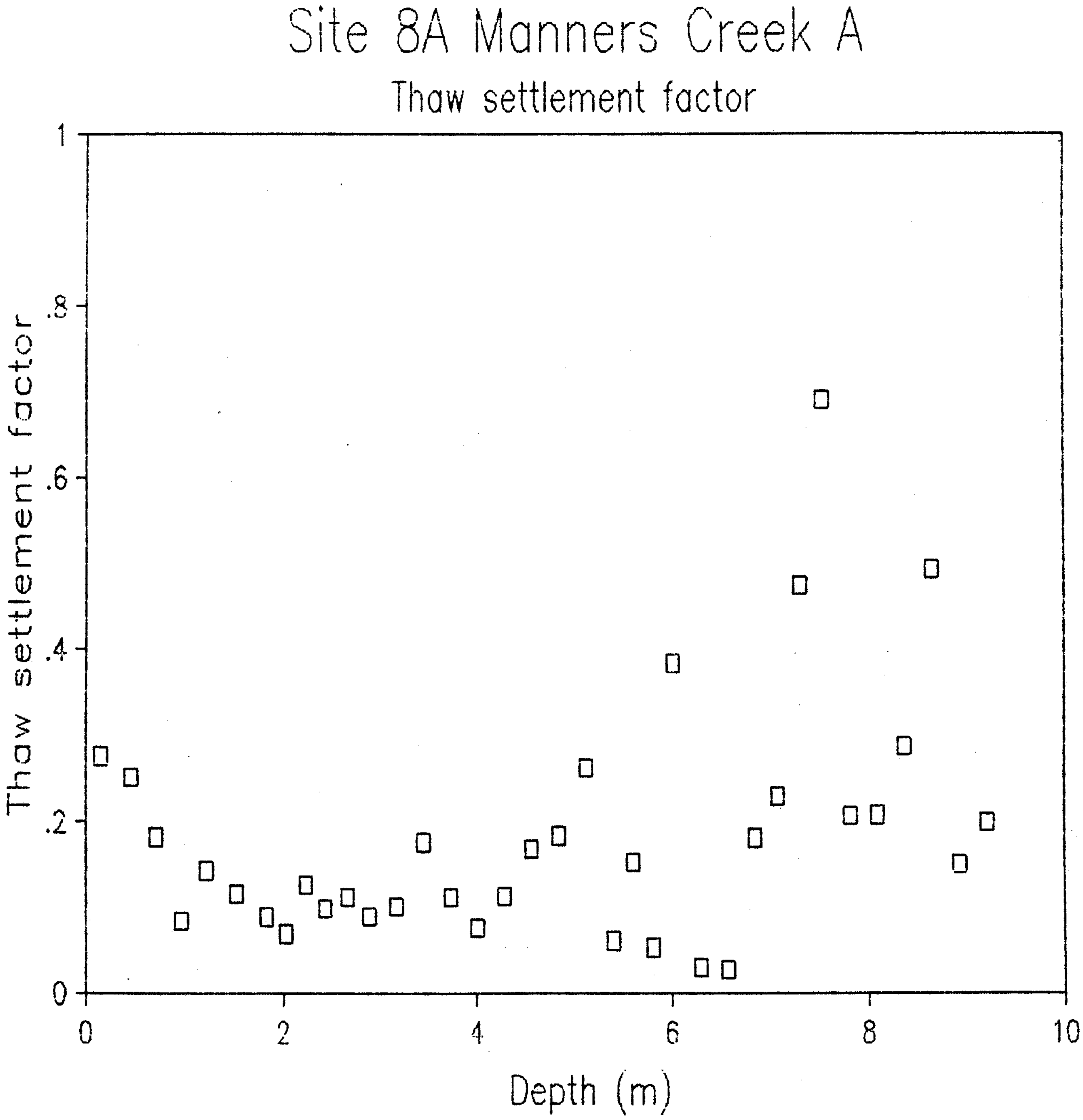
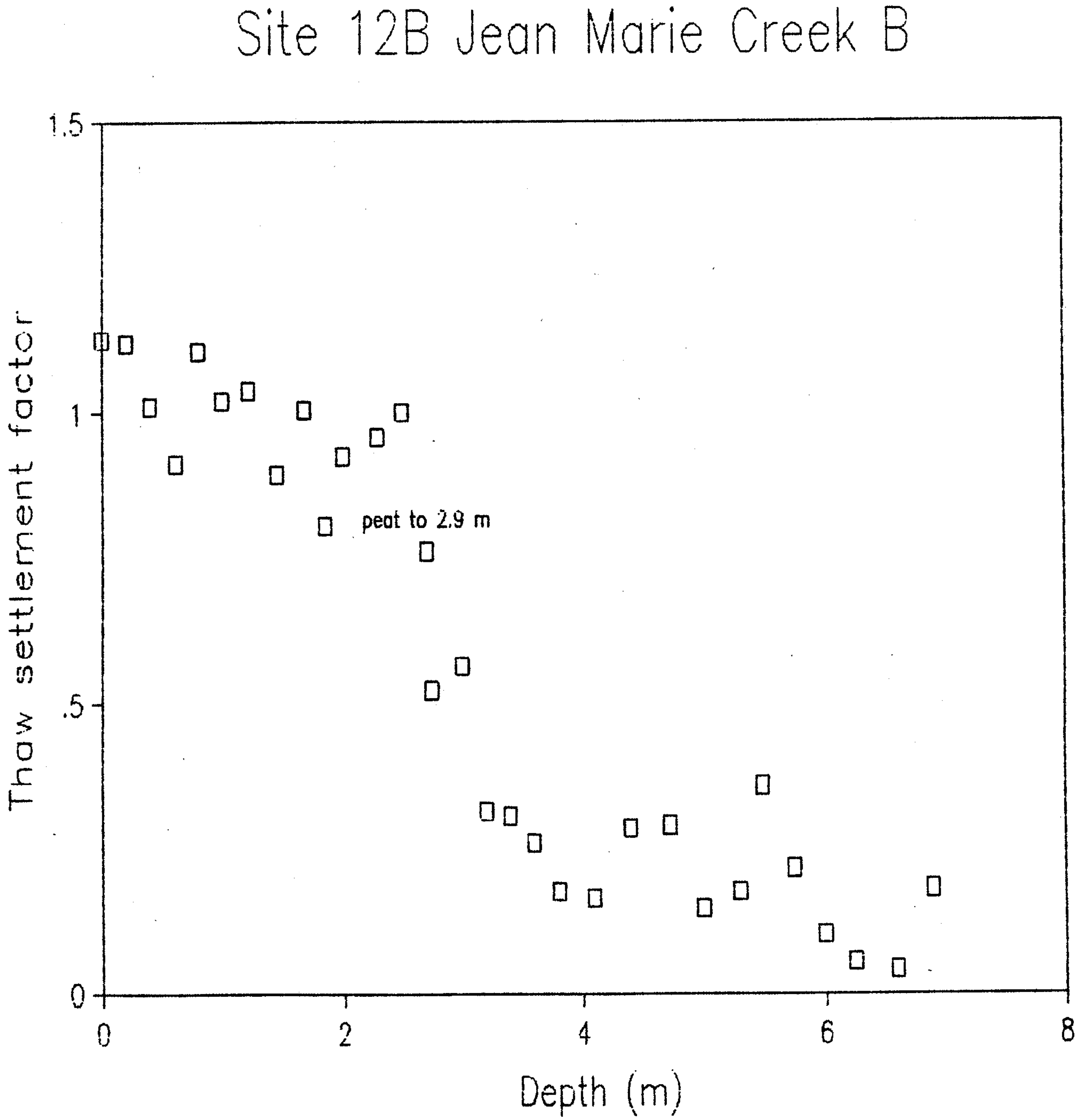

Site 8A Manners Creek A
Thaw settlement factor
Thaw settlement factor
0
.2
.4
.6
.8
1
0
2
4
6
8
10
Depth (m)

Figure 5.6


Site 12B Jean Marie Creek B
Thaw settlement factor
1.5
1
.5
0
peat to 2.9 m
0
2
4
6
8
Depth (m)

expect a smaller value for A_0, and a higher value for A_1 with these materials, due to the fibrous but flexible nature of typical peat material. Therefore, results obtained for the top portion of hole 12B are not reliable (not least because the settlement depth is greater than thaw depth).

Cumulative settlement

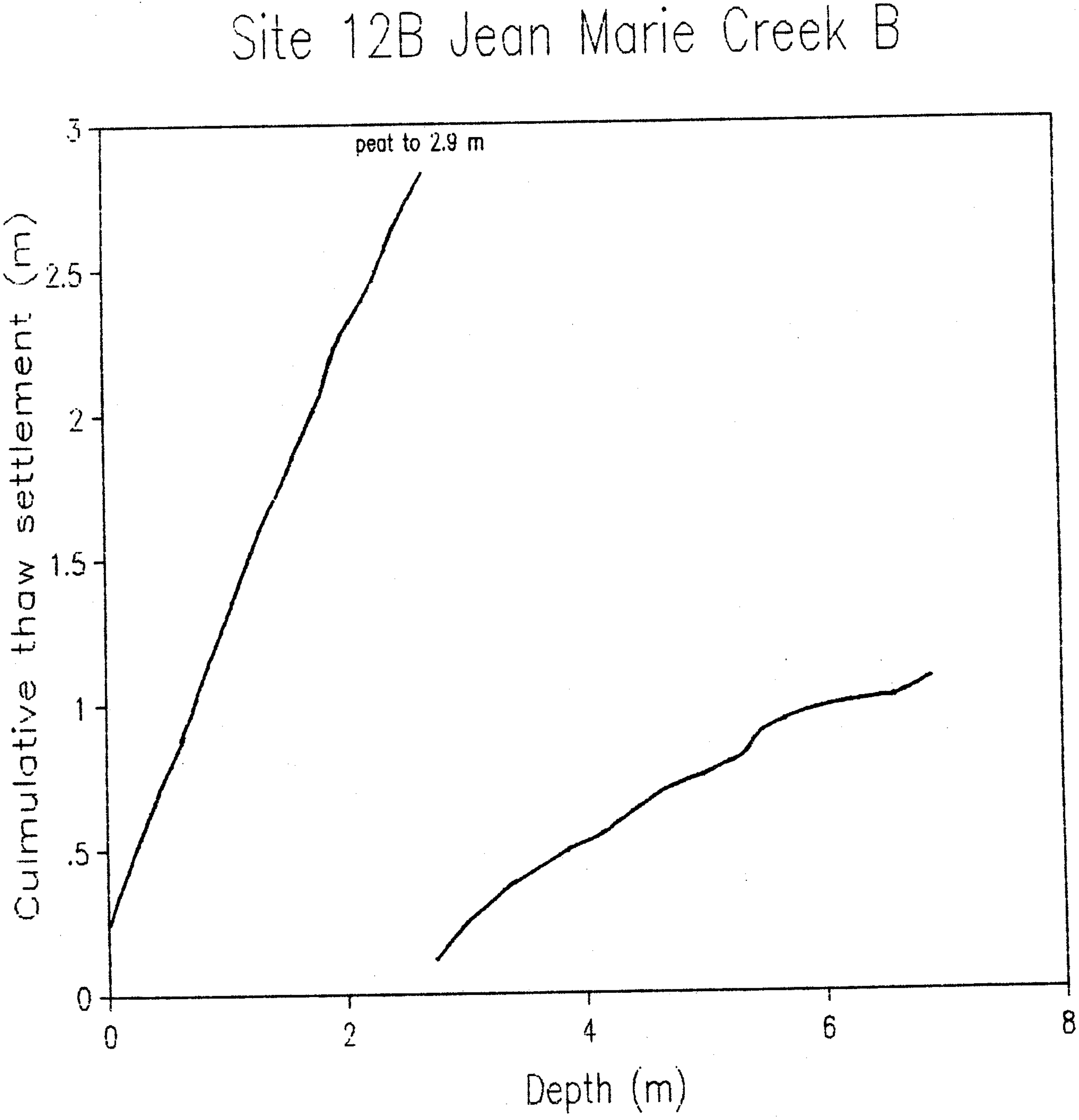
To calculate cumulative thaw settlement, individual thaw strains were calculated for each core fragment. For those sections of core where total length of core recovered did not correspond to the depth interval indicated in the drill log, the settlement factor for the missing part of the core was assumed to be the same as for the part recovered. The logged depth interval for the core was divided equally into the appropriate number of core fragments, and thaw strain was calculated by multiplying the core fraction length by the settlement factor. Individual thaw strains were then cumulated to obtain total thaw strain as a function of thaw depth. Results are presented in Figures 5.7 to 5.9.

Cumulative settlement for all sites at Table Mountain are plotted in Figure 5.7. Settlement is significantly higher at 7A.

Sites 7B and 7C are probably more similar than Figure 5.7 indicates, since the curve for 7C does not include settlement for the depth interval between 7.4 and and 10.8 meters, where no core was recovered.

The highest rate of thaw settlement is predicted at site 8A. The rate accelerates below 7 meters, where 1 meter of settlement

Figure 5.7



5.7-1

Figure 5.8

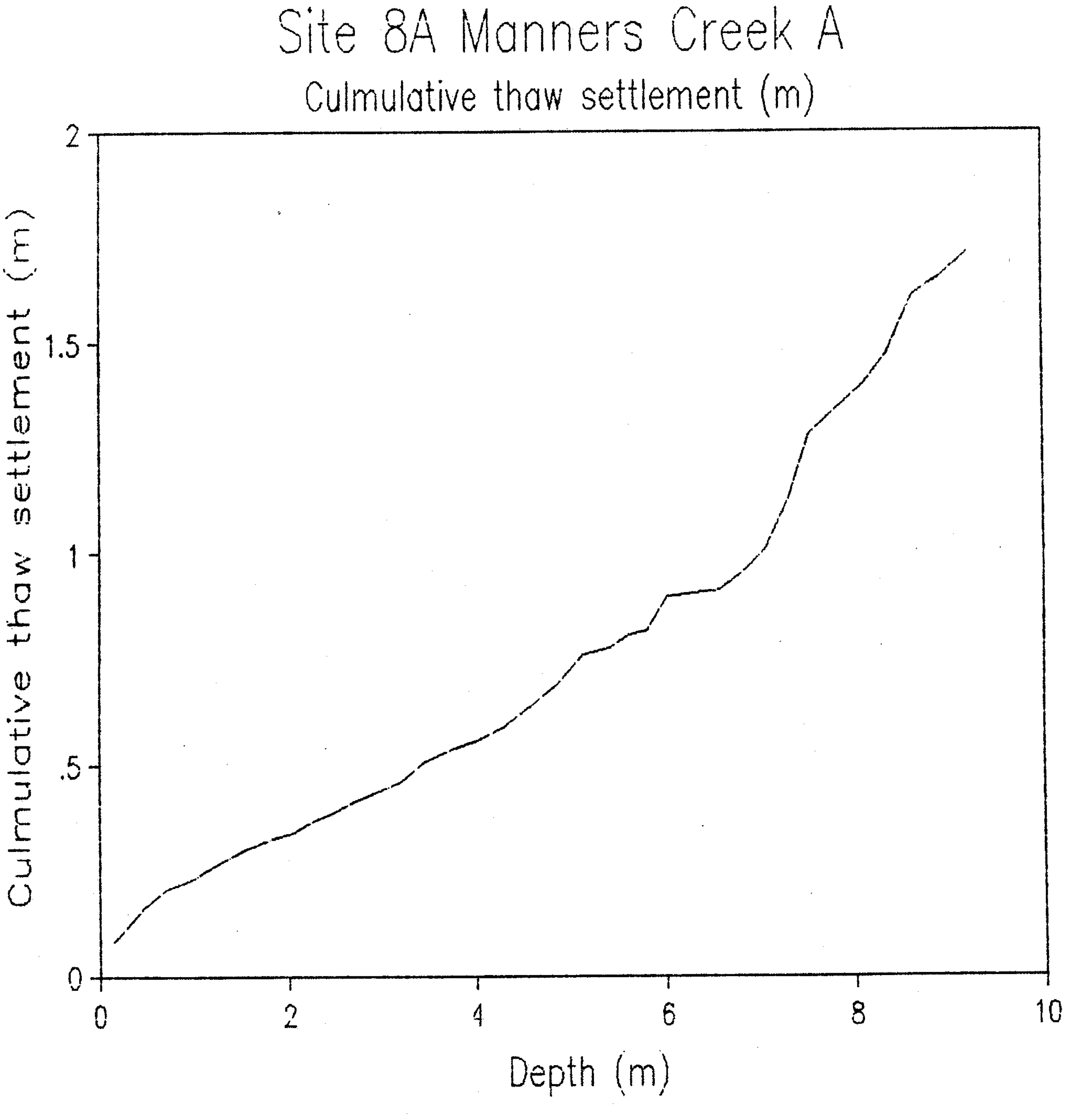
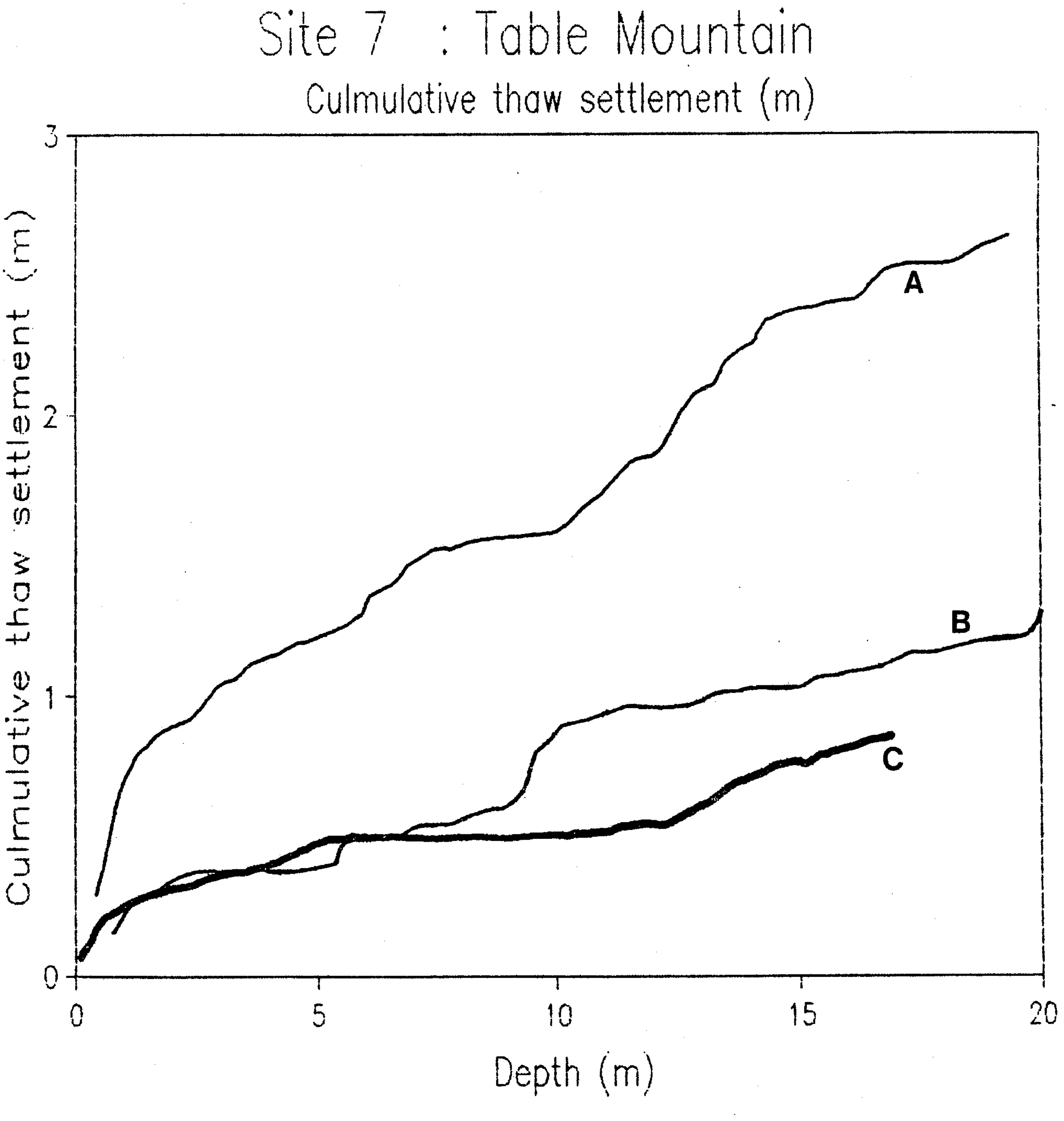

Site 8A Manners Creek A
Culmulative thaw settlement (m)
Culmulative thaw settlement (m)
2
1.5
1
.5
0
0
2
4
6
8
10
Depth (m)

Figure 5.9


Site 7 : Table Mountain
Culmulative thaw settlement (m)
Culmulative thaw settlement (m)
3
2
1
0
0
5
10
15
20
Depth (m)
A
B
C

is predicted in only 2 meters.

At site 12B, the rate of cummulative settlement predicted (below the peat layer) is slightly higher than at 7A.

5.2 Long term thaw beneath woodchip slopes

Various scenarios for long term thaw beneath wood chip slopes were investigated using the one dimensional geothermal model described in section 2.5. Two types of soil material were considered: one site having the measured thermal properties obtained for site 7b (see Table 5.1), and one having the thermal properties of ice.

A site having the thermal properties of site 7b was chosen because physical property test data are available for soil from this site as part of a concurrent testing program being undertaken under separate contract.

Ice was chosen because its thermal properties permit the evaluation of the "worst case " for thaw settlement. The ice content of soil plays a controlling role in both thaw and thaw settlement. The latent heat of fusion of the ice limits thaw front penetration, so that thaw penetration is lower for soils having more ice in them. At the same time, soils containing more ice settle more for a given thaw penetration. Jahns and Heuer(1983) and Riseborough (1982) report that the interplay of the effects of latent heat and thaw settlement result in increasing <u>cumulative</u> thaw settlement with increasing ice content for typical thaw conditions. Pure ice is the extreme case: minimum thaw front penetration, but maximum thaw settlement

Table 5.1

Thermal Properties of Site 7B
Used in Thirty Year Simulations

Thawed Heat Capacity : 2.7601×10^{7} $Jm^{-3}k^{-1}$

Temperature (C)	Unfrozen Water Content (%)	Thermal Conductivuty $W\ m^{-1}K^{-1}$
0.00	56.9	1.144
-0.02	35.2	1.546
-0.10	25.7	1.766
-0.21	24.2	1.803
-0.29	23.4	1.823
-0.40	21.6	1.870
-0.50	21.1	1.882
-0.60	20.9	1.887
-0.73	19.6	1.922
-0.83	19.2	1.934
-1.04	17.9	1.970
-1.22	18.3	1.956
-1.46	16.6	2.008
-2.02	15.3	2.046
-2.47	14.2	2.079
-2.95	13.9	2.088
-3.51	13.1	2.115
-4.47	12.7	2.131

(settlement will be 100% of thaw penetration).

In all simulations, an initial geothermal gradient of 0.02° per meter was used, with the initial surface temperatures shown in Figures 5.10 and 5.11: this established the initial permafrost thickness in each simulation. The temperatures imposed at the surface were assumed to be constant for the duration, since the ground beneath the wood chips is below the level of seasonal variation (see Figure 3.5).

One drawback of the thaw predictions presented in this section is that thaw settlement is not taken into account. As a result, the temperature gradient between the surface and the thaw front is shallower than it would be in reality, causing the model to underpredict thaw somewhat. Obvoiusly, the greater the thaw settlement, the greater the discrepency introduced by this simplification.

The two most influential parameters in this sort of thawing problem are the volumetric latent heat of the thawing soil, and the surface temperature (Nixon and McRoberts, 1973). The problem with thaw predictions in soil materials is that the volumetric latent heat is temperature dependent, as described by each soil's freezing characteristic curve. Thus, while the thaw predictions for ice are not significantly influenced by its initial temperature, the same cannot be said for the predictions for site 7B.

Results for ice (Figure 5.10) fall into two groups, each

Figure 5.10

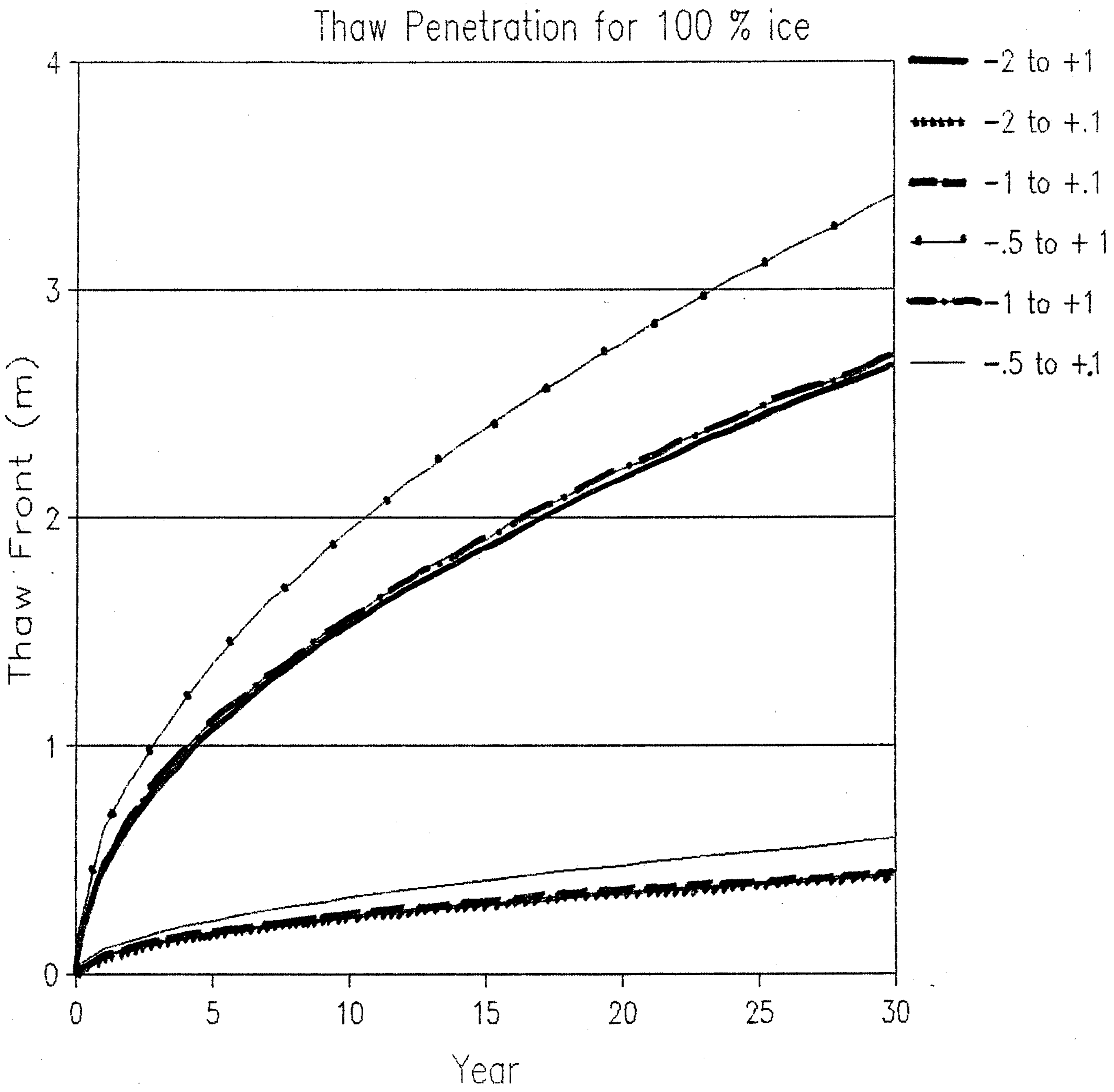
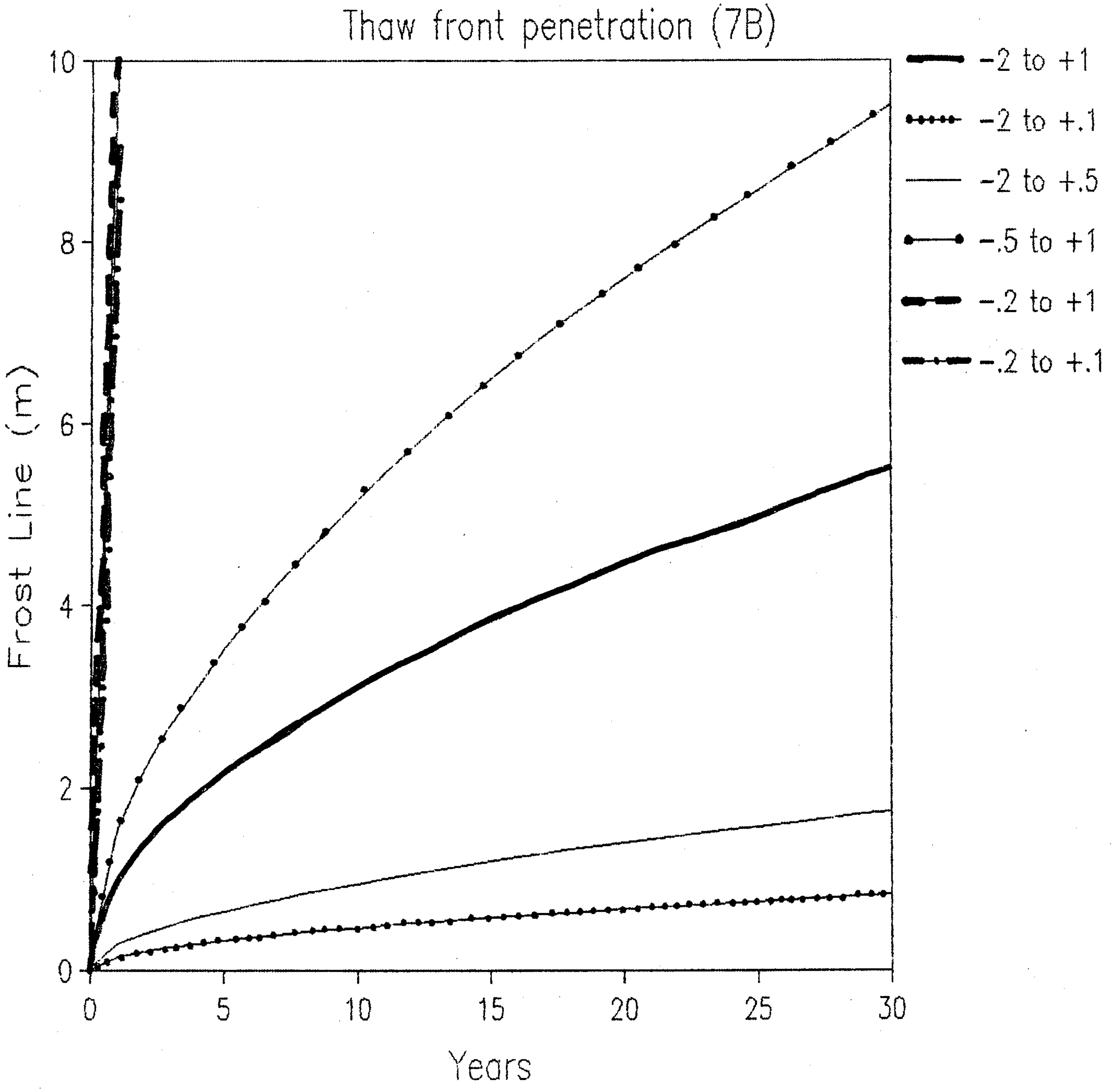

Thaw Penetration for 100 % ice
Thaw Front (m)
Year
0
1
2
3
4
0
5
10
15
20
25
30
-2 to +1
-2 to +.1
-1 to +.1
-.5 to + 1
-1 to +1
-.5 to +.1

Figure 5.11



Thaw front penetration (7B)
Frost Line (m)
Years
0
2
4
6
8
10
0
5
10
15
20
25
30
-2 to +1
-2 to +.1
-2 to +.5
-.5 to +1
-.2 to +1
-.2 to +.1

group having a common thaw temperature. This illustrates the effect of the sharp transition between the frozen and thawed states: the heat required to raise the ice temperature from -2 to 0.1° is almost the same as that required to raise it from -0.5 to 0.1°. The groupings show the dominant role played by the temperature gradients in the unfrozen layer.

At site 7B (Figure 5.11), the thaw front curves do not fall into the same groups as for ice. Here, the initial ground temperature dominates control of thaw penetration.

The two scenarios whose initial ground temperature was -0.2 both experience complete thaw (initial permafrost thickness was 10 m) within 3 years. This is primarily due to the small amount of ice remaining in the soil in the initial condition, and the ability of the unfrozen soil to thaw the premafrost layer from below. The next highest thaw penetration occured with the ground surface temperature initially at -0.5°C.

The three scenarios having an initial temperature of -2.°C behave in much the same way as for ice, showing that the surface thawing temperature does influence thaw penetration to a significant degree.

For both soil and ice, thaw penetration estimates vary by an order of magnitude for the small variations in temperature investigated. This suggests that the actual long term thaw which could occur at sites where the ground temperature goes above zero is too sensitive to the precise thermal conditions present to be predicted with confidence.

5.3 Quasi-static analysis of thaw around the pipe

Long term (30 year) depth of thaw due to the heat supplied by the pipe was estimated using Porkhayev's quasi-static method (Hwang 1977).

The model requires values for :

- surface temperature (constant for the duration);
- pipe temperature;
- initial ground temperature (initially uniform);
- pipe burial depth;
- pipe diameter;
- frozen and thawed ground thermal properties;
- latent heat of phase change for the soil.

Some of the simplifying assumptions of this approach:

1. The ground temperature is assumed to be initially uniform, so that thaw penetration in thin permafrost (and to a lesser extent in most other situations, due to the geothermal gradient) will be under-predicted, since heat must be supplied to the entire soil mass to melt the ground ice.
2. The ground surface temperature is assumed to be constant. This presents two problems : Firstly, the pipe is subjected to seasonal freezing. The effect of this on results is unclear, since mean temperatures are used to make predicitons. Secondly, results presented in section 3 of this report demonstrate that the ground temperature is changing, and may in fact go above freezing. The model does not account for changes in the thermal regime due to factors other than the pipe itself.

3. Thaw settlement is not taken into account, so that the model underpredicts thaw somewhat, as explained in section 5.2 above.

Estimates of thaw and thaw settlement after 30 years for sites 7B (Table mountain B) and 12B (Jean Marie creek B) are presented in tables 5.2, and 5.3, respectively. Thermal properties were obtained from Patterson et al. (1987), while ground and pipe temperatures were taken from the running means presented in section 3.

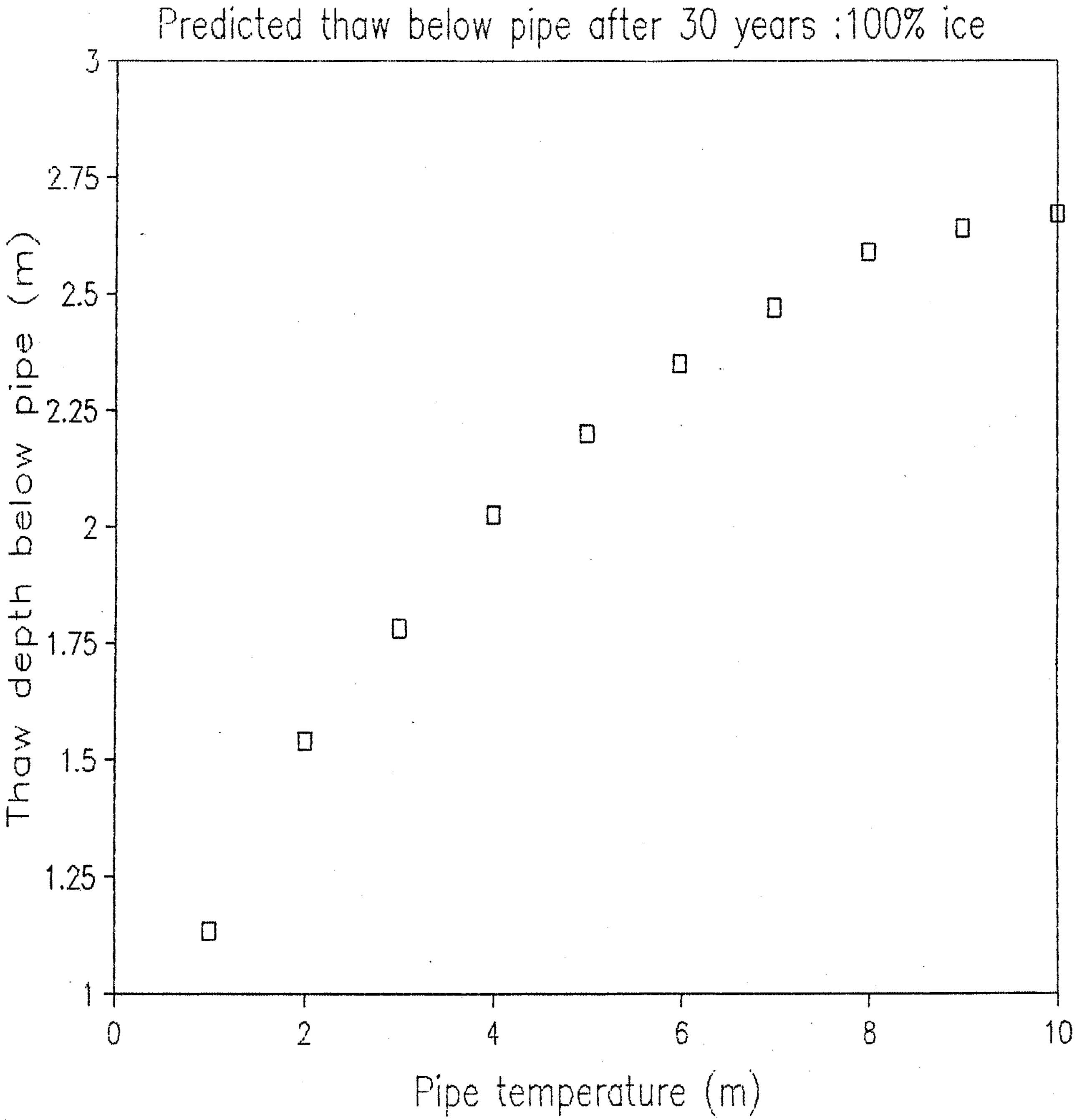
The sensitivity of the predictions was tested by varying the temperatures supplied to the model. In both tables, "case 1" represents predictions based on current ground thermal condtions.

As discussed in section 5.2, the "worst case" thaw settlement condition is that of 100% ice. Thirty year thaw depth predictions for ice, subjected to a variety of surface temperatures is presented in Figure 5.12. (For these predictions Alpha = 0 ; Mu = 6.56.) The thirty year thaw prediction for a pipe temperature of 1 degree is approximately 1.1 meters, as compared to 3.4 meters of thaw for the one dimensional thaw prediction in the previous section.

As in section 5.2, the results demonstrate that the problem solution is sensitive to the ground temperature specified, though not to the same extent as in the one dimensional situation. In Hwang's formulation of the equation, this is due to the the dimensionless parameter alpha: this is the ratio of the frozen and unfrozen thermal conductivities, multiplied by the ratio:

$$\frac{T_p - T_f}{T_f - T_s}$$

Figure 5.12


Predicted thaw below pipe after 30 years :100% ice
Thaw depth below pipe (m)
3
2.75
2.5
2.25
2
1.75
1.5
1.25
1
0
2
4
6
8
10
Pipe temperature (m)

where T_p = Pipe temperature

T_f = Freezing point temperature

T_s = Surface temperature.

When both T_p and T_s hover close to 0°, the ratio approaches indeterminacy, and predictions become uncertain.

Because the ground thermal regime hovers so close to the melting-point, estimates of long term thaw using either geothermal simulation or the quasi-static method are very sensitive to small variations in the ground and surface temperatures used for prediction. This reinforces the need for ongoing pipeline monitoring.

The scenarios examined here are based on measured ground and surface temperatures rather than the "worst case" scenarios (in the engineering design sense) used for pipeline design. Therefore,long term estimates of thaw and thaw settlement presented here do not exceed those used for the pipeline design.

Table 5.2
Quasi-static analysis Parameters for 12b:

```
                INPUT PARAMETERS:
           Thawing water content:      .50
      Frozen thermal conductivity:     1.40
      Thawed thermal conductivity:      .30
                      Pipe radius:      .16
             Depth to top of pipe:      .95

CASE 1:           Pipe temperature:     3.50
                Ground temperature:     -.80

         DIMENSIONLESS PARAMETERS:
                            Alpha:    -1.07
                               Mu:     6.86

            Year    Beta      D/r0  Thaw depth below pipe (m)
             30     30.12      4          .648


CASE 2:           Pipe temperature:     3.50
                Ground temperature:      .00
                            Alpha:      .00

            Year    Beta      D/r0  Thaw depth below pipe (m)
             30     30.12     12.5     2.025


CASE 3:           Pipe temperature:     2.50
                Ground temperature:      .00
                            Alpha:      .00

            Year    Beta      D/r0  Thaw depth below pipe (m)
             30     25.46     10.5        1.701


CASE 4:           Pipe temperature:     4.50
                Ground temperature:      .00
                            Alpha:      .00

            Year    Beta      D/r0  Thaw depth below pipe (m)
             30     34.15      14         2.268
```

Table 5.3
Quasi-static Parameters for 7b:

CASE 1: INPUT PARAMETERS:
Thawing water content: .20
Frozen thermal conductivity: 1.77
Thawed thermal conductivity: 1.20
Pipe radius: .16
Depth to top of pipe: .90

Pipe temperature: .50
Ground temperature: -.10

DIMENSIONLESS PARAMETERS:
Alpha: -.29
Mu: 6.56

Year	Beta	D/r0	Thaw depth below pipe (m)
30	36.41	9	1.458

CASE 2:
Thawing water content: .36
Pipe temperature: .50
Ground temperature: -2.00
Alpha: -5.90

Year	Beta	D/r0	Thaw depth below pipe (m)
30	26.77	.65	.1053

CASE 3:
Thawing water content: .16
Pipe temperature: 1.00
Ground temperature: -.10
Alpha: -.15

Year	Beta	D/r0	Thaw depth below pipe (m)
30	56.52	16	2.592

SECTION 6

SUMMARY

1. At most monitoring sites, mean annual pipe temperature is greater than the mean annual temperature in the T3 cables. Similarly, the mean annual temperatures in the T3 cables is warmer than in the T4 cables at most sites.

2. Comparison of mean annual ground/pipe temperatures and the air temperatures measured at nearby weather stations shows that the relationship between them is not straightforward. The effects of ponding on the right-of-way, snow clearance, and the dry summer of 1987 all contribute to the relationship between air and ground temperatures.

3. Comparisons of pipe and ground temperatures show that the length scale required for the pipe temperature to come into equilibrium with ambient ground temperatures (when oil is flowing) is much greater than the scale of spatial variation of ground thermal regimes.

4. Thaw settlement estimates for the Table Mountain sites indicate that the material at site 7A is much more ice rich than at the other two sites. The soil at Site 8A has a low settlement factor down to 5m, below which the settlement factor increases significantly. At site 12B, the rate of cumulative settlement predicted below the peat layer is slightly higher than at 7A.

5. Thaw settlement scenarios examined here are based on measured

ground and surface temperatures rather than the "worst case" scenarios (in the engineering design sense) used for pipeline design. Therefore,long term estimates of thaw and thaw settlement do not exceed those used for the pipeline design.

6. Because the ground thermal regime hovers so close to the melting-point, estimates of long term thaw are very sensitive to small variations in the ground and surface temperatures used in the model. This reinforces the need for ongoing pipeline monitoring.

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