GEOLOGICAL SURVEY OF CANADA

OPEN FILE 2888

Measurement frequency analysis for pipe and ground temperatures from the Norman Wells to Zama pipeline thermal monitoring program, Northwest Territories

Dan Riseborough

1994

Natural Resources Canada Ressources naturelles Canada

Canada

MEASUREMENT FREQUENCY ANALYSIS
FOR PIPE AND GROUND TEMPERATURES
FROM THE NORMAN WELLS TO ZAMA PIPELINE
THERMAL MONITORING PROGRAM

by

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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 869 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 Line Inc. was established following the signing of an Environmental Agreement between the pipeline company and the Department of Indian and Northern Affairs (INAC). The Geological Survey of Canada of the Department of Natural Resources is a principal participant in this program.

A major component of the research involves the detailed quantification of changes in the ground thermal regime and geomorphic conditions at a series of instrumented sites along the pipeline route. This project was developed in cooperation with the Terrain Sciences Division 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 consultant's report describes but one aspect of these site investigations. Interpretations contained herein are often limited to the specific database under analysis and thus may not represent 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 Canada.

Funding for the research and analyses reported herein was largely provided by INAC through their Northern Affairs Program and the Northern Oil and Gas Action Plan.

Margo Burgess
Scientific Authority
Terrain Sciences Division
Geological Survey of Canada

March 1994

Measurement Frequency Analysis for Pipe and Ground Temperatures from the Norman Wells - Zama Pipeline Thermal Monitoring Program.

for

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Measurement Frequency Analysis for Pipe and Ground Temperatures from the Norman Wells - Zama Pipeline Thermal Monitoring Program.

Introduction

Background

Temperature measurements have been obtained manually at Norman Wells - Zama Pipeline Thermal Monitoring Program sites approximately six to nine times per year since 1985. This measurement frequency was chosen to allow adequate characterization of the annual ground thermal regime. Monthly and annual mean temperatures are estimated from the manual measurements using computer generated spline interpolations.

Much more frequent measurements are available for selected sites with automatic data acquisition systems. At several sites (7A,B and C and Site 12B) Seadata dataloggers were installed in 1989. At these sites, temperatures are recorded 3 times per day.

Shortly after the first year of operation of the earliest Seadata datalogger installation, an analysis of the reliability of the manual measurement frequency was undertaken (Burgess and Riseborough, 1989), using the data from loggers to compile synthetic "manual" measurement records with various measurement intervals. With the availability of logged data for more sites, now extending over several years, the analyses undertaken in the earlier study can now be repeated with more general usefulness.

The analysis presented in Burgess and Riseborough (1989) was limited in several respects:

-The period of record was limited to one year;

- Only one "manual" data set was examined for each measurement interval and sensor. The term "manual" data set used here and throughout the report (that is, with quotation marks) refers to data sets generated from datalogger data which are intended to represent a data set which could have been produced as part of the Monitoring Program's manual measurement program.

- All data sets had the same starting date, with subsequent measurement dates following at regular intervals. This lead to inconsistencies in results, since some data sets with relatively long measurement intervals produced smaller errors than some with a shorter interval. Fortuitous selection of measurement dates which adequately characterized the underlying curve reduced the interpolation error in these cases.

- The actual monitoring program data consists of measurements taken at nearly regular intervals, while the earlier analysis used data sets with measurements at precisely spaced intervals.

The distinctive thermal behaviour of the pipe temperature sensors was not considered in the earlier analysis. Manually and automatically recorded data for temperature sensors attached to the pipe as well as those adjacent but unattached (on a separate datalogger) are now available. Similar analytical techniques may be used to assess the adequacy of the manual measurement program to describe the pipe thermal regime.

Statement of Work

1. Use the data for two sites obtained using dataloggers to establish "true" values for the important temperature statistics for the pipe and ground.

2. Using the data from the logger data set, examine the relationship between measurement frequency and the accuracy of monthly and annual mean ground and pipe temperatures. Examine the reliability of the current measurement program by comparison of monthly and annual means based on interpolations between manual measurements taken at the present interval.

3. Examine the significance of pipe shutdowns to the monthly and annual pipe thermal regimes. Explore (if necessary) possible means of correcting for this effect when site monitoring visits coincide with a pipe shutdown.

4. Examine the relationship between temperatures recorded by attached and unattached pipe temperature sensors (at one site).

Methods

Spline Interpolation

Soil and pipe temperatures were estimated between temperature measurements using cubic spline interpolation, a standard interpolation technique in which a continuous curve is fit to a finite data set. Starting with the first 4 measurements in the data set, a separate third degree (i.e. "cubic") polynomial is found for each successive (overlapping) set of 4 consecutive data points. Each curve has three segments (between points 1 and 2, 2 and 3, and 3 and 4). The spline procedure produces a continuous curve for the whole time series by concatenating the central segments of the individual curves, and forcing their solutions (the polynomial coefficients) so that adjoining segments have the same slope (first derivative) where they join.

Mean annual temperatures were calculated from the interpolated curves by using the coefficients of the spline equations to integrate temperature over a one year interval, and dividing by 365 days.

Monte Carlo Sampling

To address the shortcomings in Burgess and Riseborough (1989) outlined above, an approach was used which considered any particular "manual" data set to be only one of a potentially infinite number of equally likely data sets. By repeatedly producing alternate "manual" data sets with a given measurement interval, it is possible to characterize the uncertainty about the underlying temperature wave when it is sampled at that interval. The errors (i.e. the differences between the interpolated curves and the actual temperature curve) for each particular interpolation are considered a single sample of the errors from the universe of possible data sets. With a sufficiently large number of samples, errors can be summarized using standard statistical measures (averages and standard deviations).

Operational Procedure

A standard procedure was established for all analyses:

1. For each measurement interval examined, sets of "manual" measurement files were created using the datalogger files supplied by the scientific authority. A small random variation in the measurement interval was included in the files created, to simulate the

character of the manual data files of the monitoring program. The procedure to create each file was as follows:

> Given a specified measurement interval "m" (in days) and a range of random uncertainty "u" (set at +/- 5 days for all analyses), measurement times "T_n " were selected as follows :
>
> - The time of the first measurement (T_1) was selected at random for some date within the first m days of the datalogger record.
>
> - Subsequent measurements were selected from the datalogger record. Measurement T_n is selected at random from the data for the period (m - u) to (m+u), calculated from the time of the previous measurement (i.e. T_n is in the range [T_{n-1} + m - u] to [T_{n-1} + m + u]). The "manual" measurement date was selected at random from the set of all measurements available from the datalogger record over this interval.

For all operations involving random number selection, a randomized shuffle routine was employed to avoid serial auto-correlation in the random numbers (Press et al. 1989). Thirty different files were created for each measurement interval. This number was chosen as the minimum required to permit the reliable use of standard "summary" statistics to describe the distribution of interpolated temperatures around the measured values.

2. Spline interpolation was performed for each of the 30 manual measurement files. Interpolated values were calculated at 10 day intervals. Mean annual temperatures were calculated from the spline coefficients. (Use of the spline coefficients for the mean annual temperature calculation eliminates errors in the mean due to a coarse interpolation interval.)

3. Spline results for all 30 files were collected into two files (one each for spline results and mean annual temperatures based on the spline results) for analysis using a spreadsheet program. The record in the files for each interpolation consisted of time series of (typically around 100) interpolated values for each sensor.

- for each day in the time series, the 30 different interpolated values were summarized by calculating the range of uncertainty (or error) in the estimate (maximum estimated value minus minimum estimated value) as well as the standard deviation of the estimates.

- The time series of uncertainty ranges and standard deviations (for both the spline and the mean annual of the spline) were then summarized with 4 statistics:
  - Maximum range of uncertainty/error for any day
  - Maximum standard deviation for any day
  - Average range of uncertainty/error for the time series
  - Average standard deviation for the time series.

Analyses of typical results show a strong relationship between the range and standard deviation both for individual dates and for the summary statistics, as would be expected from sampling theory. Each set of 30 data files represents a finite sample of the potentially infinite number of possible data files which could be created from a nearly continuous measurement record. The analyses which follow use the standard deviation of the time series to further explore the results, since the extreme values and uncertainty ranges exhibit the idiosyncracies of the particular samples used. It is relatively straightforward to move from statements about uncertainty expressed in terms of the standard deviation to statements in terms of the probable range of uncertainty.

4. This procedure was repeated for several different "manual" measurement intervals: 30, 35, 42, 49, 56, 63, 70 and 90 days.

Analysis of Ground Temperatures.

Introduction

The relationships between measurement interval and uncertainty about interpolated and mean annual temperatures were explored using data from the T1 cable at Canyon Creek (site 2A, located at kilometre 19 south of Norman Wells. This cable was chosen because of the relatively small distance between sensors (50 cm compared to 1m and greater in the deeper cables T3 and T4), and because the data record for this cable was relatively free of measurement "noise". The sensor at 2 m depth experienced a drift in calibration over time. However, this drift was so gradual that it did not influence the analysis which follows.

Measured Ground Temperatures

The datalogger record for the T1 sensors is shown in Figure 1. The data are characterized by a decreased temperature range and a smoother temperature trend at increasing depths. Seasonal cyclic temperature changes at the surface of the soil combined with the finite thermal diffusivity of the soil result in the exponential attenuation of the surface wave with depth:

$$A_z = A_0 e^{-z\sqrt{\Omega/2\alpha}} \qquad (1)$$

Where

A_z = temperature wave amplitude at depth z.

A_0 = surface temperature amplitude.

Ω = angular frequency, = $2\pi/P$, where P = the period of the temperature cycle

α = Diffusivity

The typical behaviour described above is apparent in the data for Canyon Creek (Figure 2.). This behaviour influences temperature fluctuations of any period, so that the ground temperature cycle at greater depths does not reflect short term (higher frequency) variations due to daily or synoptic scale changes at the surface. As a result, measurements taken at a given time interval will give a more precise estimate of the annual temperature regime at greater depths in the ground.

The effect of the release/absorbtion of latent heat upon freezing/thawing is to produce an abrupt change of thermal behaviour as the soil temperature moves into or out of the

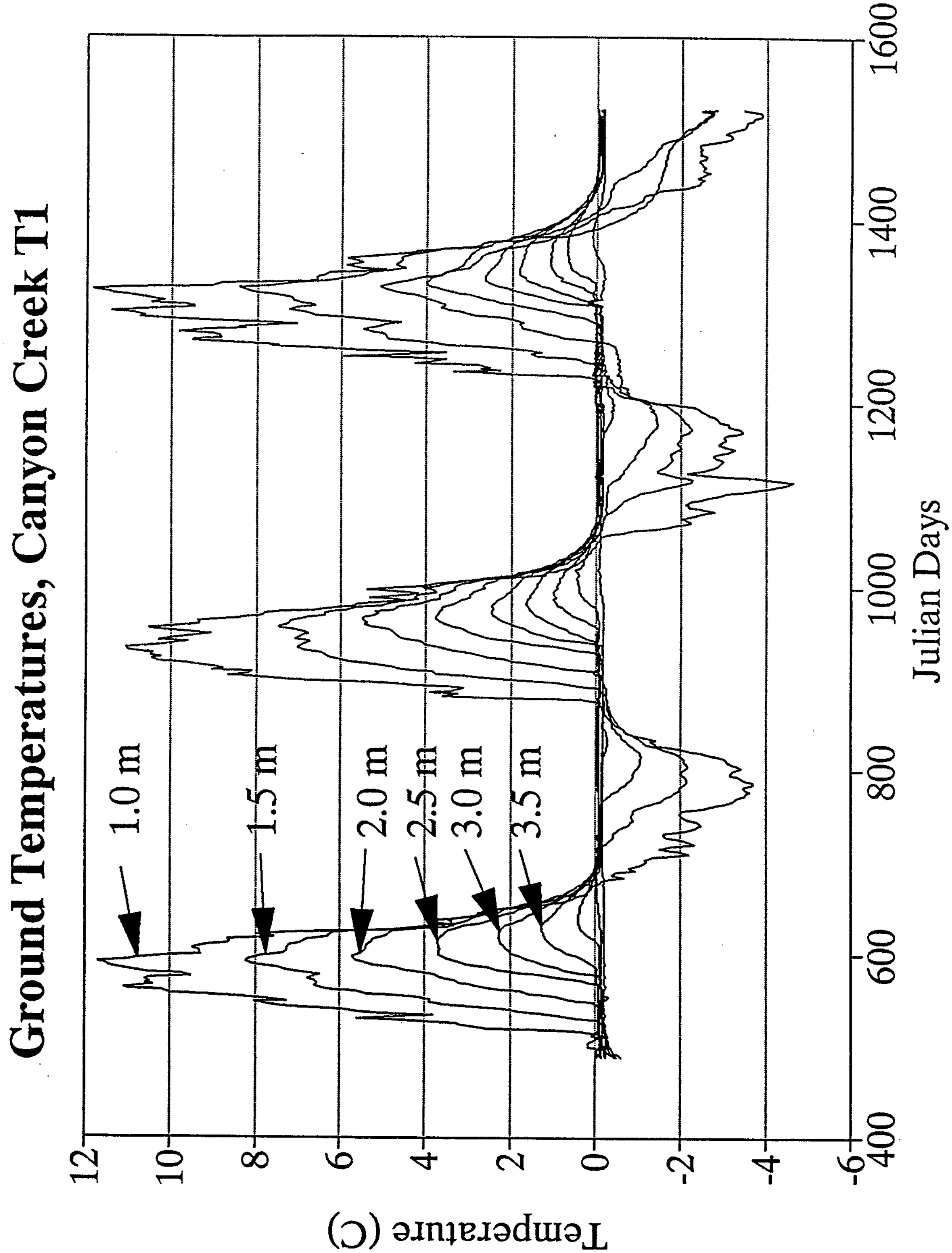


Figure 1 Base date for Julian days (day 1) is January 1, 1984.

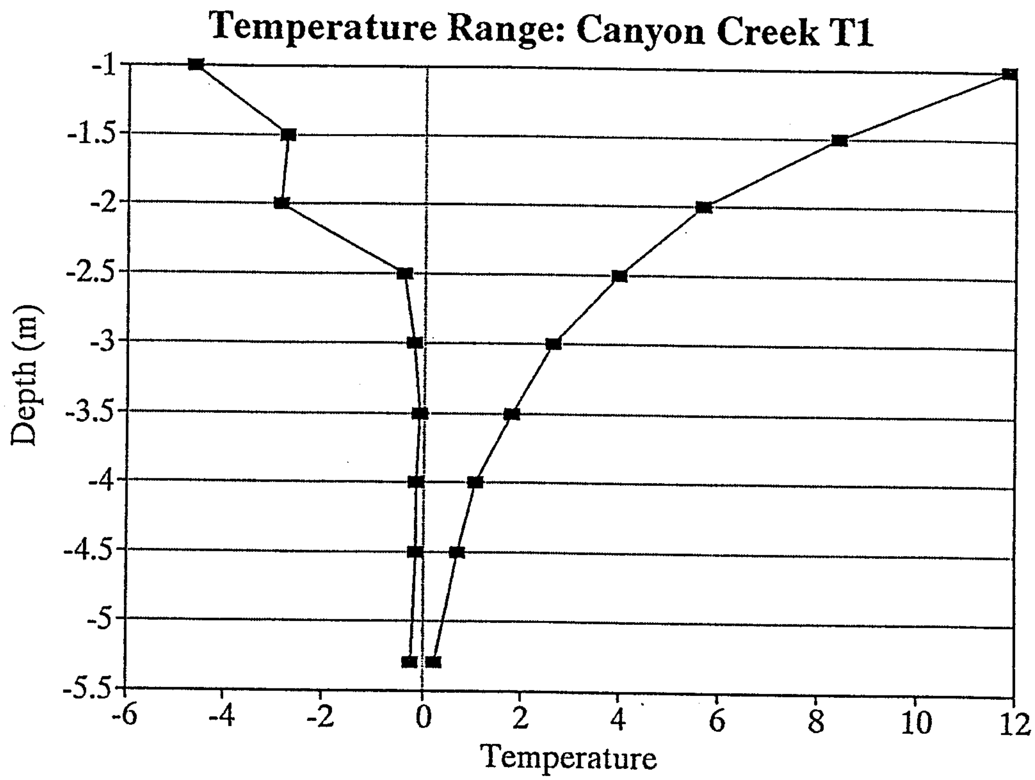


Figure 2

temperature range in which latent heat is a significant factor: this is apparent in the temperature envelop for Canyon Creek as a distortion of the temperature envelop toward relatively uniform temperature minima at depths below 2 metres. The abrupt change in temperature behaviour can reduce the accuracy of results obtained using spline interpolation, since the assumption of curve fitting is that the underlying behaviour is characterised by smooth rates of change. Fortunately, this behaviour is limited to depths in the ground where short term temperature variations have been filtered out of the temperature wave, effectively isolating these two sources of error to different parts of the ground temperature profile.

Figures 3 and 4 show the trends in mean annual temperature for all sensors on this cable. Between the upper sensor and the lower sensor is a shift of about 2°C in the mean annual temperature. Over the course of the measurement record, at all depths the mean annual temperature has varied by about 0.2°C.

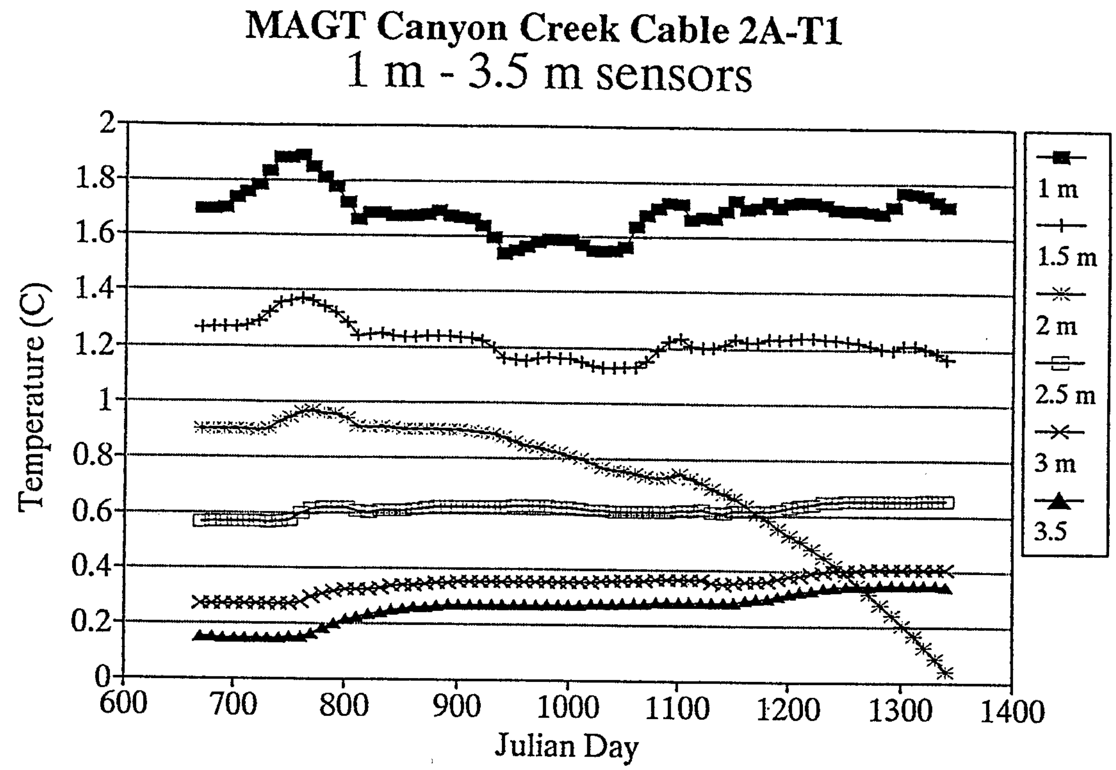


Figure 3

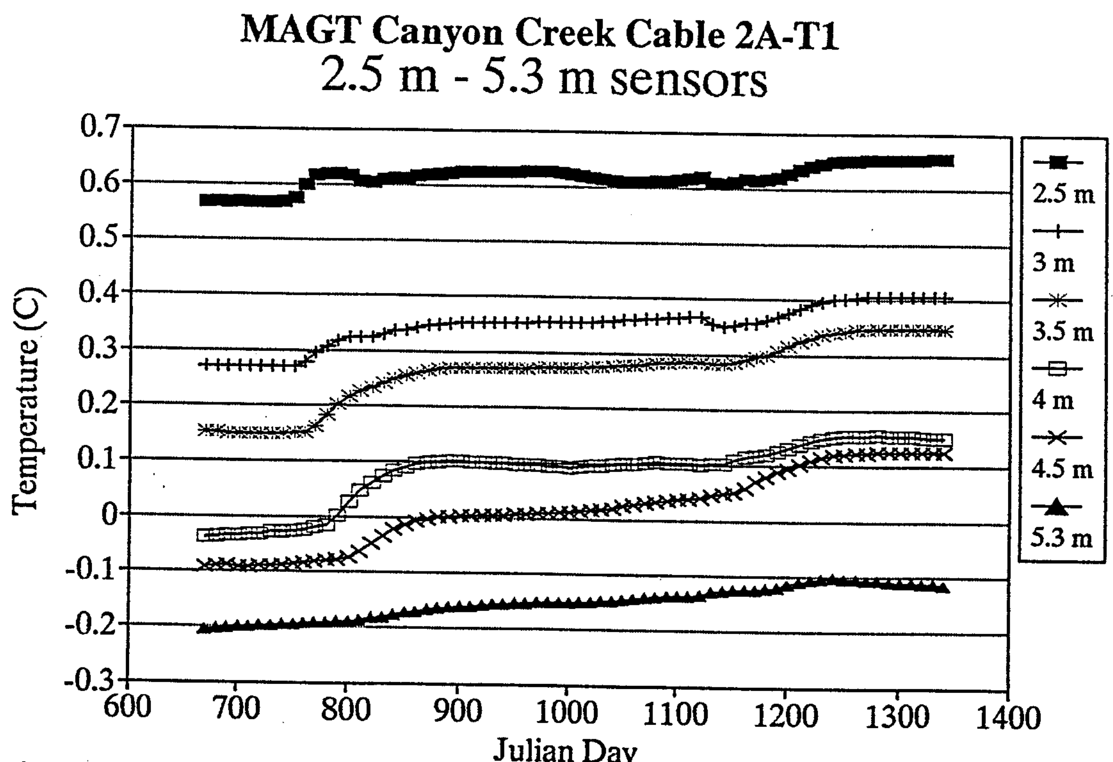


Figure 4

Typical Results

For each sensor on Canyon Creek cable 2A T1, Figures 5-13 show ground temperatures measured using the datalogger (upper Figures 5A-13A), compared to the suite of 30 interpolated curves for the 30 day measurement interval, obtained using the procedure outlined above (lower Figures 5B-13B). Some general features of these curves are evident:

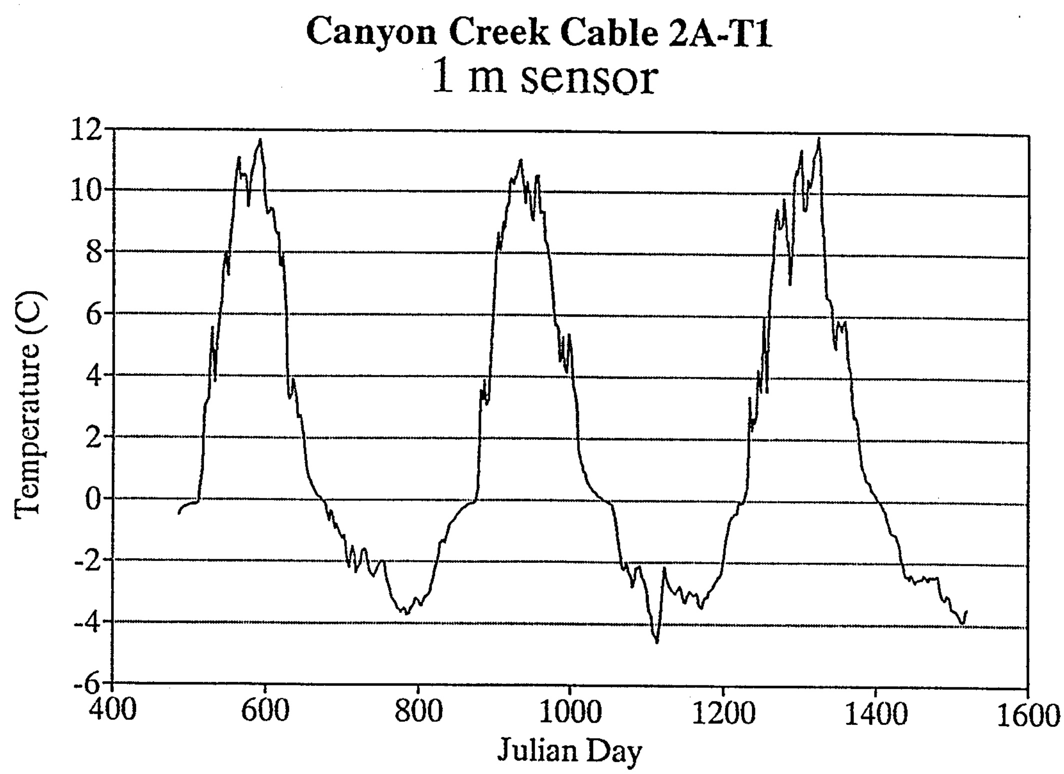
At all depths, the average uncertainty in the interpolated temperature curves (that is, the spread between the highest estimate and the lowest estimate at any point in time) is fairly constant as a proportion of the total variation at each depth.

The spread in uncertainty tends to be greatest where the rate of change in curvature of the underlying temperature curve is greatest.

Short term temperature variations, due either to actual temperature change nearer the ground surface (such as the 1 m sensor), or to datalogger "noise" (such as in the 4 m sensor and below) have an erratic influence on the family of curves at each depth. The measurement resolution of the Seadata loggers is on the order of 0.01°C to 0.02°C Most "manual" measurement sets will miss these deviations from the long term trend, but those that do include them are significantly different from the majority of the curves.

Figures 14-17 show the families of interpolation curves obtained for the 2.5 m sensor at some of the longer measurement intervals examined. At this depth, the temperature wave is relatively free from both types of short term temperature variation, but is strongly influenced by latent heat effects. The summer temperature wave is a short pronounced increase in temperature above 0°C, while during the rest of the year the temperature remains just below 0°C. Adequate sampling of temperatures near this short summer season are vital to the accuracy of any interpolation.

The range between the highest and lowest interpolated temperature varies with time along the temperature curves. The distribution of values between the extremes will depend on the shape of the underlying data curve, and the distribution of the nearby manual measurement dates used to produce the interpolated curves. Within the family of interpolated curves, the error is likely to be greatest midway in time between manual



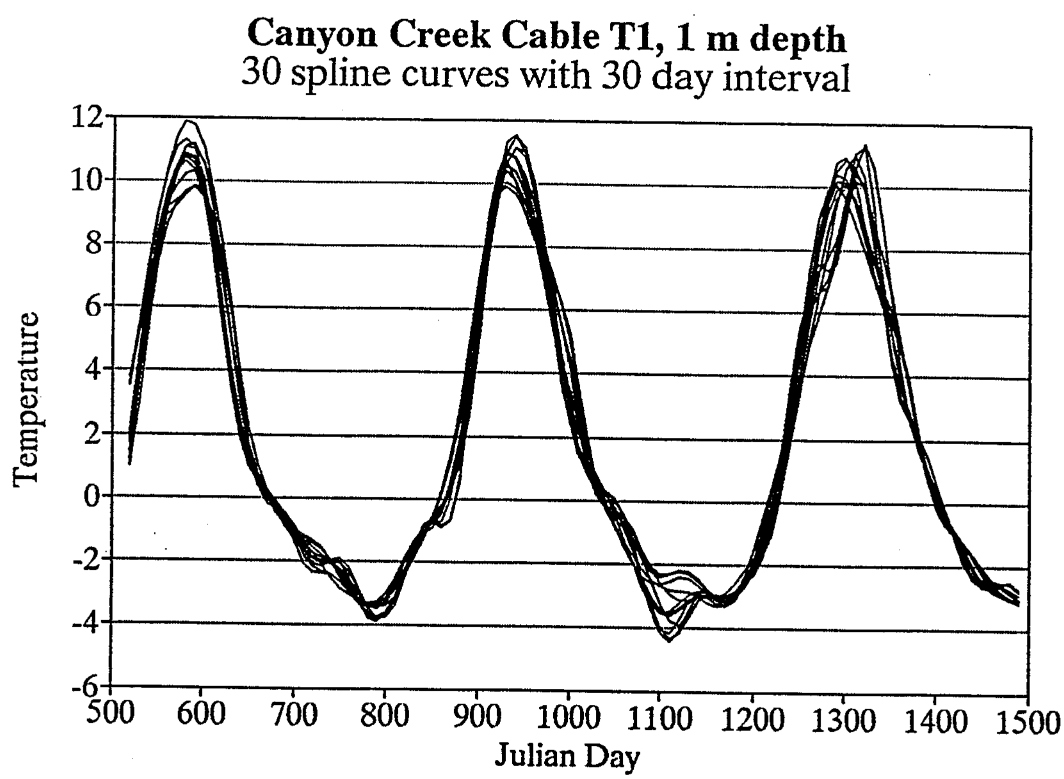
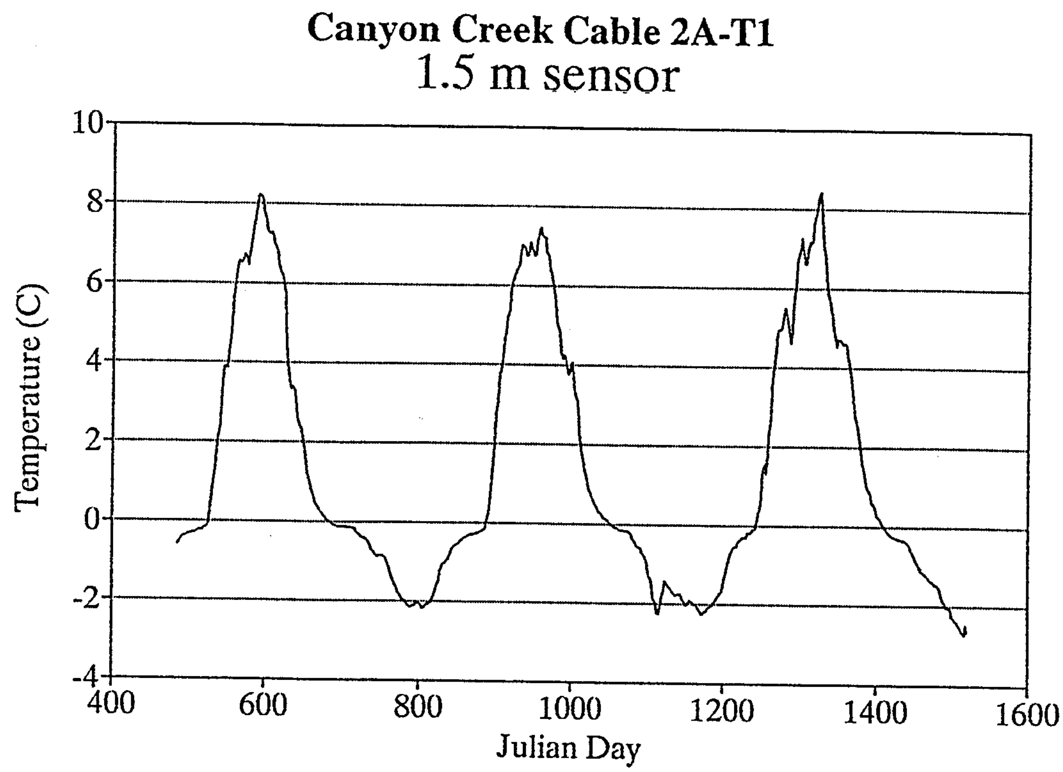
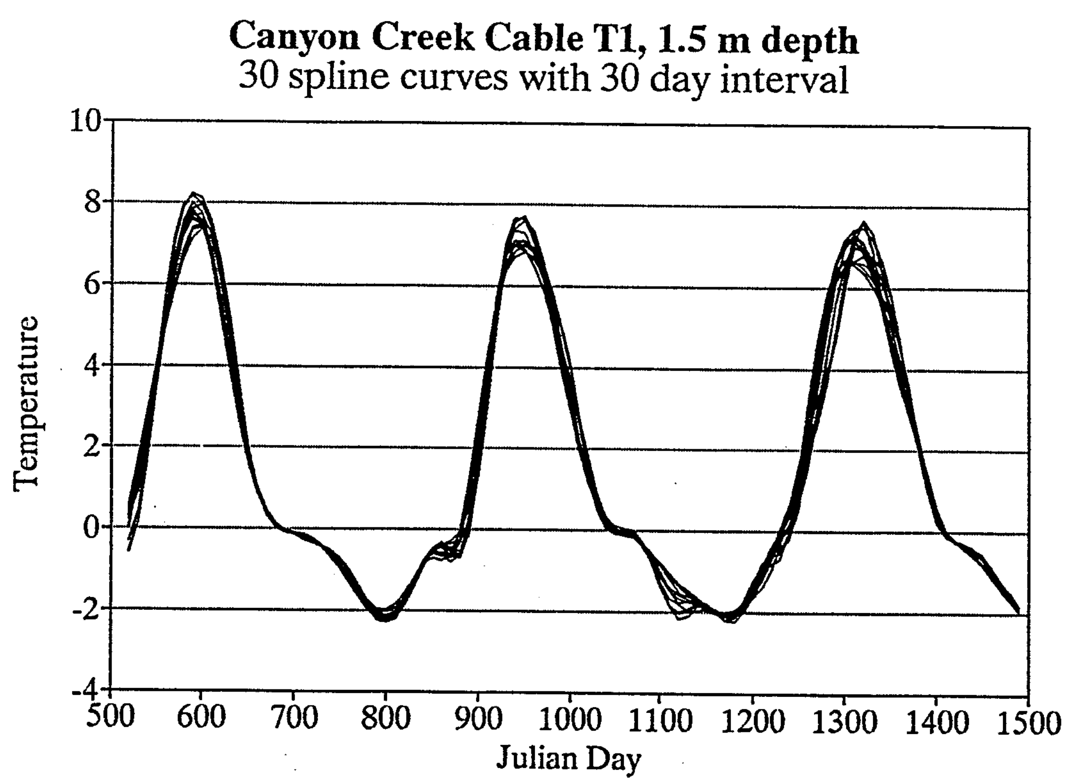


Figure 5. Upper figure is A, Lower is B





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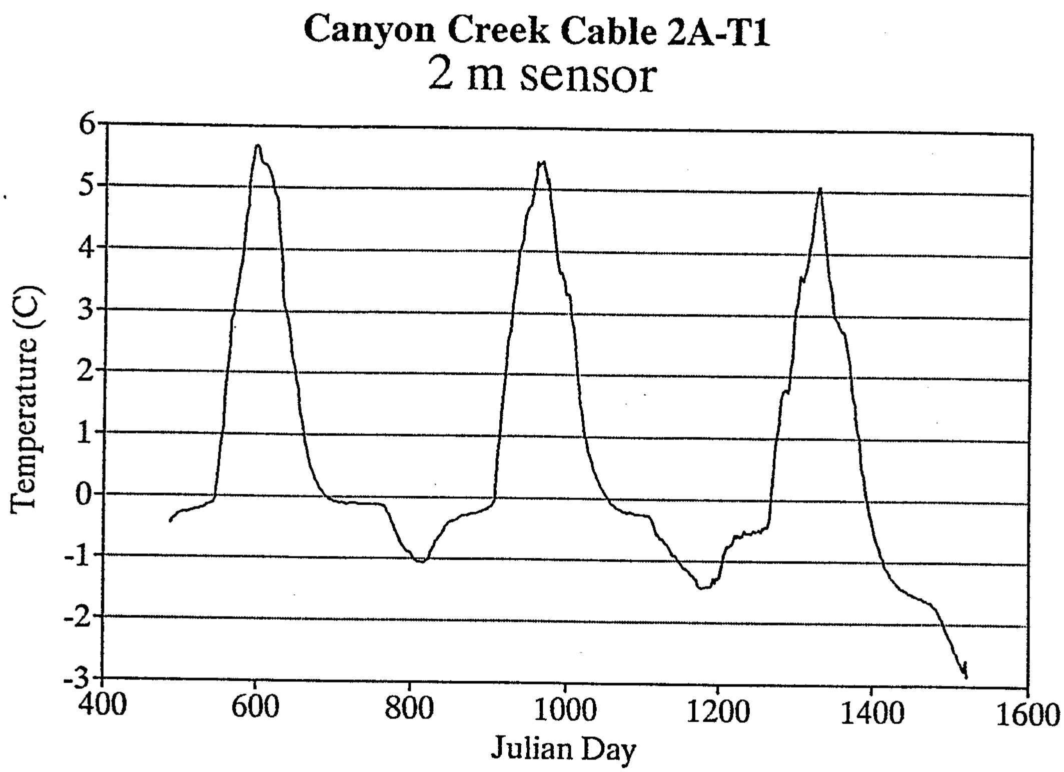

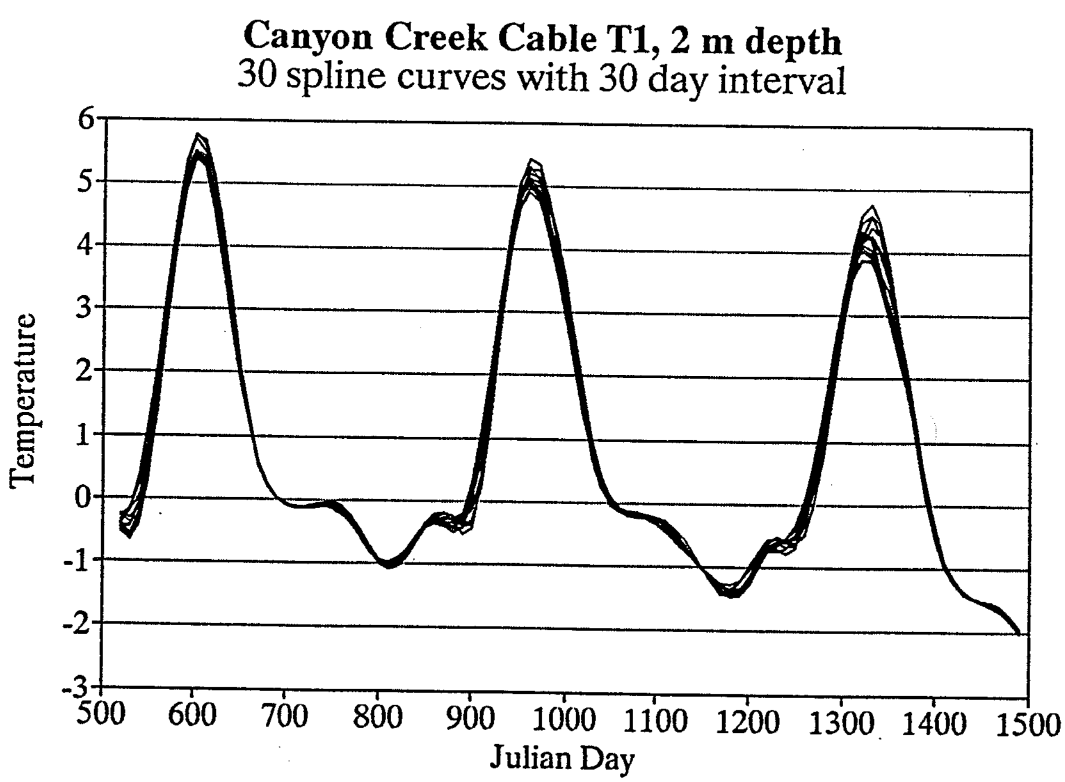

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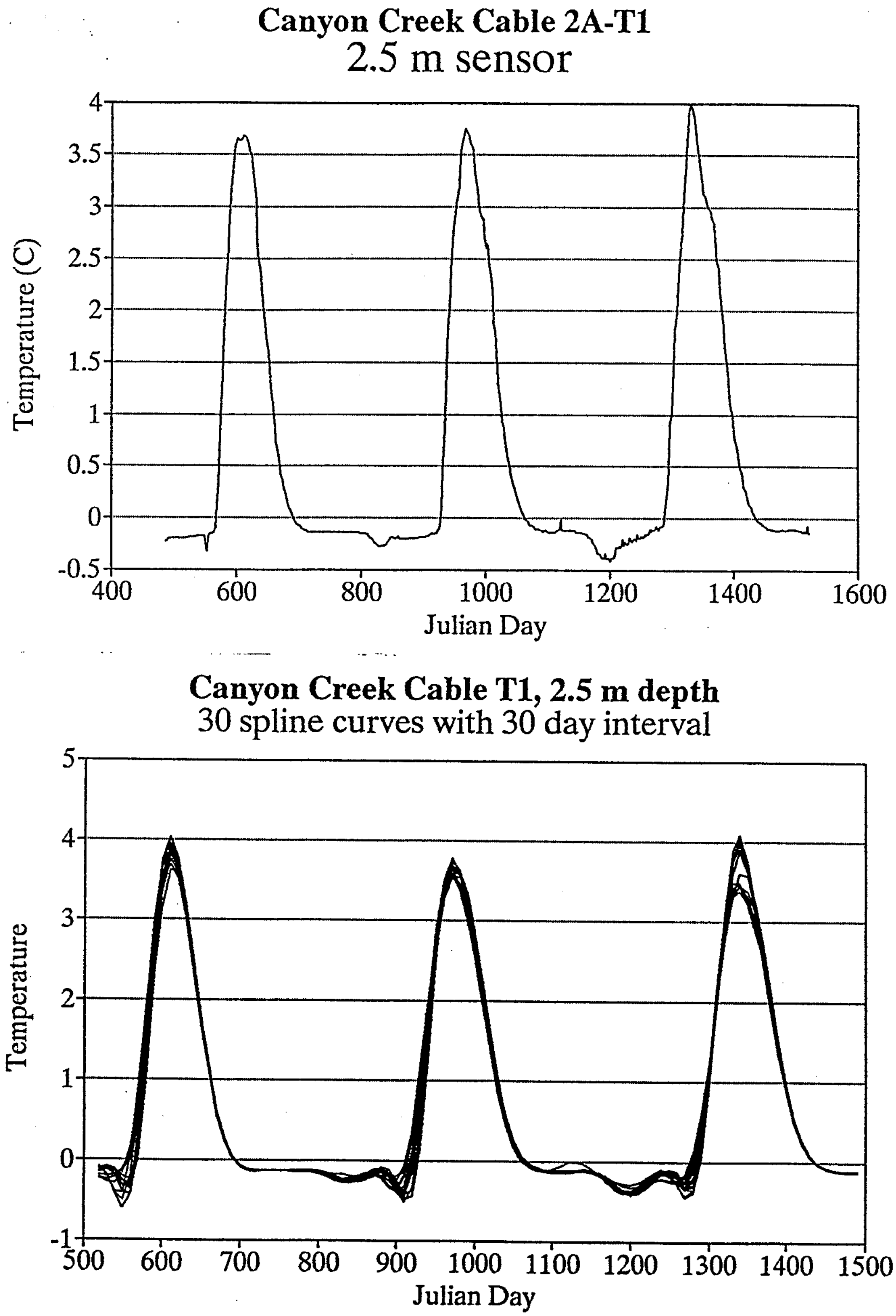

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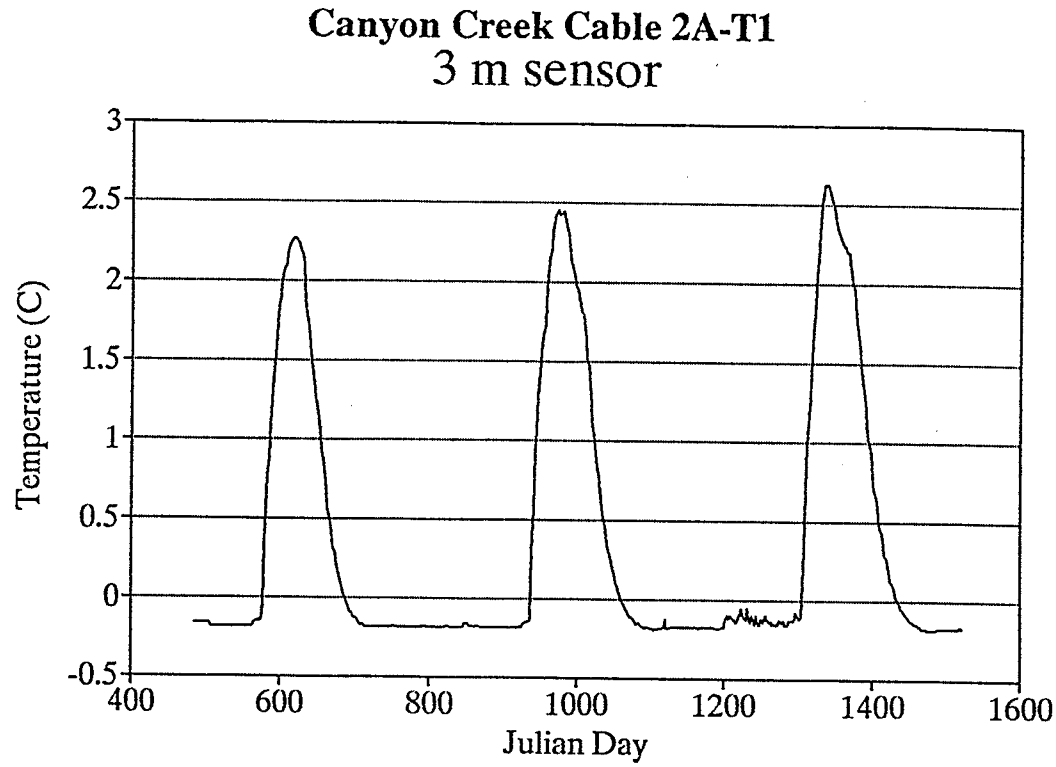

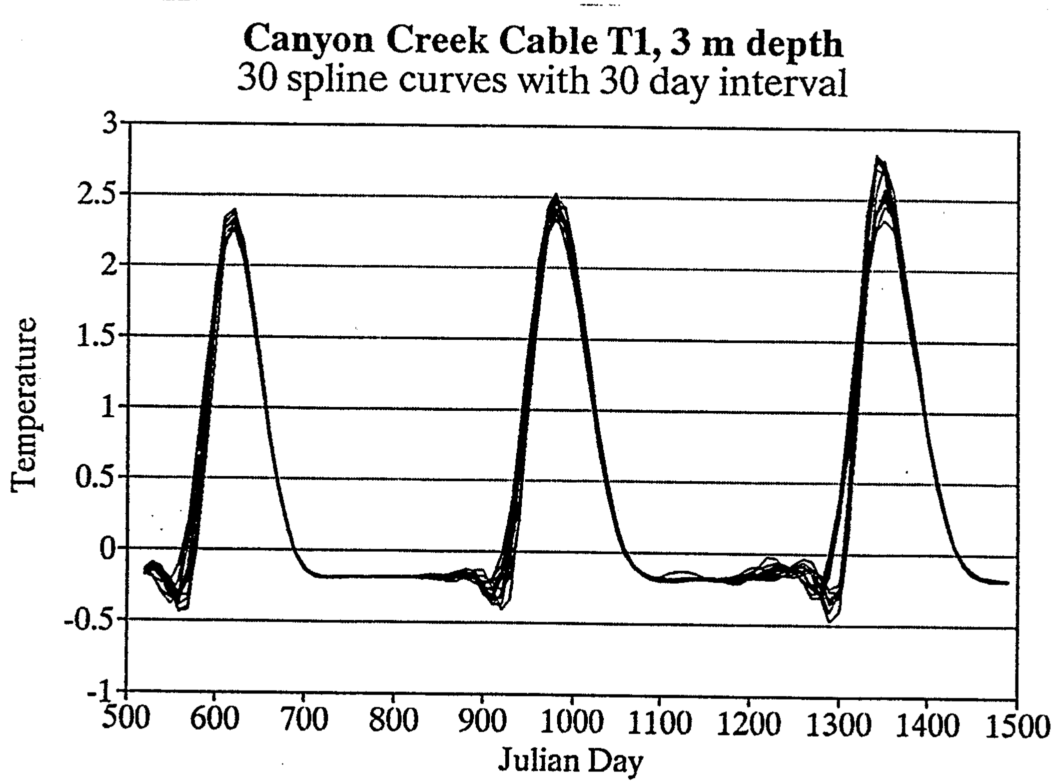

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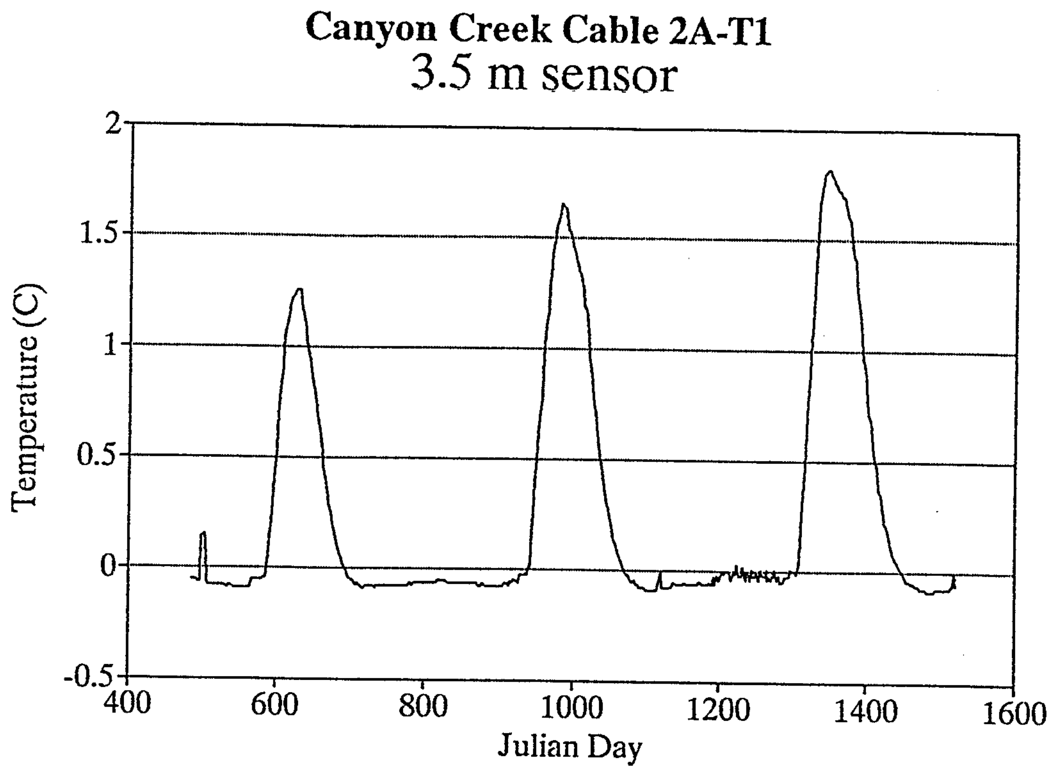

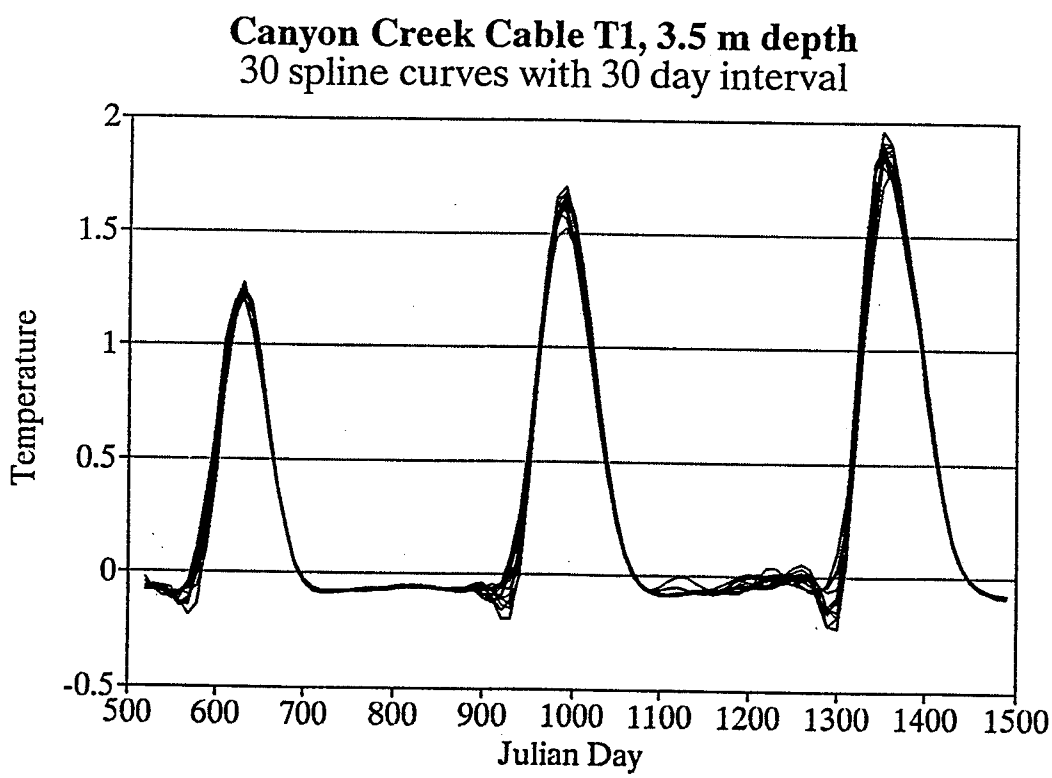

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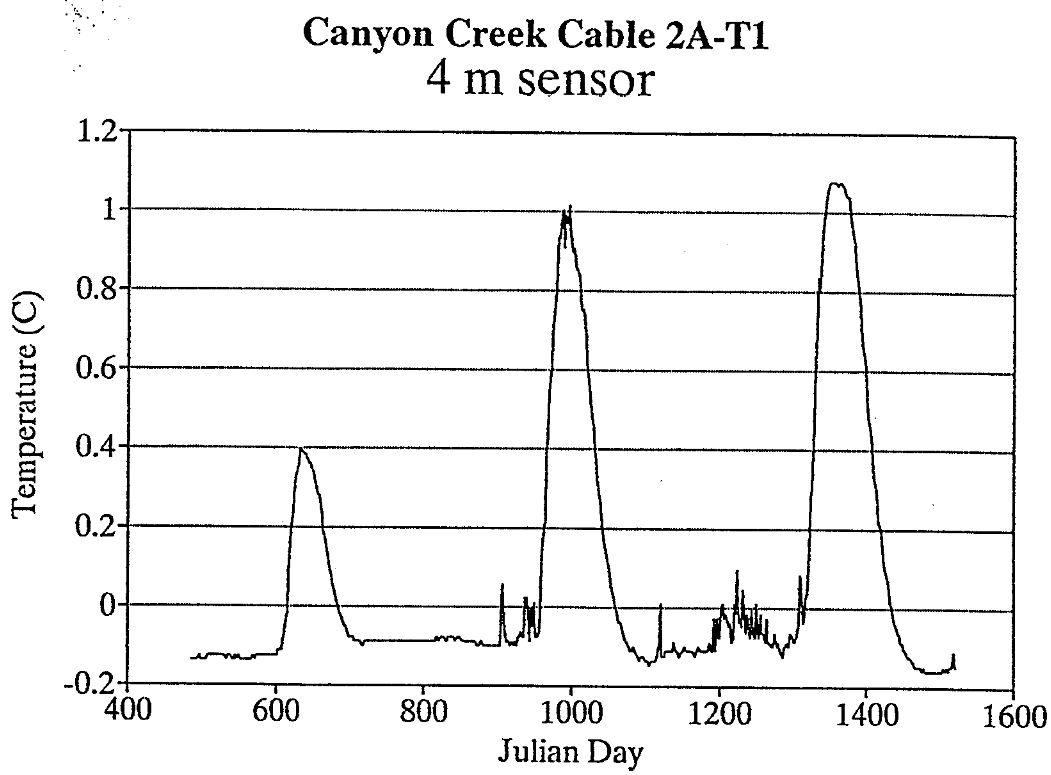

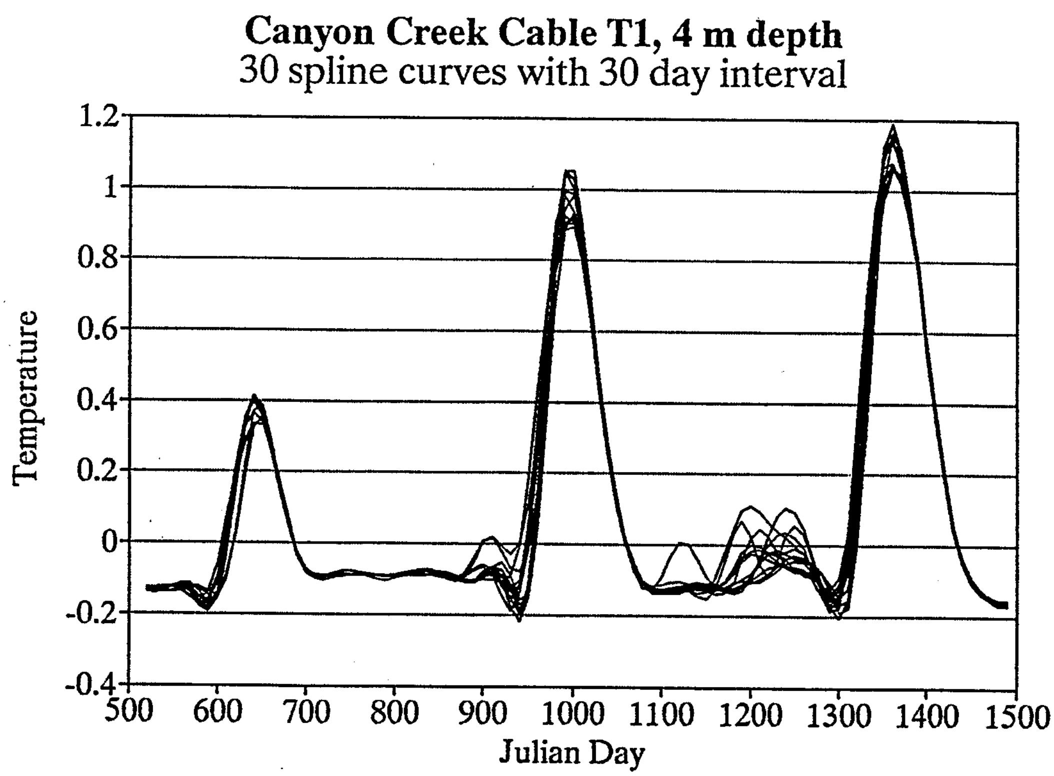

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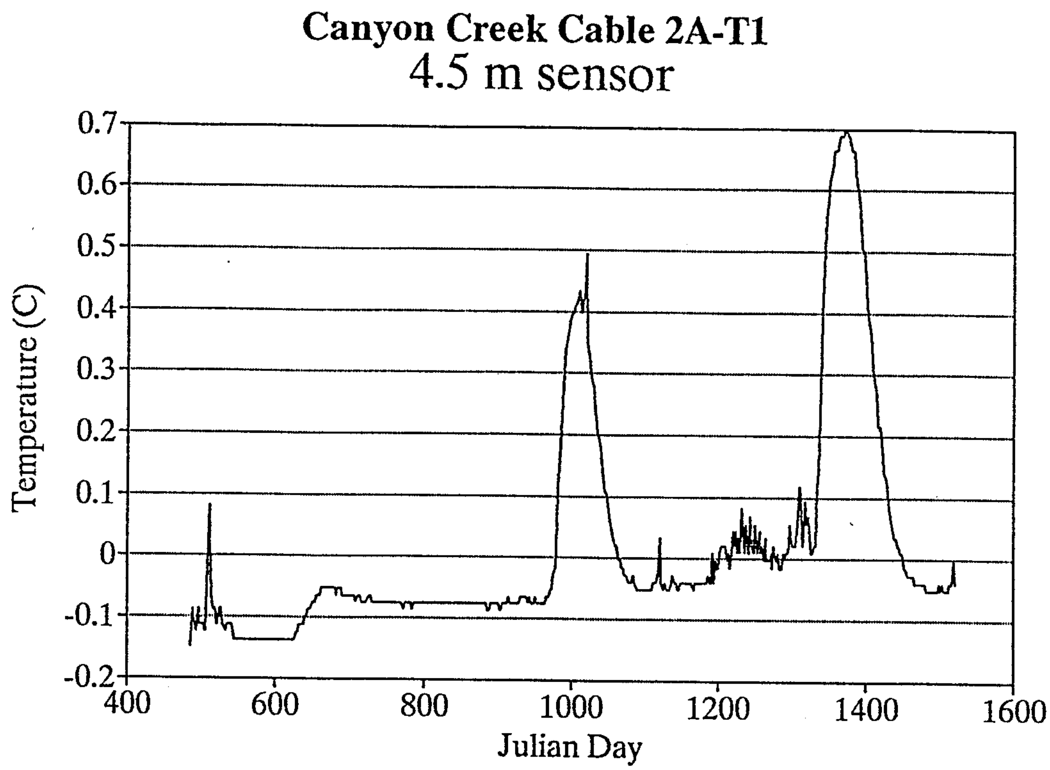

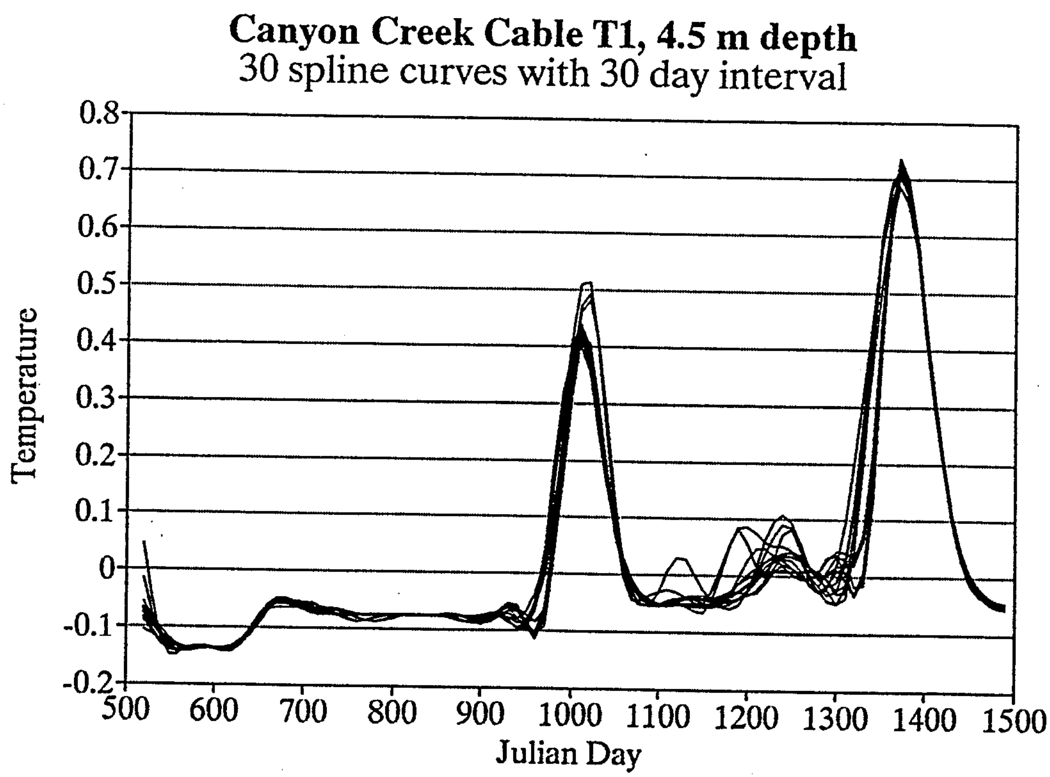

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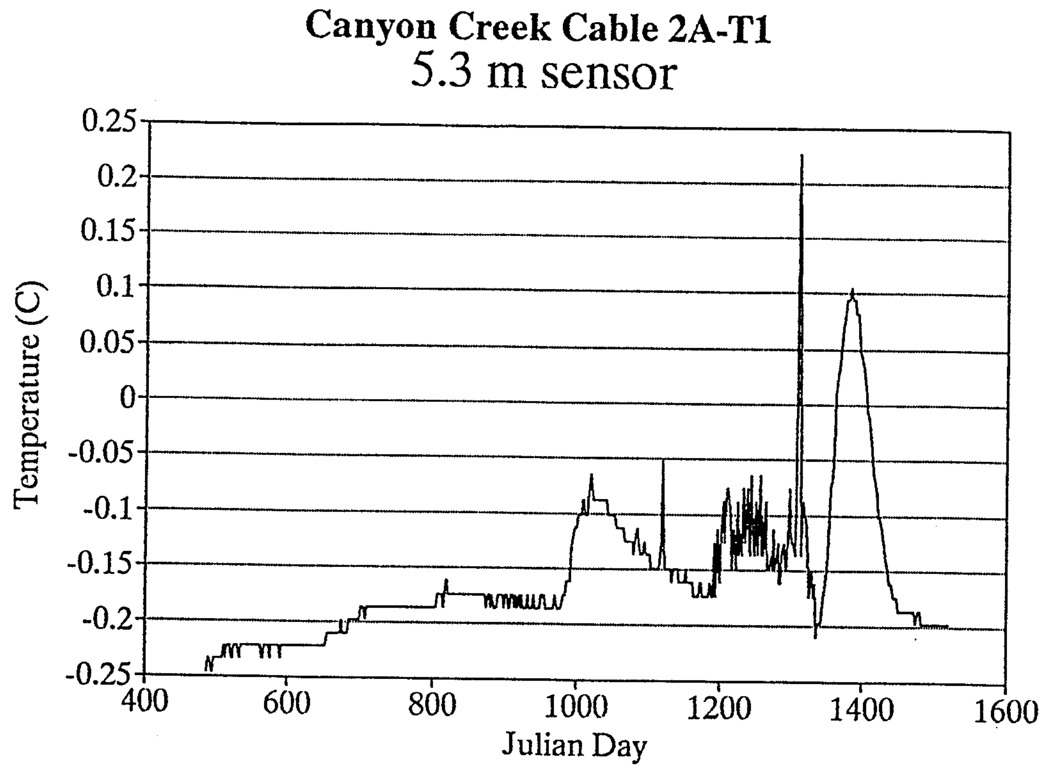

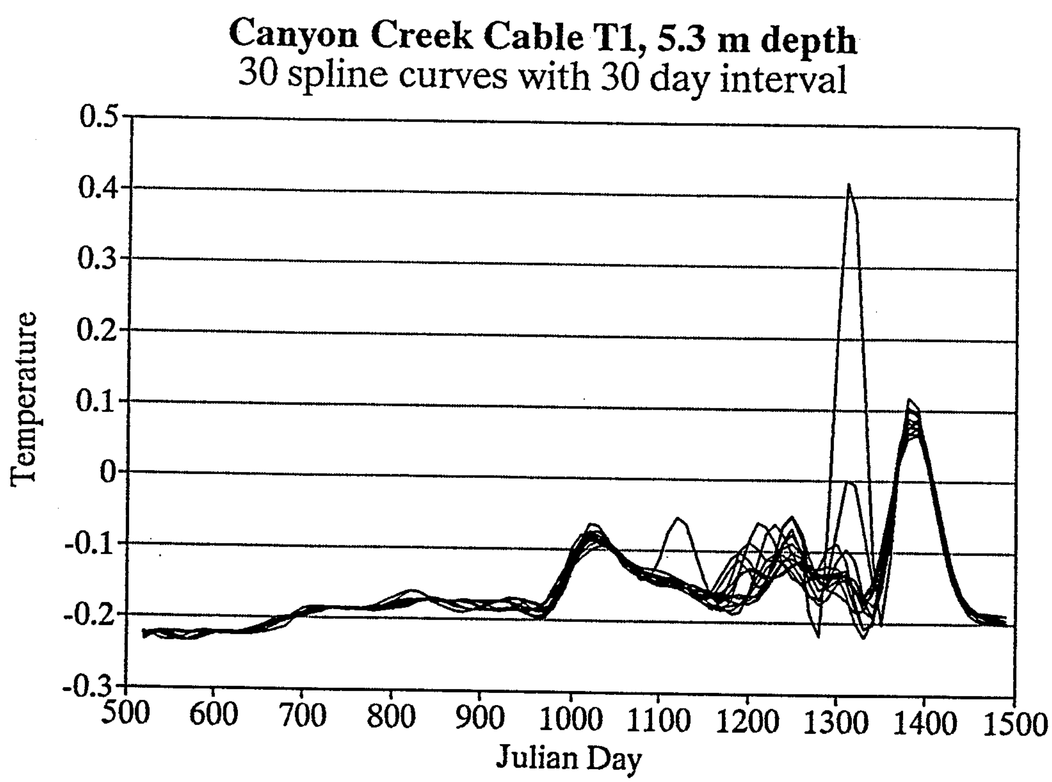

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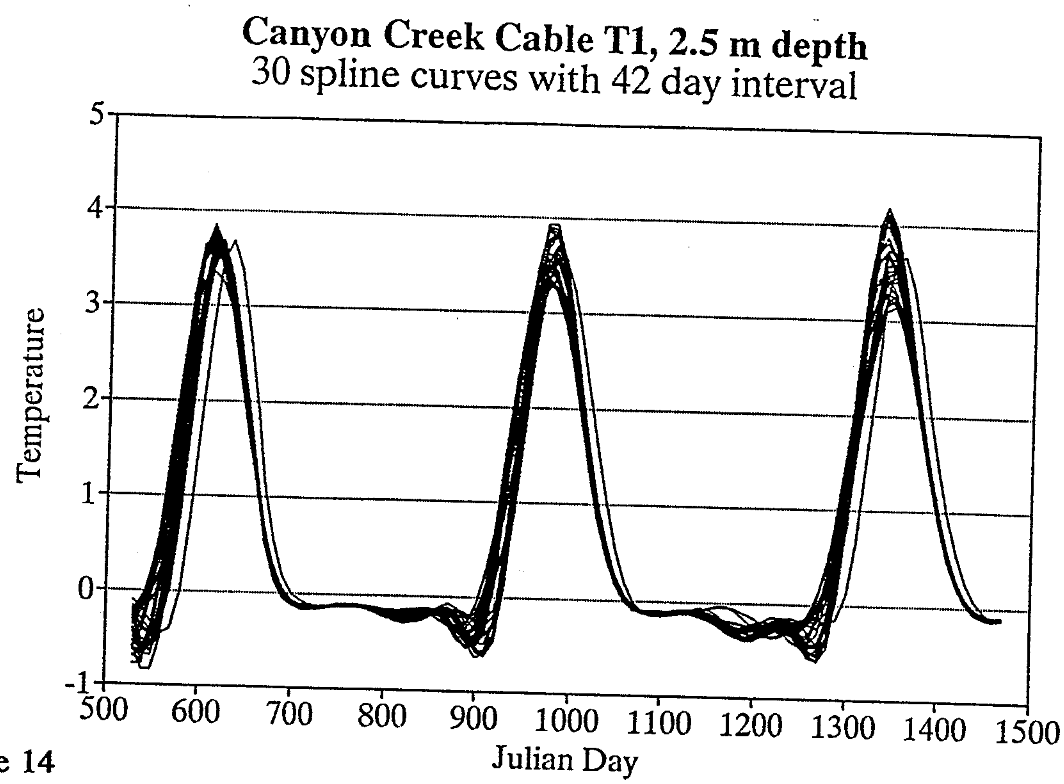


Figure 14

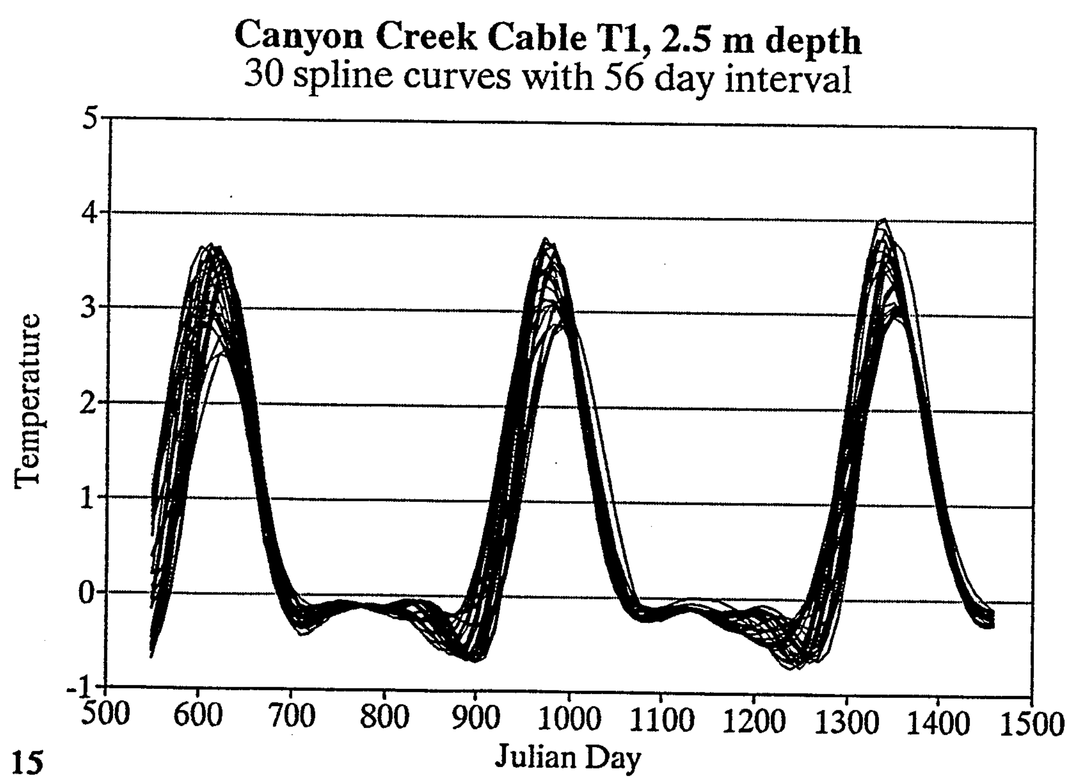


Figure 15

Canyon Creek Cable T1, 2.5 m depth
30 spline curves with 70 day interval

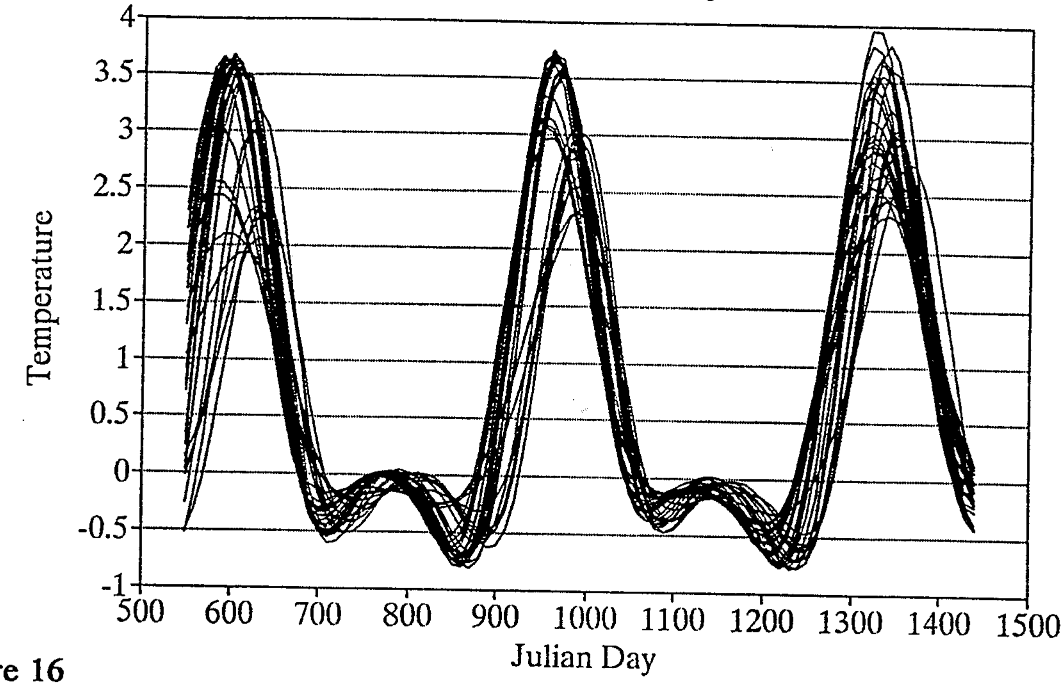


Figure 16

Canyon Creek Cable T1, 2.5 m depth
30 spline curves with 90 day interval

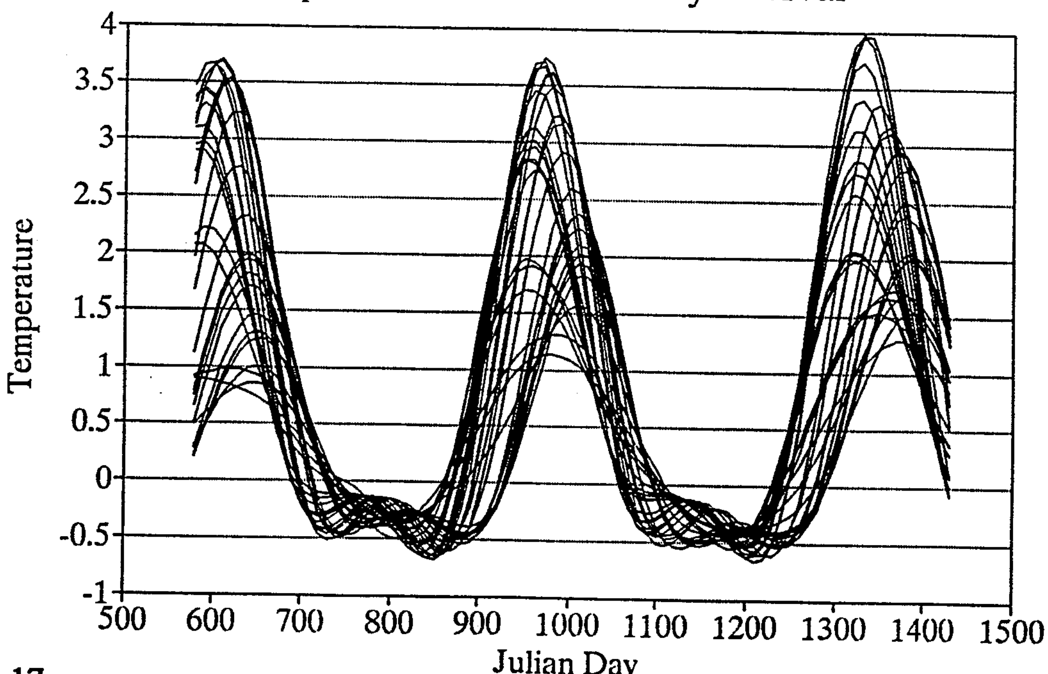


Figure 17

measurements. For the 30 day measurement interval for the 1 m sensor, Figures 18 and 19 show frequency distributions of interpolated temperatures at the points of maximum and minimum range, respectively. Both distributions show a central tendency which is close to the actual (measured) temperature. In the case of the maximum range (Figure 18), a single outlier increased the spread between extreme values to about 6 °C: without this outlier the range would be about 4°C.

The mean annual temperatures determined from the spline curves have uncertainties which relate to the average annual uncertainty in the temperature interpolation. Figure 20 shows the families of mean annual temperature curves obtained for the upper 3 sensors of the T1 cable, with a 30 day measurement interval. As with the spline curves, the range between the highest and lowest temperatures for each sensor decreases with depth, reflecting the increasing precision of the interpolation procedure with greater depth.

Figures 21 and 22 show frequency distributions of mean annual temperature at the points of maximum and minimum range in this statistic, respectively (as above, for the 30 day measurement interval for the 1 m sensor). Unlike the distributions for temperature, these distributions do not exhibit a strong central tendency, although the "actual" mean annual temperature is close to the middle of the range in both cases. The difference in character can be attributed to the nature of the mean, which integrates over a period extending 6 months (i.e. several measurement intervals) on either side, so that its value is not dependent on proximity to adjacent measurements.

Figure 23 shows the time variation in the uncertainty in mean annual ground temperatures (MAGT) at 2.5 depth for different measurement intervals. Overall, the upper and lower bounds on the uncertainty appear symmetrically disposed on either side of the true value, with the greatest deviations from this occurring near the beginning and end of the time period. As was found with the earlier analysis (Burgess and Riseborough 1989), the time variation of individual mean annual temperature curves appears to mimic the true variation, even when the estimated mean annual temperature is displaced from the actual temperature curve. This is the visual impression found in Figure 20.

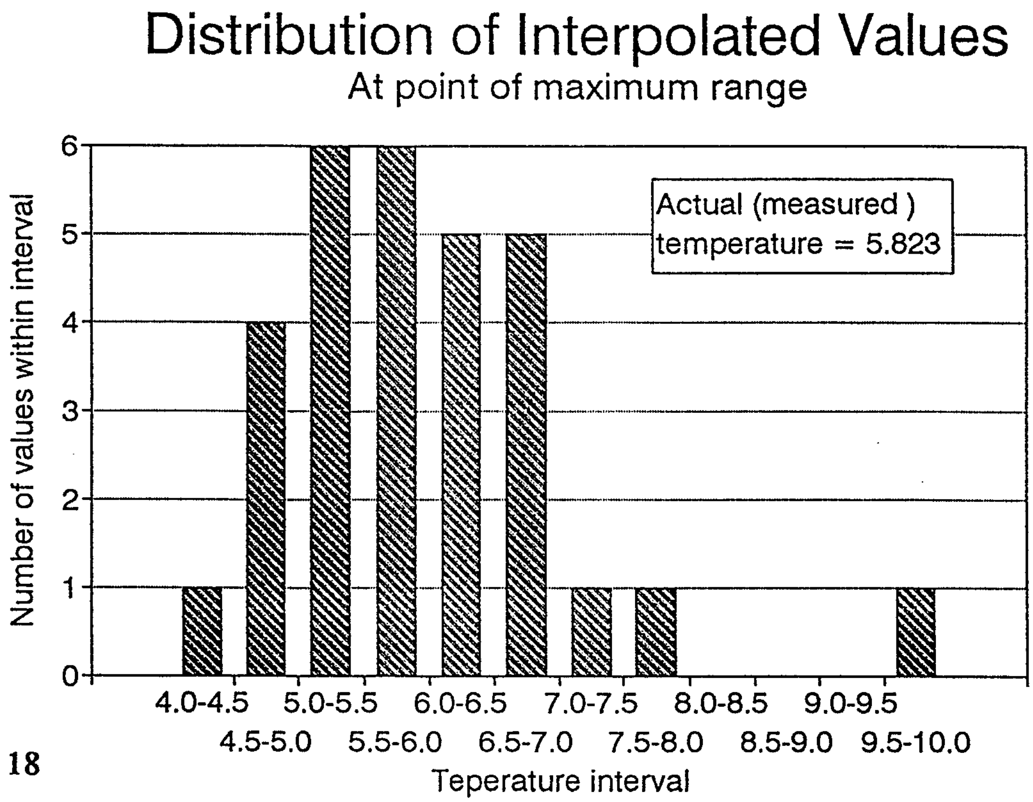


Figure 18

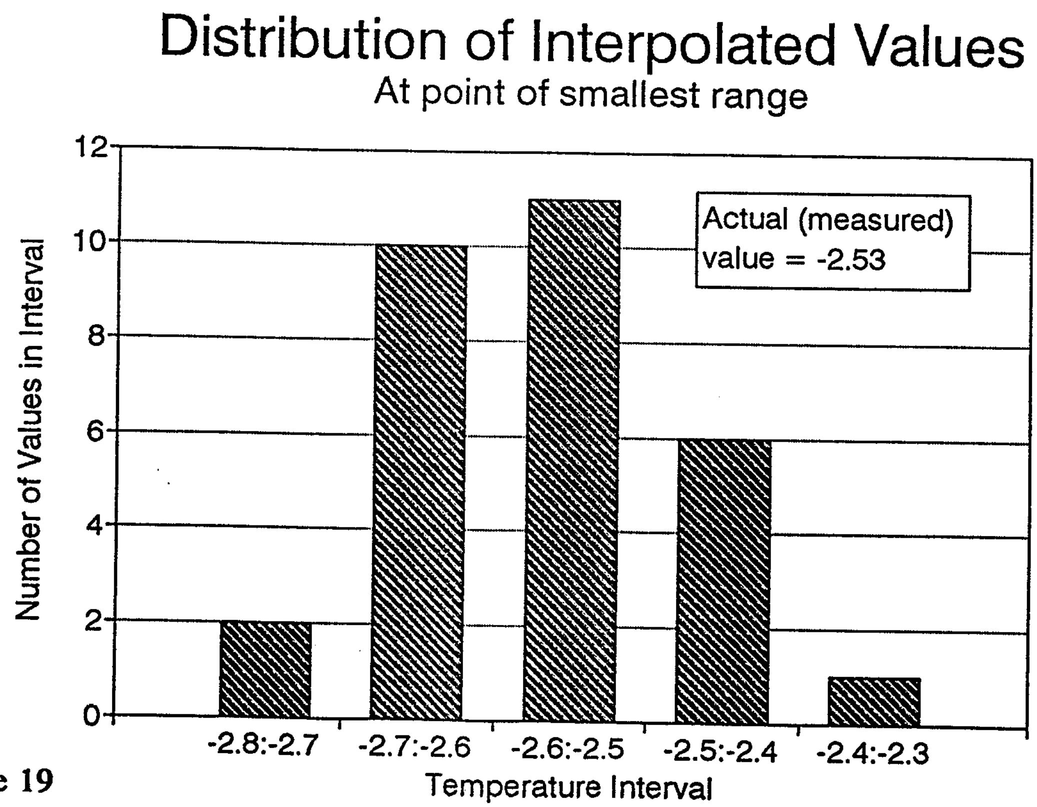
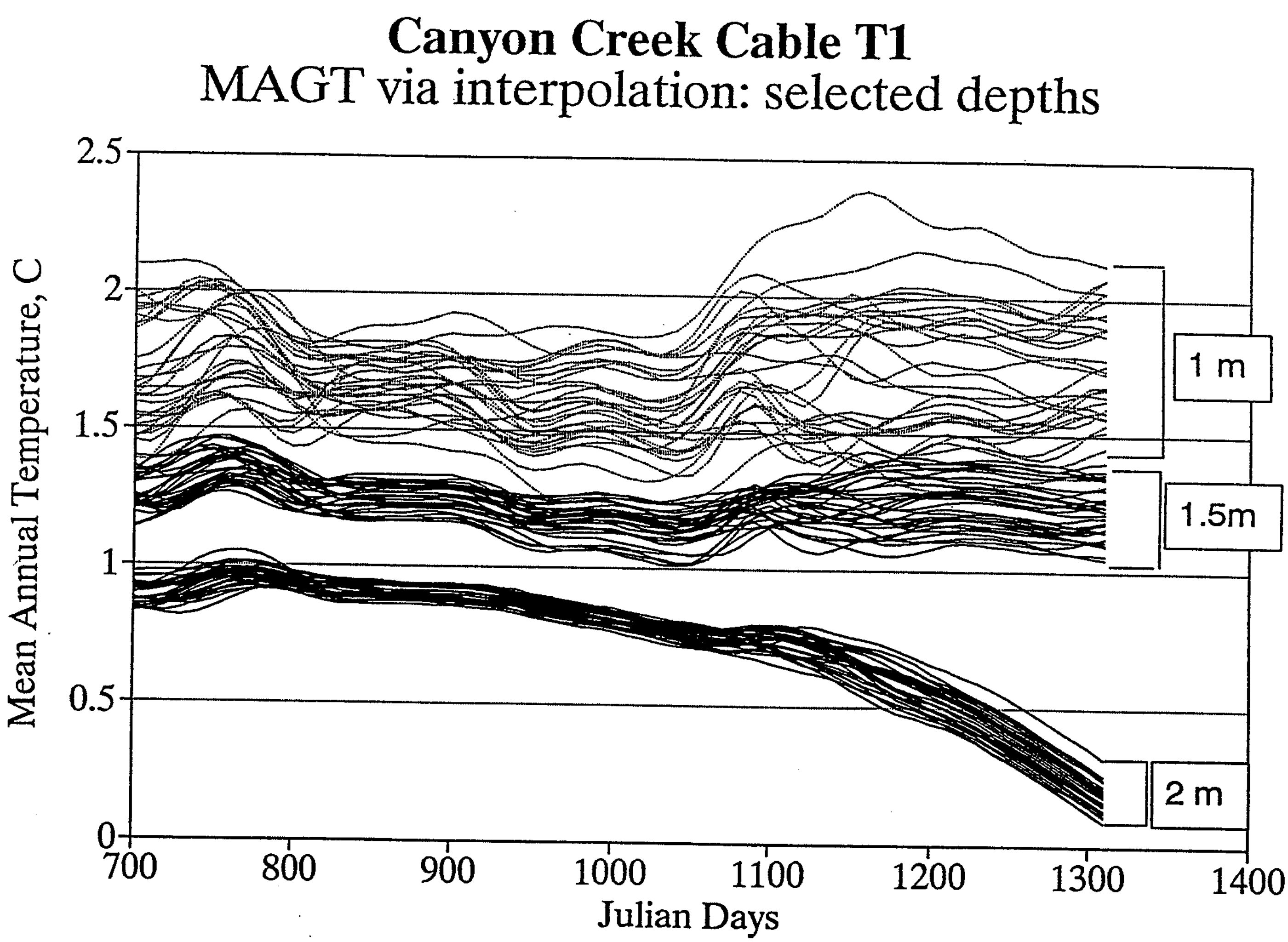


Figure 19



Canyon Creek Cable T1
MAGT via interpolation: selected depths
Mean Annual Temperature, C
Julian Days
2.5
2
1.5
1
0.5
0
700
800
900
1000
1100
1200
1300
1400
1 m
1.5m
2 m

Figure 20.

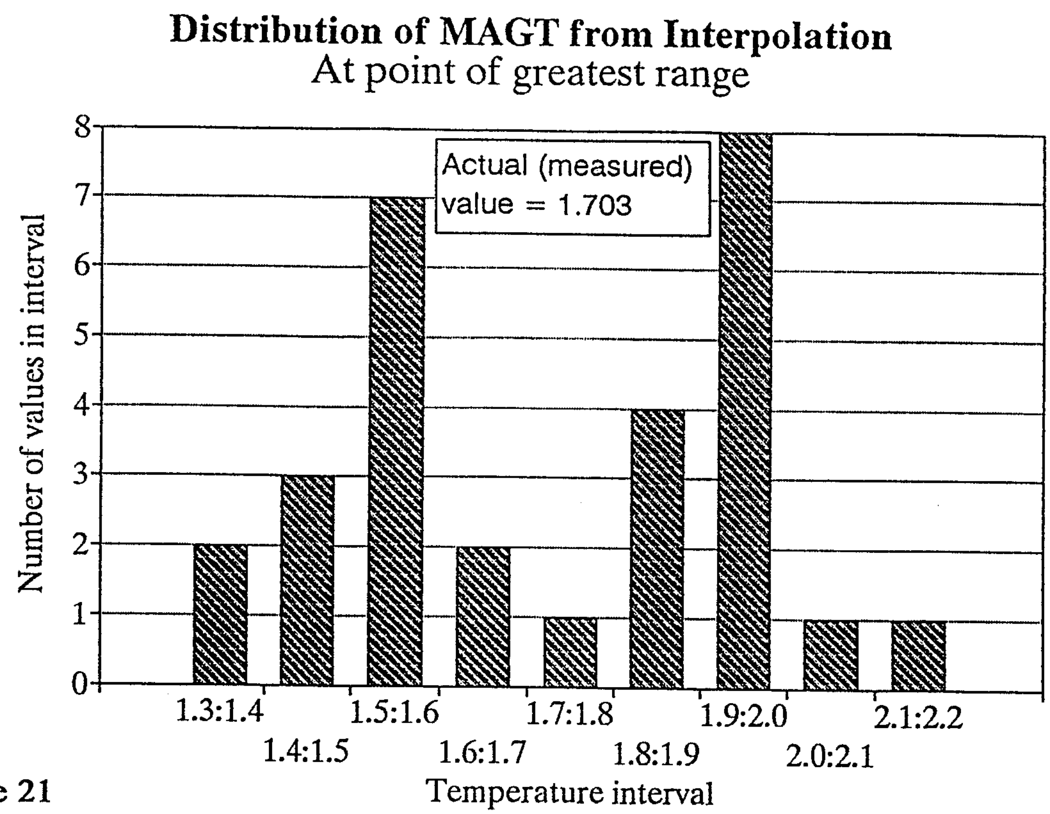


Figure 21

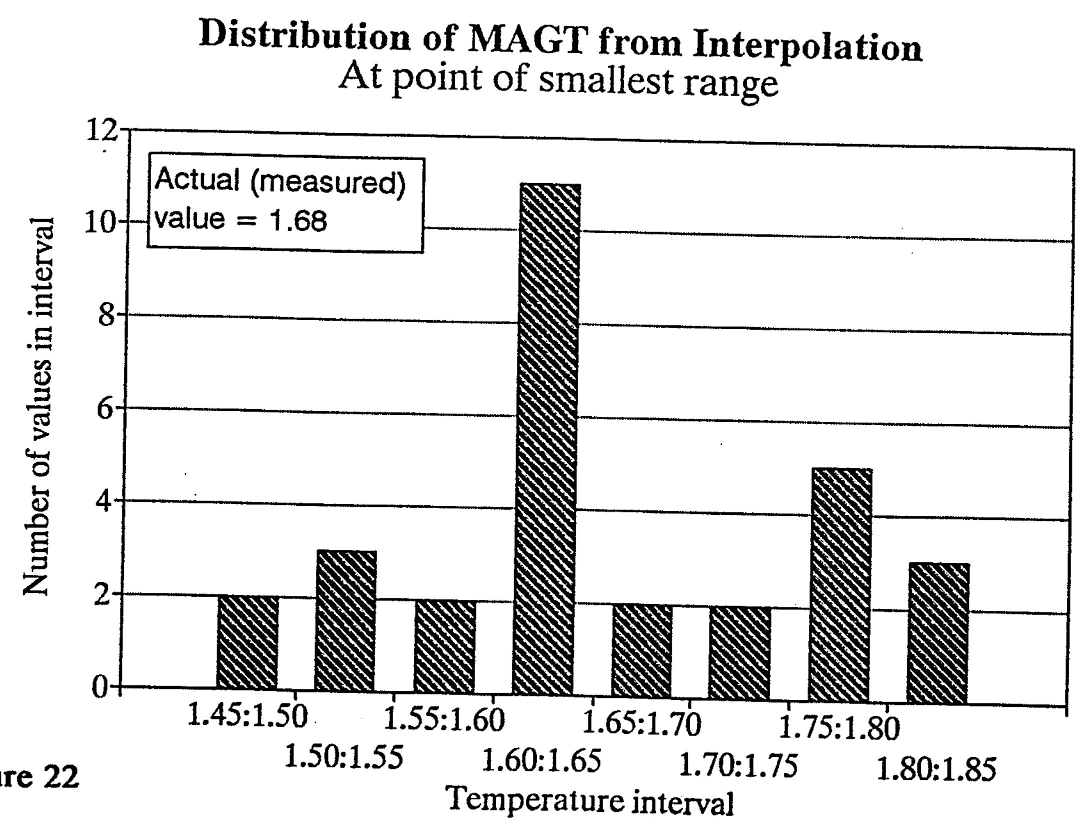


Figure 22

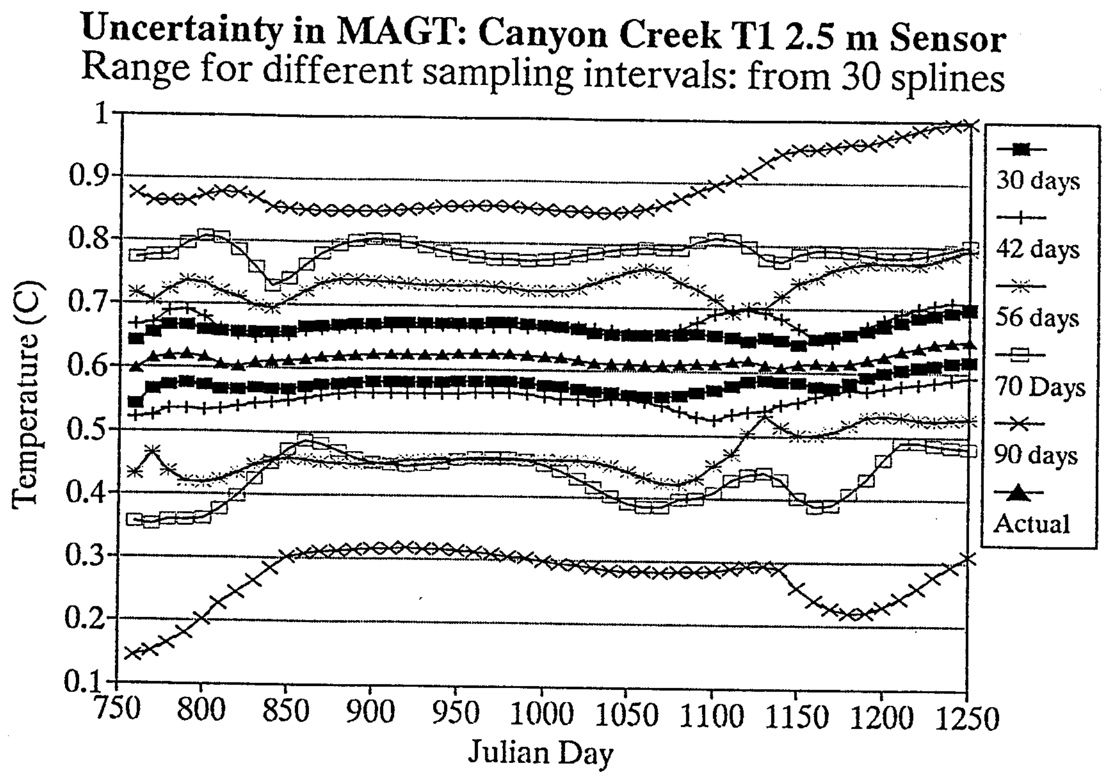


Figure 23

Interpolation Results

The analysis presented in this section is an attempt to characterize, for different depths in the ground, the relationship between measurement interval and the degree of uncertainty about the thermal regime. The average of the standard deviations obtained for each time point on the 30 spline curves provided the most reliable index of all of the statistics generated to characterize the results of the analysis, as discussed above. This statistic was therefore used as the basis for generalization about relationships between sensor depth, measurement interval, and uncertainty.

The relationship between the average standard deviation and depth of sensor is shown for all measurement intervals in Figure 24. At all depths, an increase in the measurement interval increases the standard deviation, although the dependence on the measurement interval is greatest at intermediate depths. Similar behaviour can be seen in the relationships between measurement depth, measurement interval, and the standard deviation of the estimates for the Mean annual ground temperature curves (Figure 25).

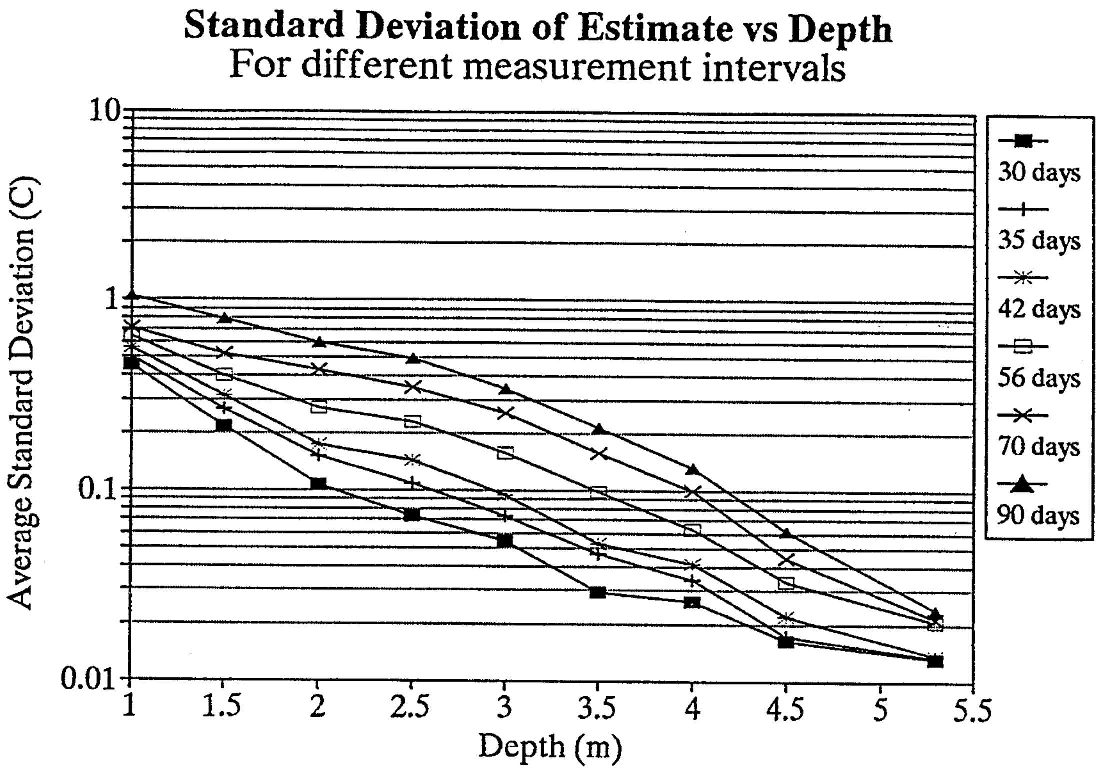


Figure 24

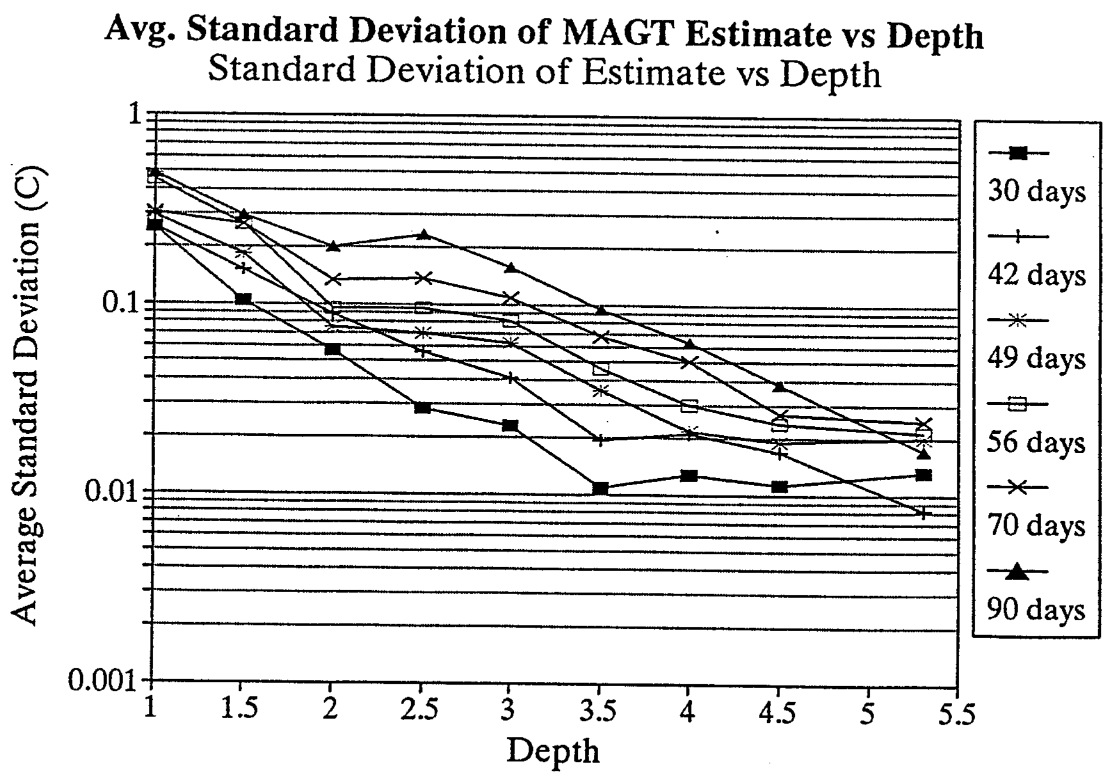


Figure 25

As mentioned above, the thermal behaviour at these depths is characterized by abrupt changes in temperature behaviour near 0°C, with a short summer season of rapid temperature change. A larger time interval between measurements increases the probability that less frequent sampling of the short summer season will reduce the accuracy of results.

The average standard deviation declines with depth, due to the increasing smoothness of the temperature wave as well as the decrease in the absolute magnitude of the temperature variation at each depth. As a first attempt to standardize the relationship between measurement interval and the uncertainty of the estimates for all depths, the average standard deviations were divided by the measured temperature range at each depth. The relationship between this dimensionless ratio and measurement depth is shown for all measurement intervals in Figures 26 and 27 (for temperature estimates and mean annual temperature estimates, respectively). Note that the temperature range used in both analyses is the same in both i.e. the ratio for the mean annual temperature does not use the range of the mean annual temperature. At the 30 day measurement interval, the ratio is nearly constant with depth, suggesting that the "relative uncertainty" is constant. Up to an interval of 56 or 63 days, the ratio remains relatively uniform with depth, although it increases most at intermediate depths, for the reasons suggested in the paragraph above. For the temperature estimates, at intervals of 70 and 90 days this behaviour produces a ratio which is about twice as great between 2 and 3.5 metres depth as it is for deeper or shallower depths. For the mean annual temperature estimates, intervals of 70 and 90 days show a ratio which is much higher for all depths below 2 metres.

To further simplify the relationship between uncertainty and measurement interval, the average ratio for all depths can be plotted against the measurement interval (Figure 28). (Note in the Figure that the two curves are scaled according to separate left and right y-axes.) Results of this simplification show that estimation by spline interpolation of both temperature and mean annual temperatures behave in a relatively predictable way. Results of regression on these curves, with the y-intercept either held at 0 or free, are summarized in Table I.

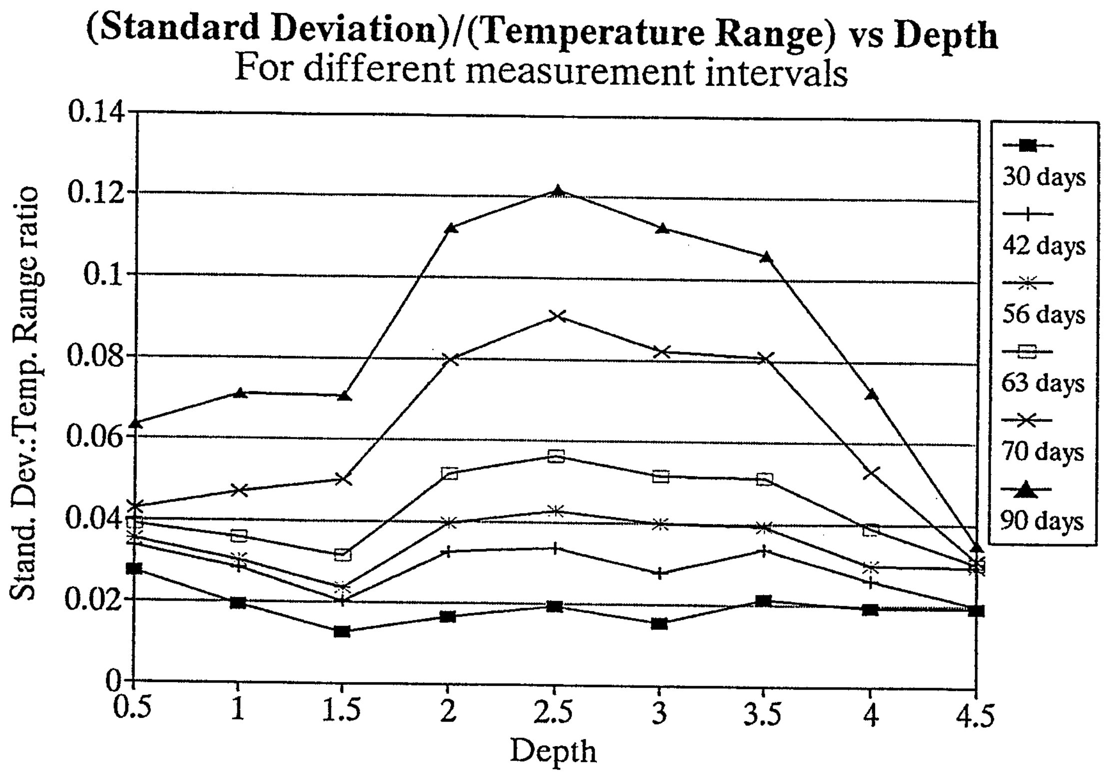


Figure 26

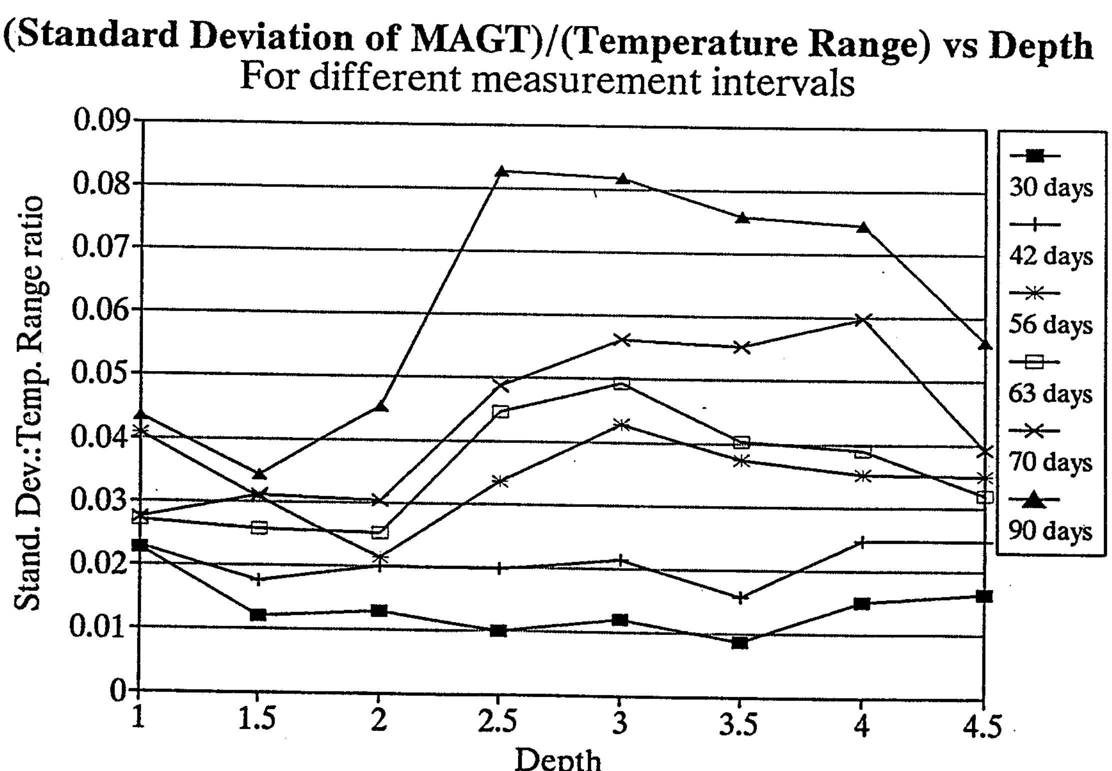


Figure 27

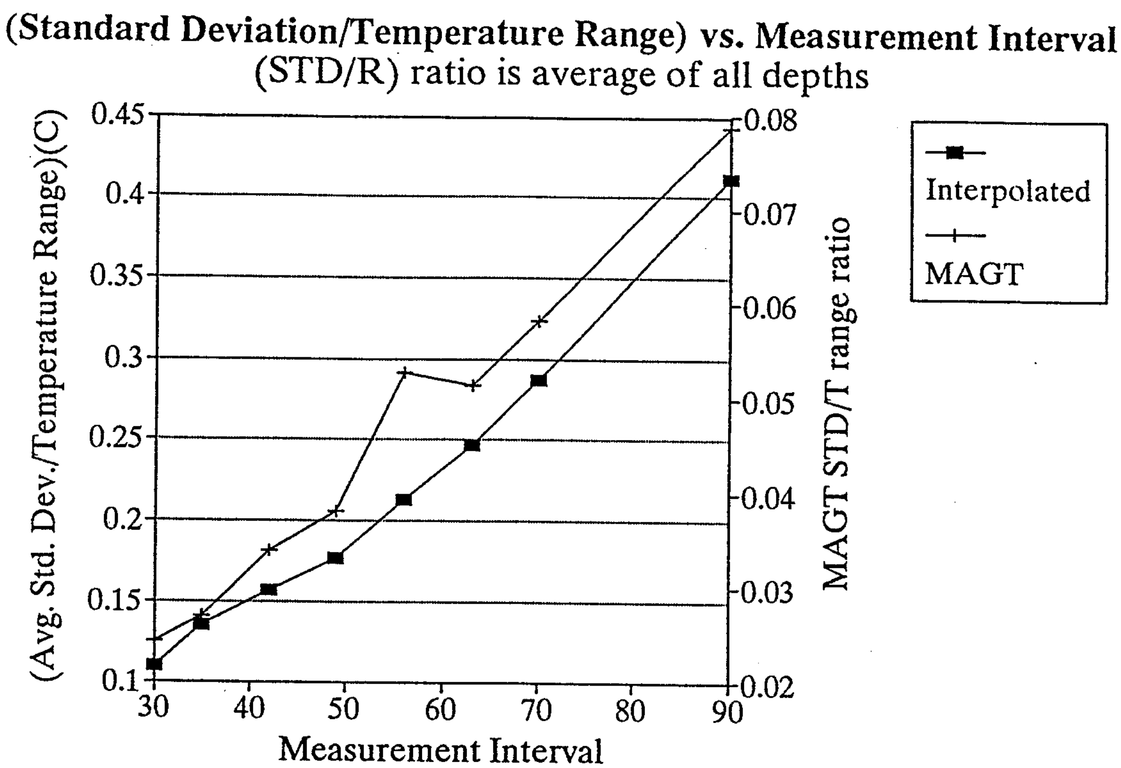


Figure 28

Regression with y-intercept held at 0

Spline:		Mean:	
Constant	0	Constant	0
Std Err of Y Est	0.02166	Std Err of Y Est	0.002986
R Squared	0.951099	R Squared	0.973386
No. of Observations	8	No. of Observations	8
Degrees of Freedom	7	Degrees of Freedom	7
X Coefficient(s)	0.004087	X Coefficient(s)	0.000847
Std Err of Coef.	0.000133	Std Err of Coef.	1.84E-05

Regression with calculated y-intercept

Spline:		Mean	
Constant	-0.04952	Constant	-0.00415
Std Err of Y Est	0.014415	Std Err of Y Est	0.002831
R Squared	0.981437	R Squared	0.979492
No. of Observations	8	No. of Observations	8
Degrees of Freedom	6	Degrees of Freedom	6
X Coefficient(s)	0.004903	X Coefficient(s)	0.000915
Std Err of Coef.	0.000275	Std Err of Coef.	5.41E-05

On the assumption that these relationships will hold for other thermal conditions, it is possible to estimate the degree of error that will result for a given measurement interval, knowing only the annual temperature range. Reconstructing actual standard deviations for particular depths from these relationships will result in somewhat pessimistic estimates of the uncertainty for depths where asymmetry due to latent heat effects is not significant, and somewhat optimistic estimates for depths where it is.

For the interpolated temperature curve:

$$\overline{\sigma_z} = 0.0041 R_z m \qquad (2)$$

and for the mean annual temperature:

$$\overline{\sigma_z} = 0.00085 R_z m \qquad (3)$$

where

$\overline{\sigma_z}$ = average standard deviation at depth z

m = measurement interval (days)

R_z = Temperature range at depth z (twice the annual amplitude)

Note that the temperature range is the same in both equations (i.e. it is <u>not</u> the range of the mean annual temperature in equation 3). These relationships also imply that the average standard deviation for the mean annual temperature is 21% of its value for the interpolated temperatures.

Analysis of Pipe Temperatures

Measured Pipe Temperatures

Datalogger pipe temperature records for Table Mountain sites 7A, B and C (located 270 kilometres south of Norman Wells pump station), and Jean Marie Creek Site 12B (located at kilometre 608, 22 km south of Mackenzie Highway pump station) are shown in Figures 29-36. Figures 29-32 show data for all sensors at these sites, while Figures 33-36 show data for a single sensor (the first sensor) at these sites. The record for site 7C is longer than presented in Figure 31. Long gaps in the later part of the record made it necessary to truncate the record for use in the analysis. Figures 37-39 show measured mean annual temperature curves for sites 7A, 7B, and 12B.

Temperatures at the Table Mountain sites are ideally suited to the interpolation technique: short term fluctuations about the annual wave are relatively small, and the transition from freezing to thawing conditions occurs relatively gradually. All three sites include one or more sensors which are gradually drifting toward temperatures lower than the all-sensor average, due either to sensor detachment (resulting in temperatures reflecting the thermal regime away from the pipe surface), or to sensor degradation affecting the resistance-temperature calibration.

At Jean Marie Creek (site 12B), short term fluctuations of relatively large magnitude in wintertime become increasingly important with time. By the last winter of the record, short term fluctuations of about +/- 1°C around the long term trend persist for a period of several months. This behaviour may be a result of an increasingly noisy measurement signal, although evidence presented below points to non-uniform artificial temperature control at the pump station nearby as the cause of these variations. As discussed in the following section, this behaviour has a significant impact on the precision of the interpolation procedure.

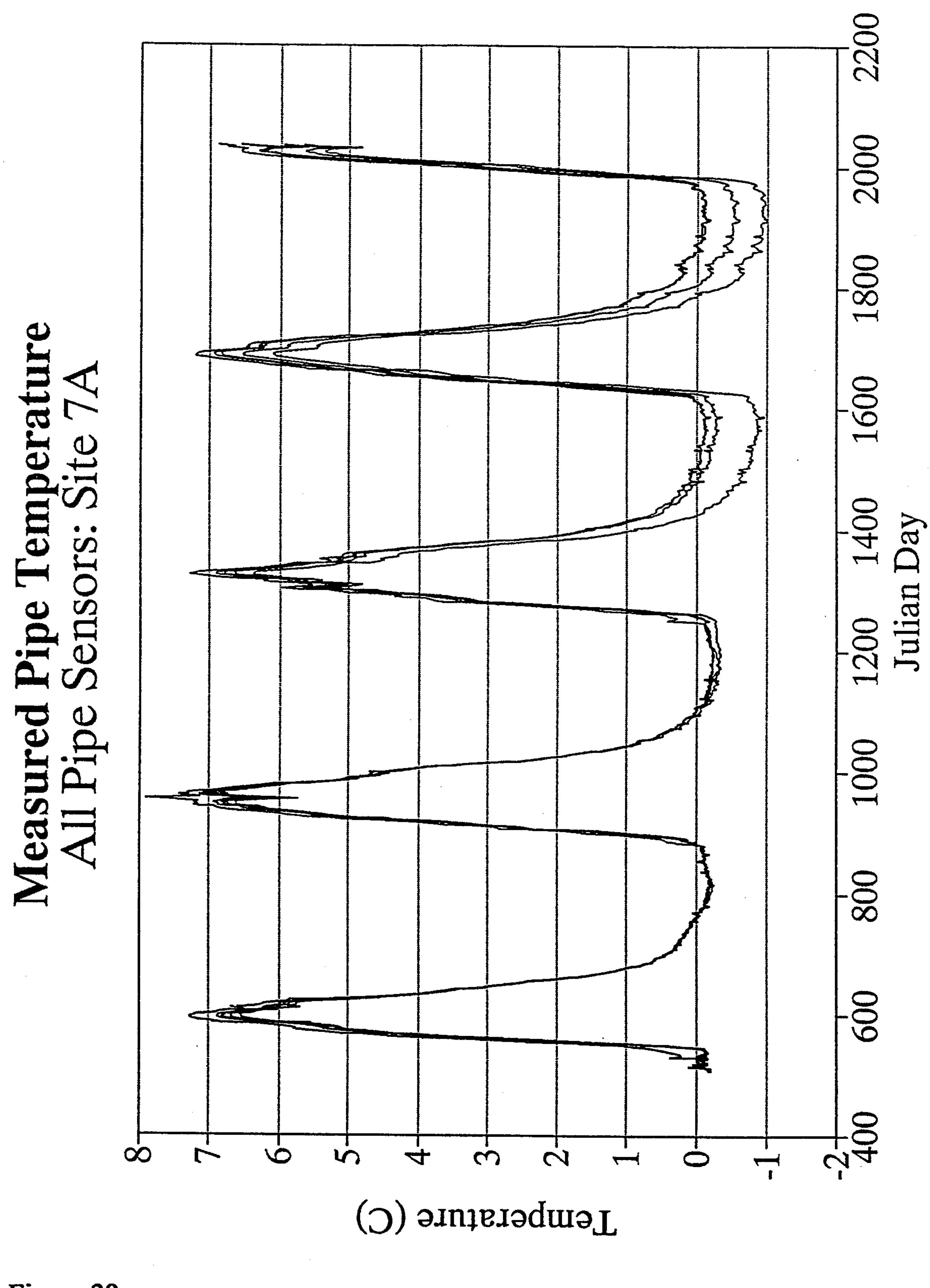

Measured Pipe Temperature
All Pipe Sensors: Site 7A
Temperature (C)
Julian Day
8
7
6
5
4
3
2
1
0
-1
-2
400
600
800
1000
1200
1400
1600
1800
2000
2200

Figure 29

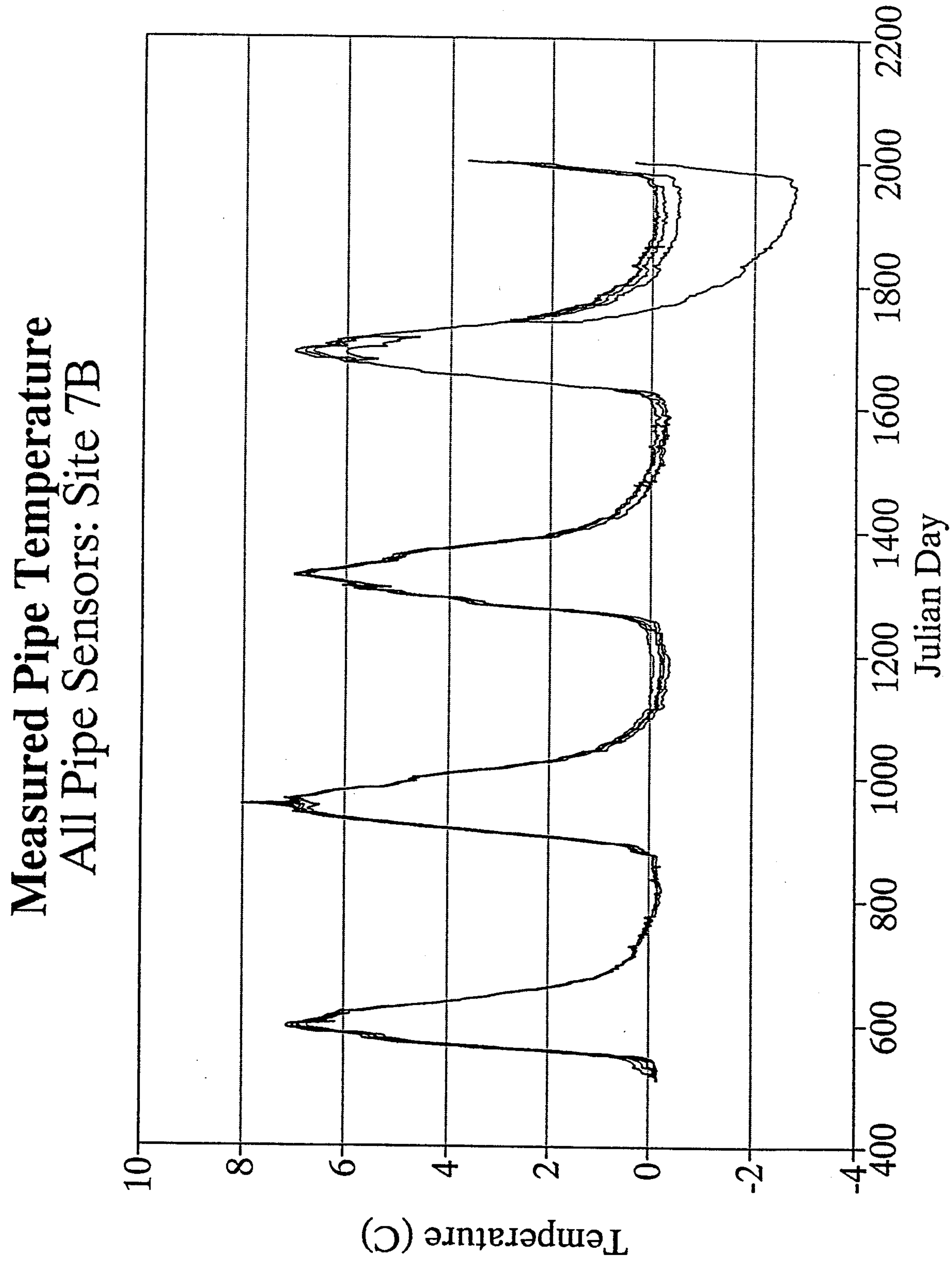

Measured Pipe Temperature
All Pipe Sensors: Site 7B
Temperature (C)
10
8
6
4
2
0
-2
-4
400
600
800
1000
1200
1400
1600
1800
2000
2200
Julian Day

Figure 30

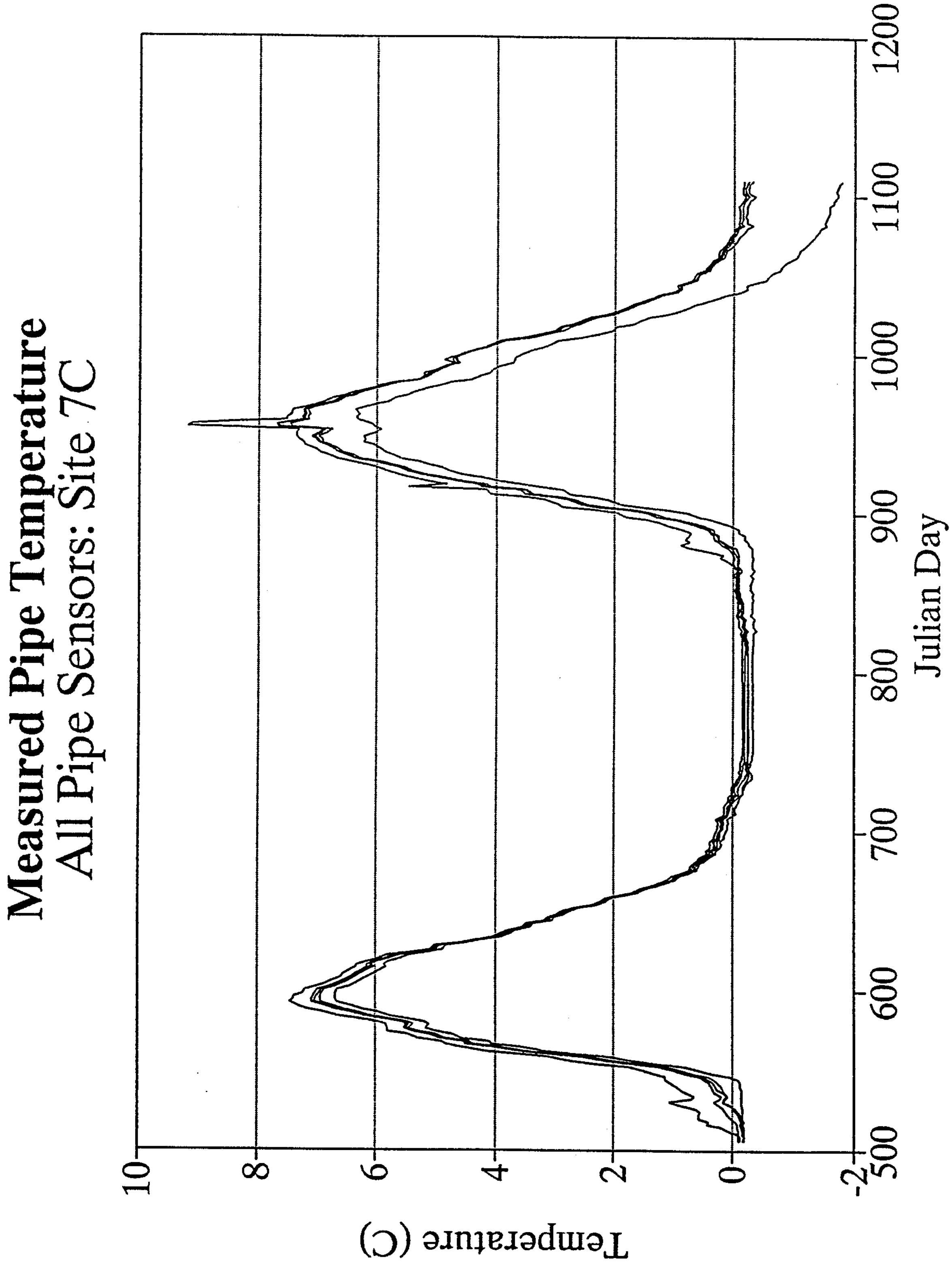

Measured Pipe Temperature
All Pipe Sensors: Site 7C
Temperature (C)
10
8
6
4
2
0
-2
500
600
700
800
900
1000
1100
1200
Julian Day

Figure 31

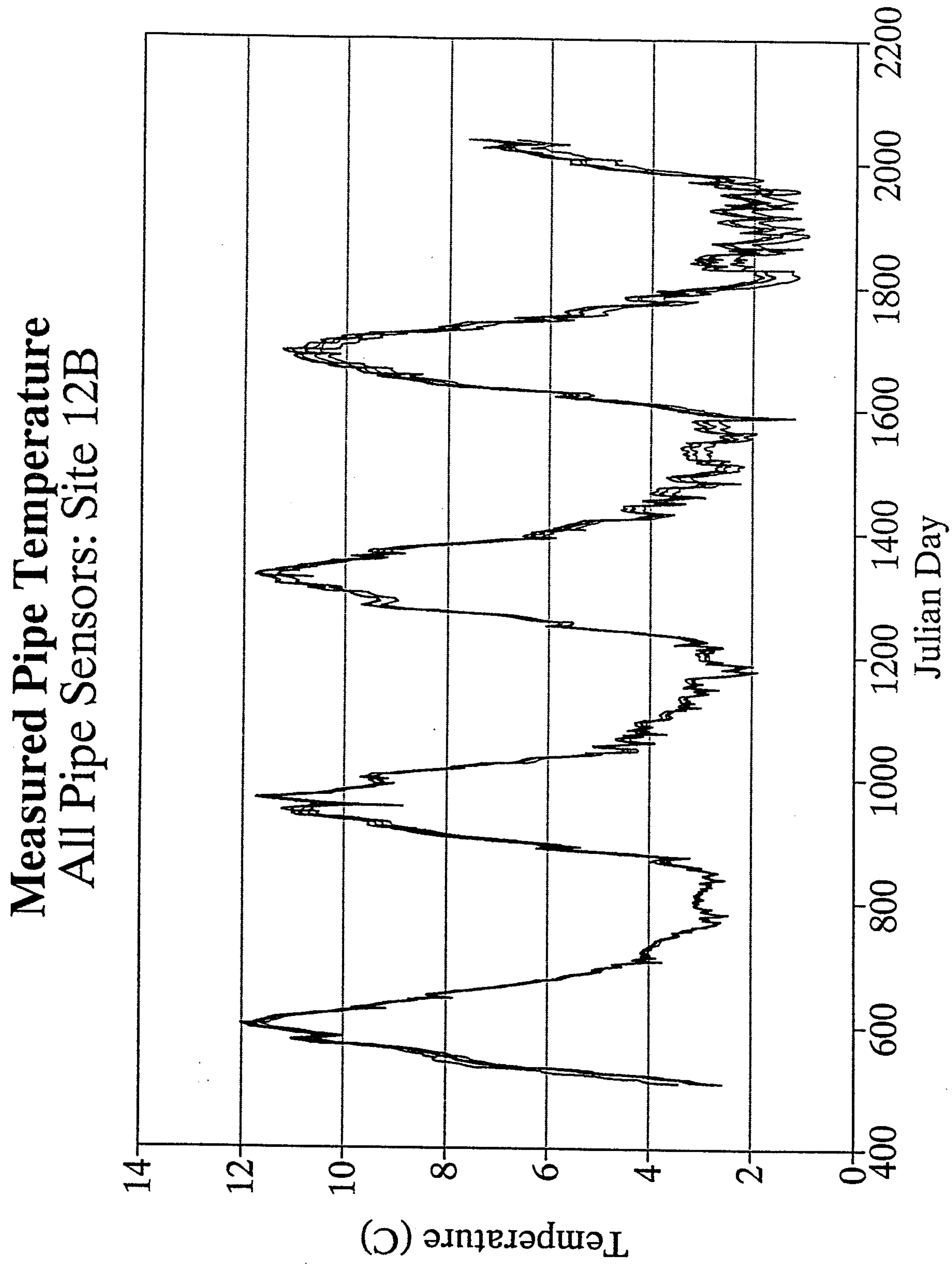

Measured Pipe Temperature
All Pipe Sensors: Site 12B
Temperature (C)
0
2
4
6
8
10
12
14
Julian Day
400
600
800
1000
1200
1400
1600
1800
2000
2200

Figure 32

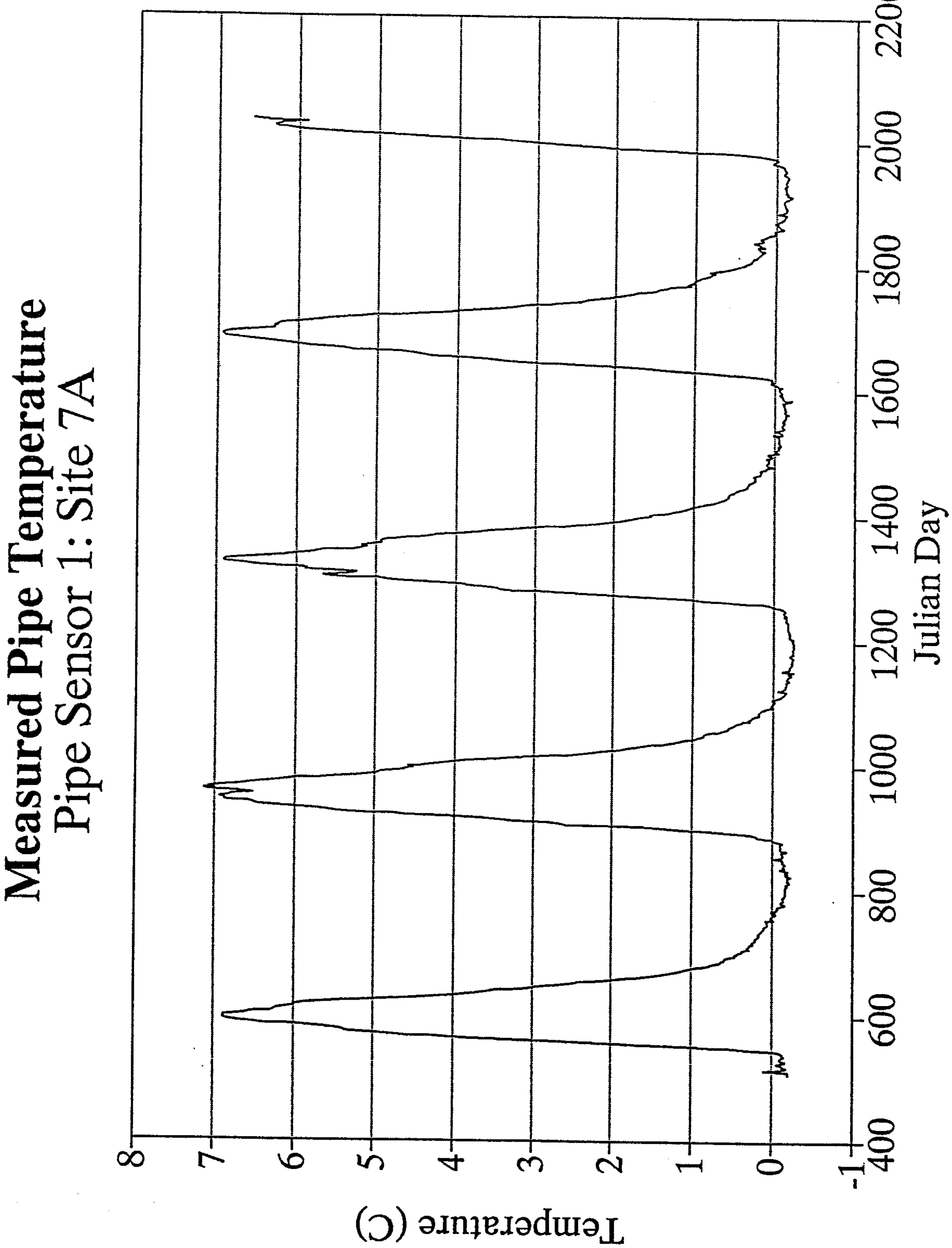
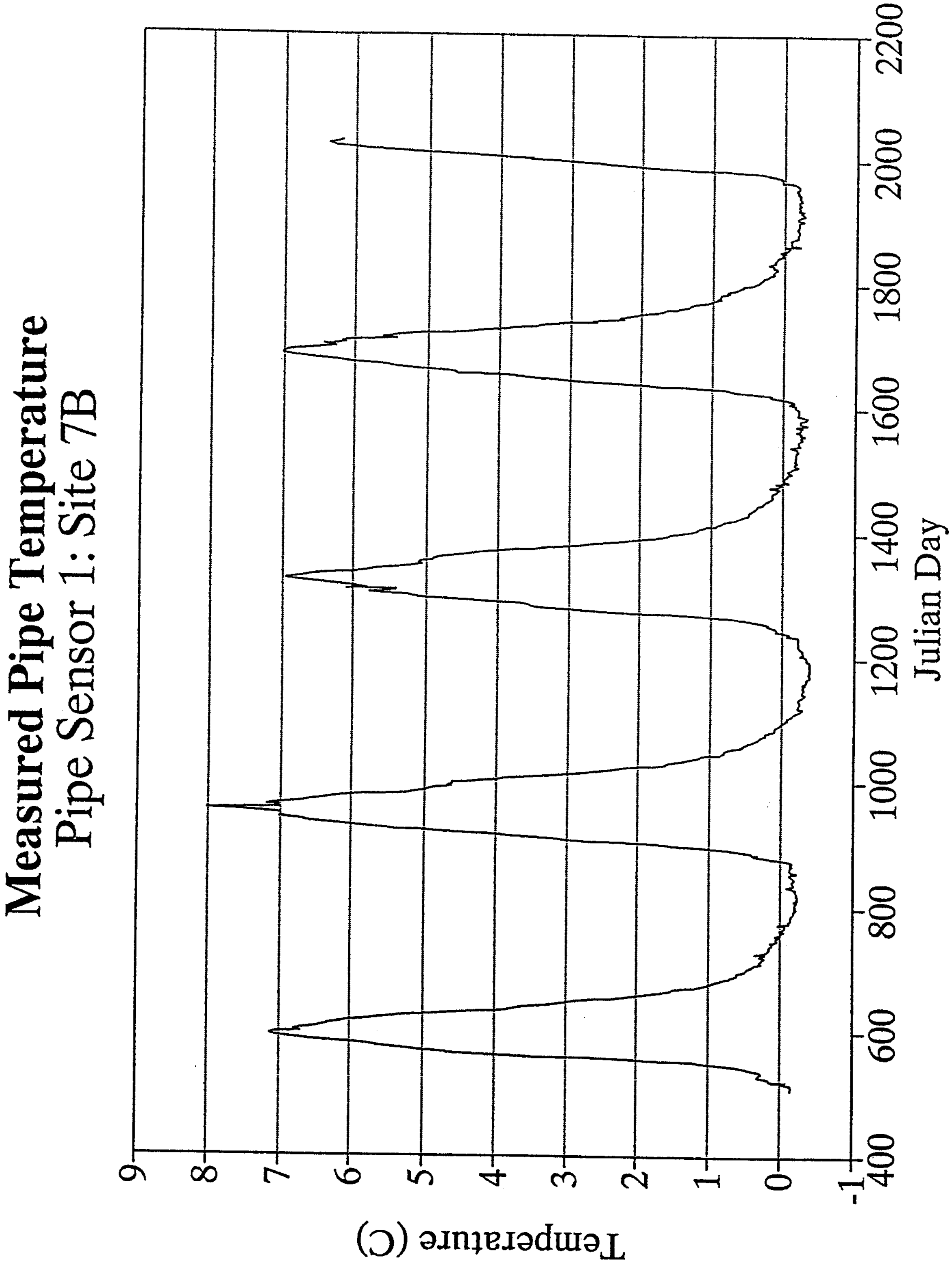

Measured Pipe Temperature
Pipe Sensor 1: Site 7A
Temperature (C)
8
7
6
5
4
3
2
1
0
-1
400
600
800
1000
1200
1400
1600
1800
2000
2200
Julian Day

Figure 33



Measured Pipe Temperature
Pipe Sensor 1: Site 7B
Temperature (C)
9
8
7
6
5
4
3
2
1
0
-1
400
600
800
1000
1200
1400
1600
1800
2000
2200
Julian Day

Figure 34

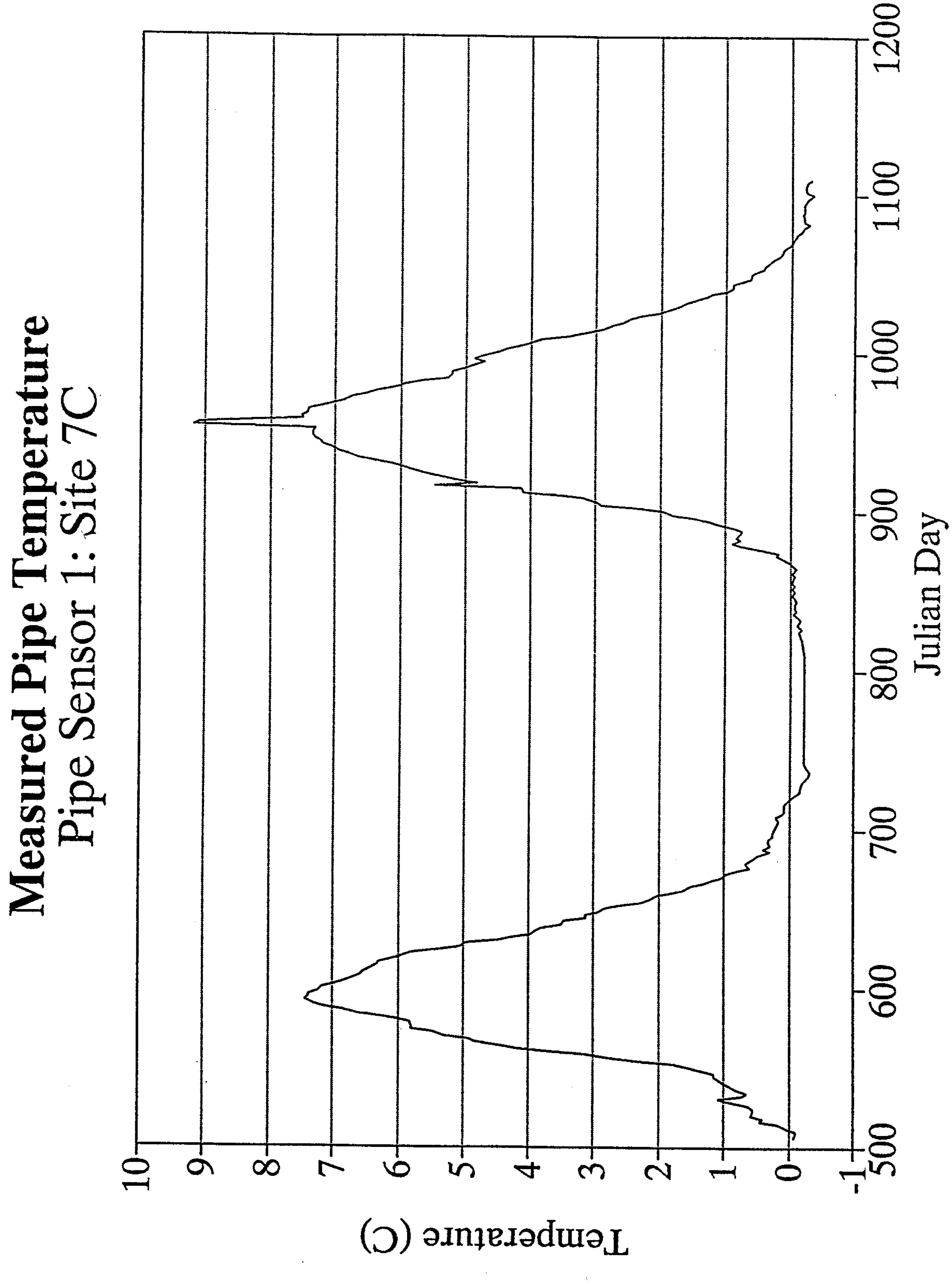
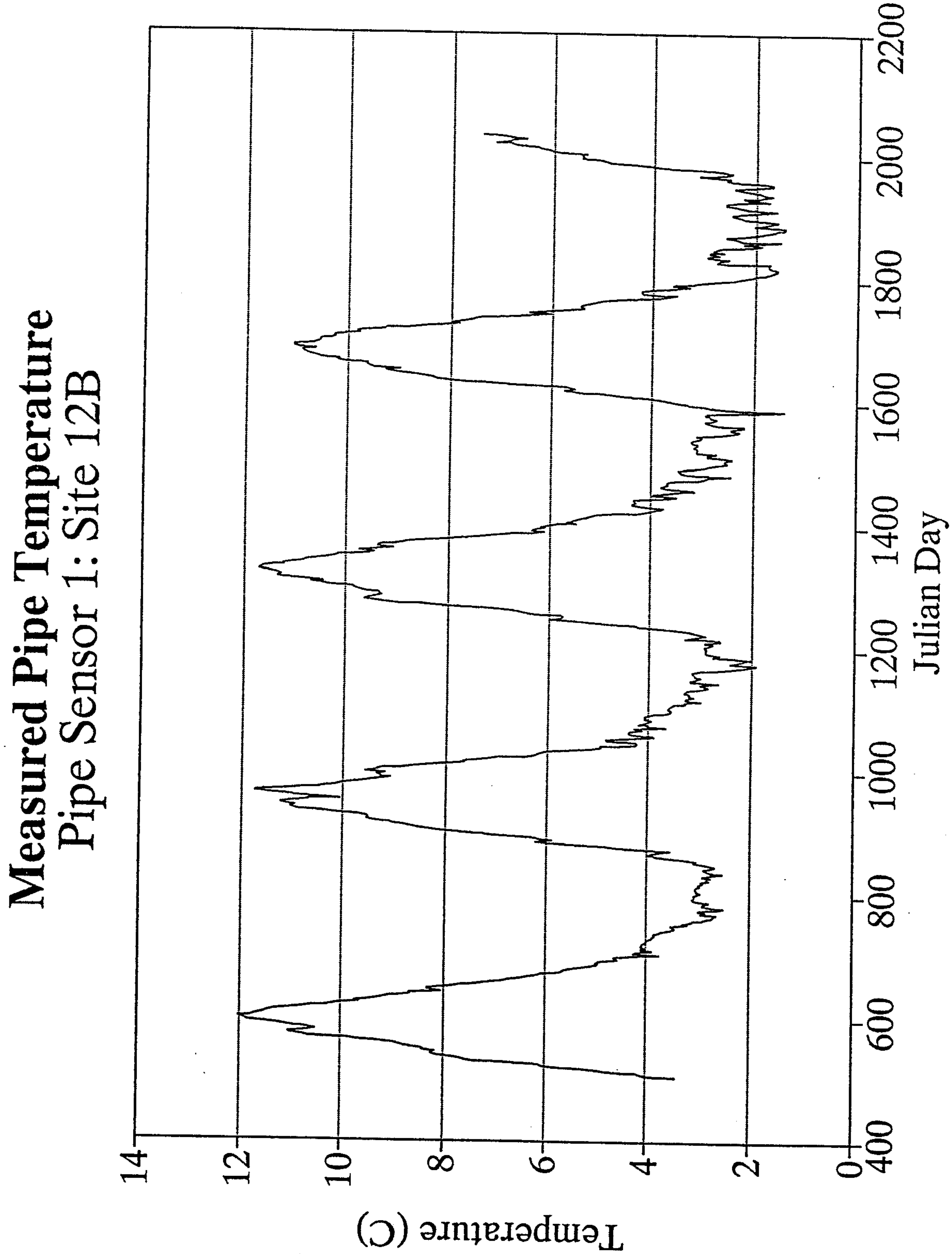

Measured Pipe Temperature
Pipe Sensor 1: Site 7C
Temperature (C)
10
9
8
7
6
5
4
3
2
1
0
-1
500
600
700
800
900
1000
1100
1200
Julian Day

Figure 35



Measured Pipe Temperature
Pipe Sensor 1: Site 12B
Temperature (C)
0
2
4
6
8
10
12
14
Julian Day
400
600
800
1000
1200
1400
1600
1800
2000
2200

Figure 36

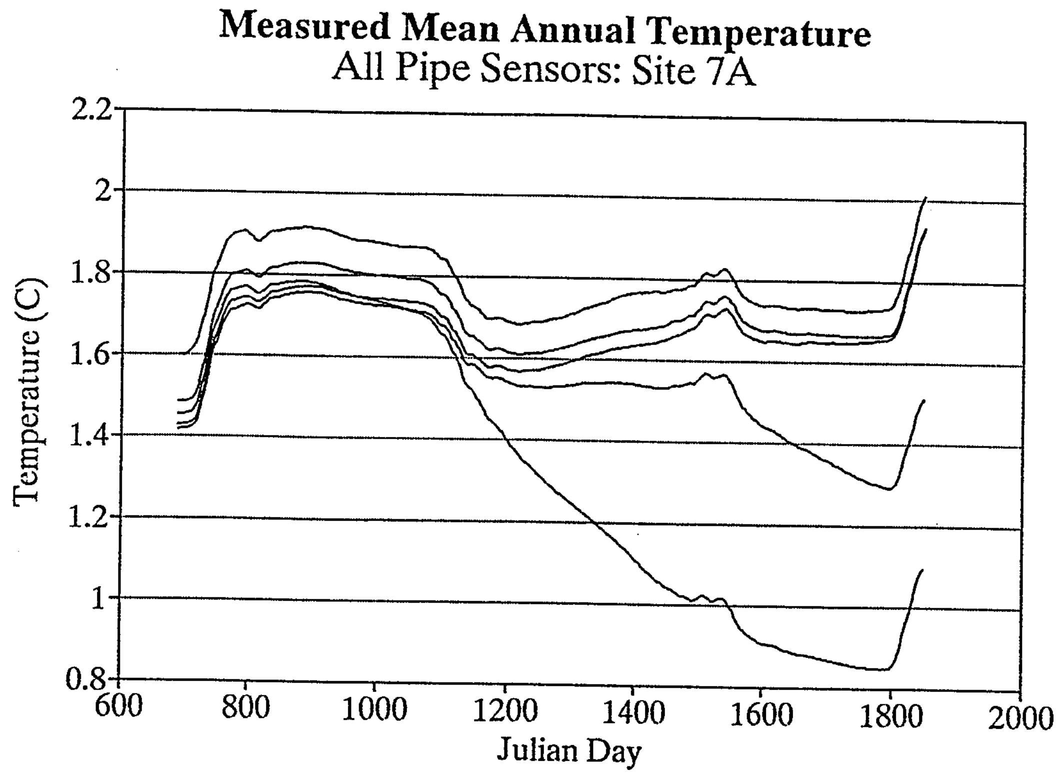


Figure 37

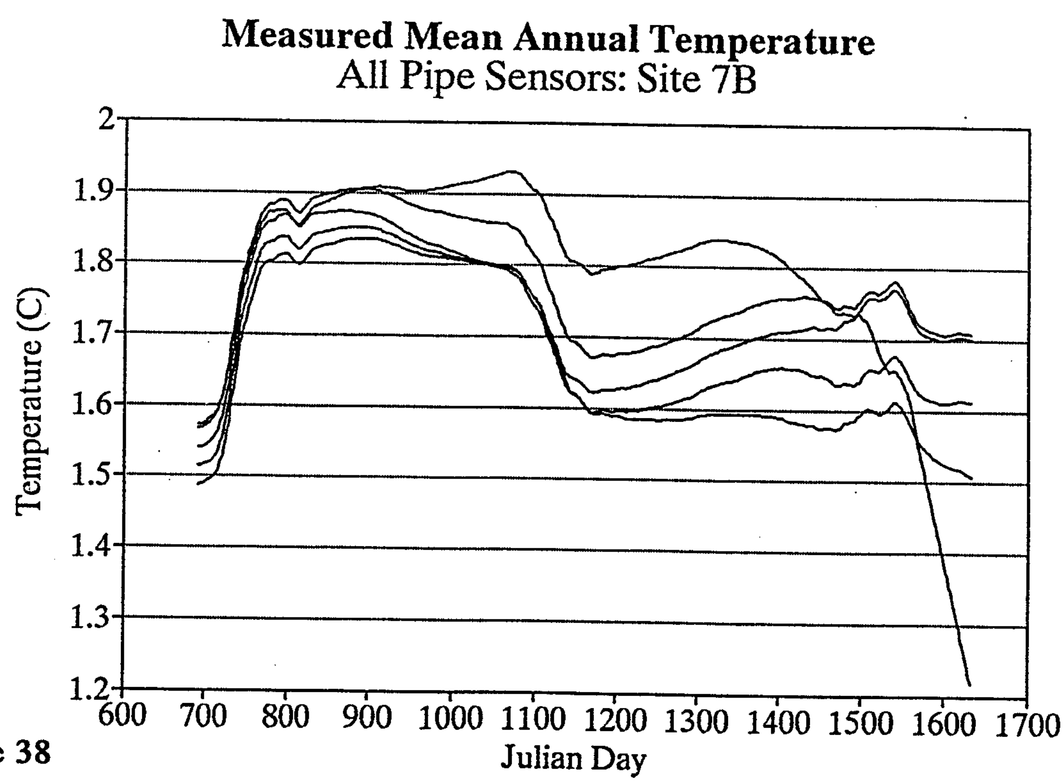


Figure 38

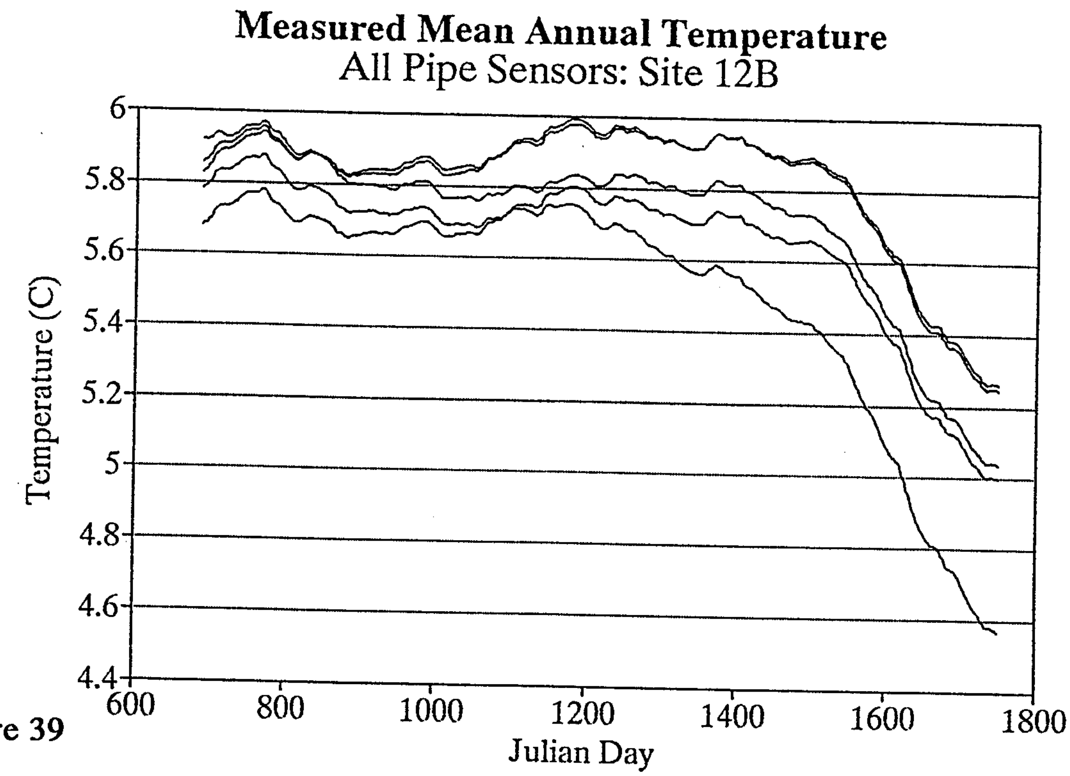


Figure 39

Interpolation Results

The standard analytical procedure was used on the pipe temperature records to establish the relationships between measurement interval and temperature uncertainty. Results are shown in Figures 40 to 47. These Figures show the four summary summary statistics (maximum range, maximum standard deviation, average range, average standard deviation) for all five pipe sensors at each measurement interval. Overall, the behaviour of the pipe sensor data when used with spline interpolation is similar to that for ground temperature. Because of the strong correlation between syncronous temperature measurements of the five sensors, the statistics generated for the five sensors at a site cluster near the same values for all but a few instances.

Figures 48 and 49 compares the average standard deviation - measurement interval relationships for the four pipe locations. For both interpolated temperature and mean annual temperature, site 12B shows significantly higher errors than at the other sites for shorter measurement intervals. This is due to the signifcant short term fluctuatuations in pipe temperature, which add a signifcant random element to the sample taken at an

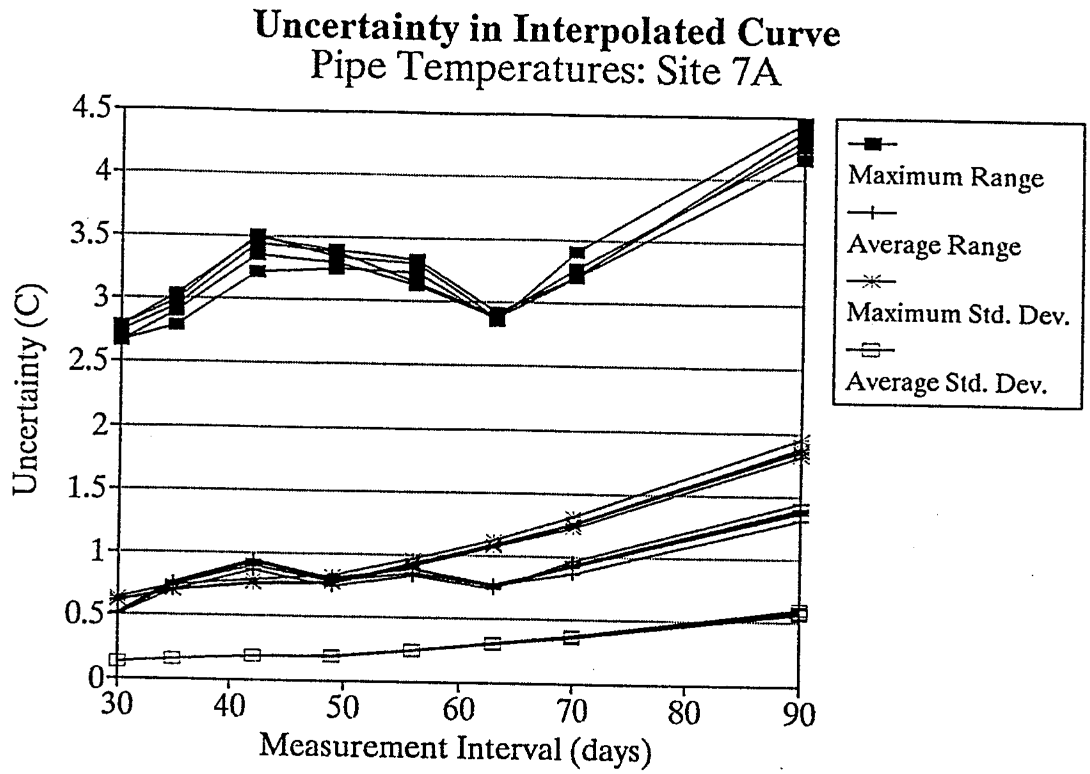


Figure 40

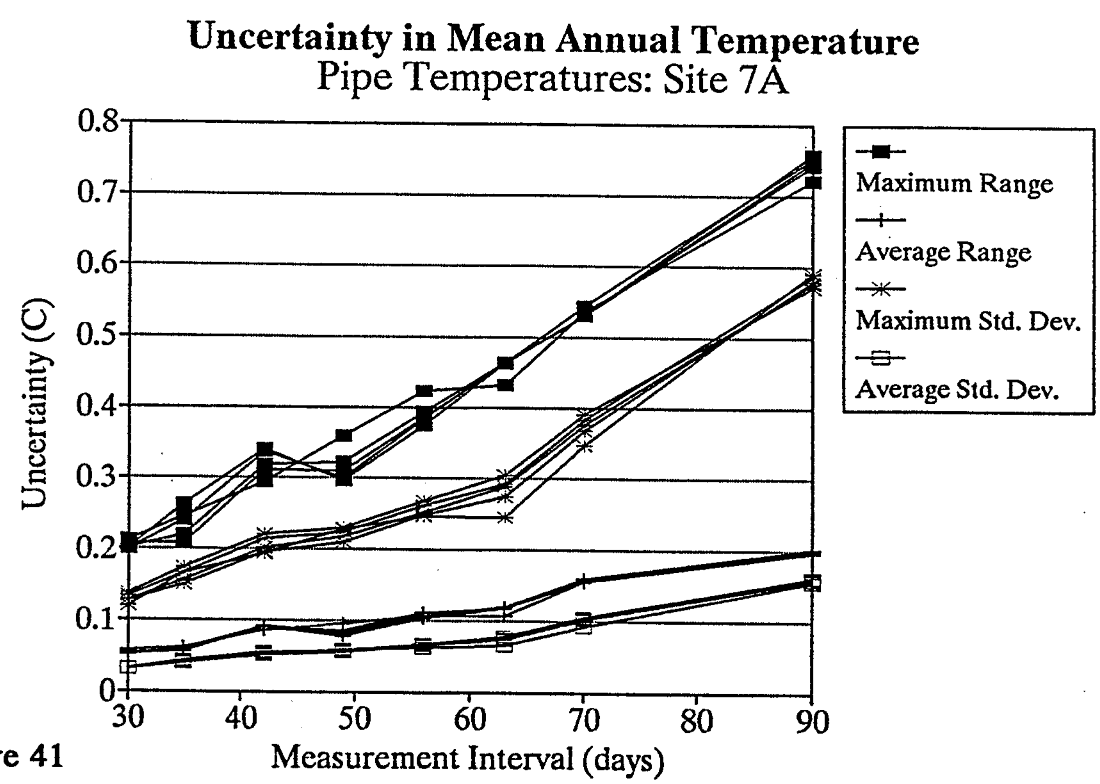


Figure 41

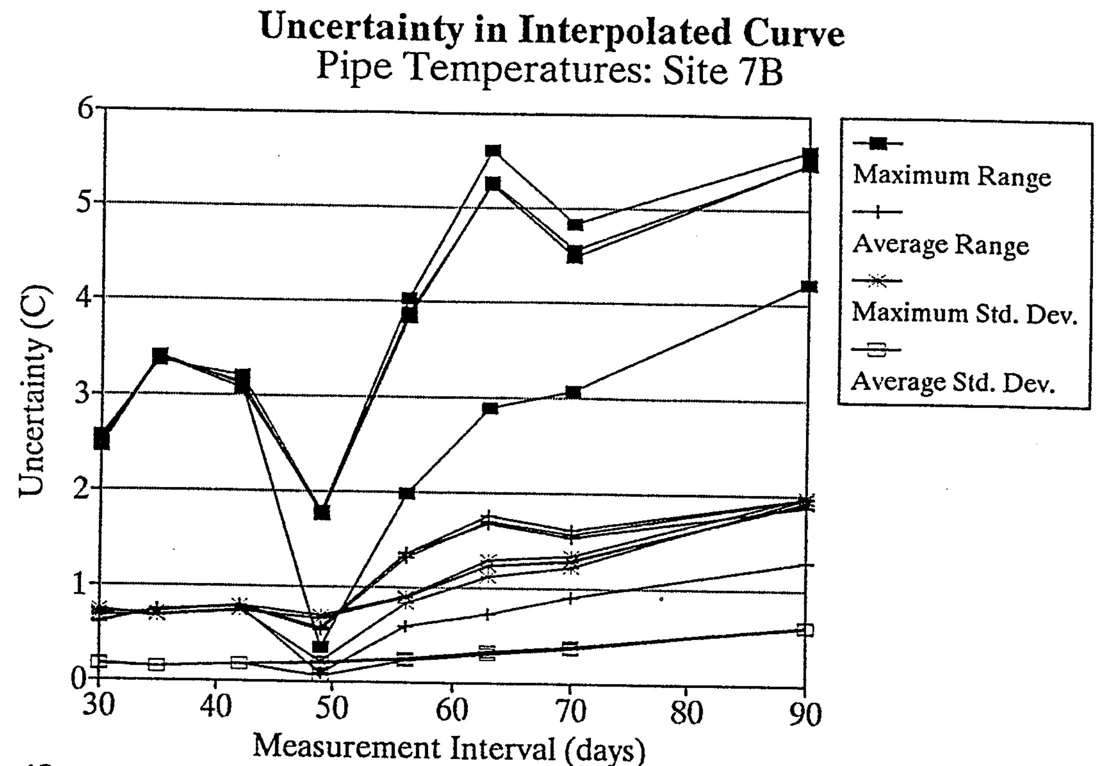


Figure 42

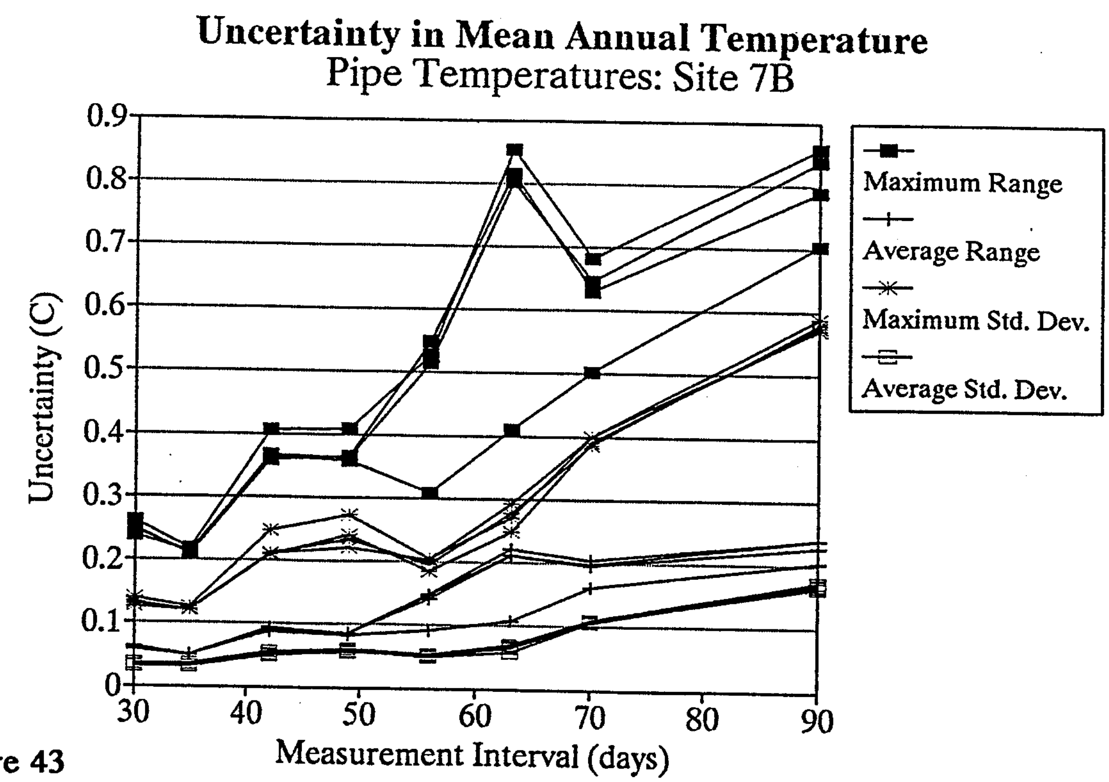


Figure 43

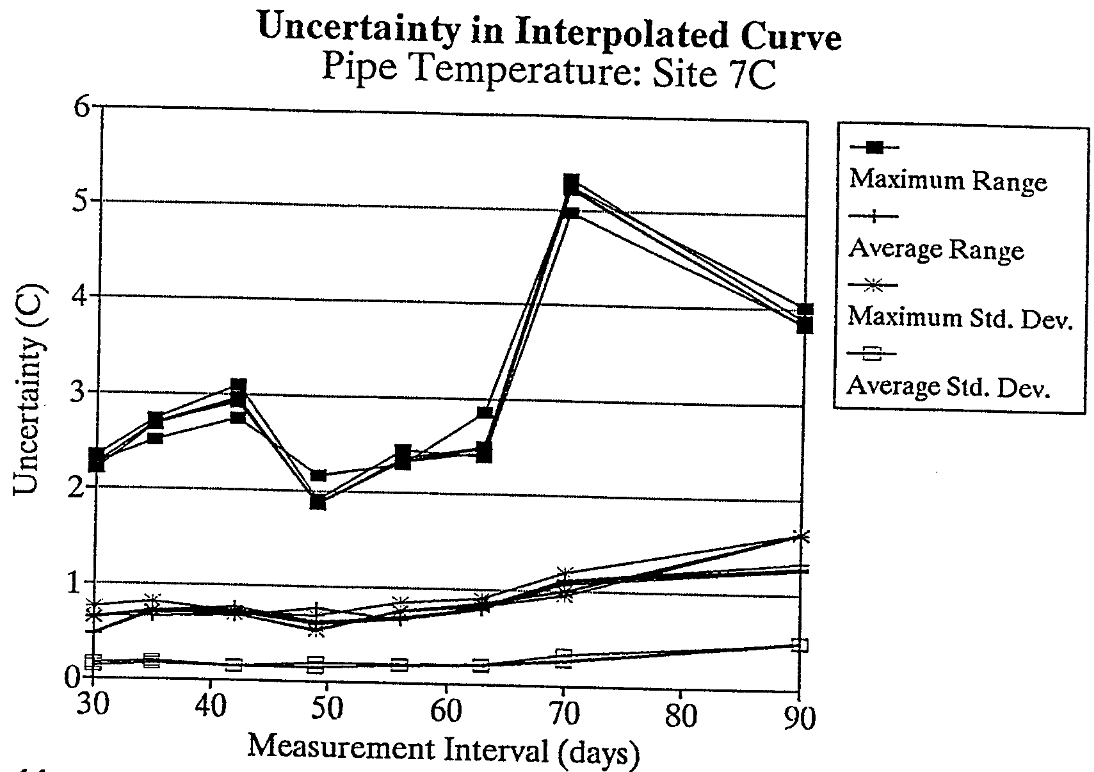


Figure 44

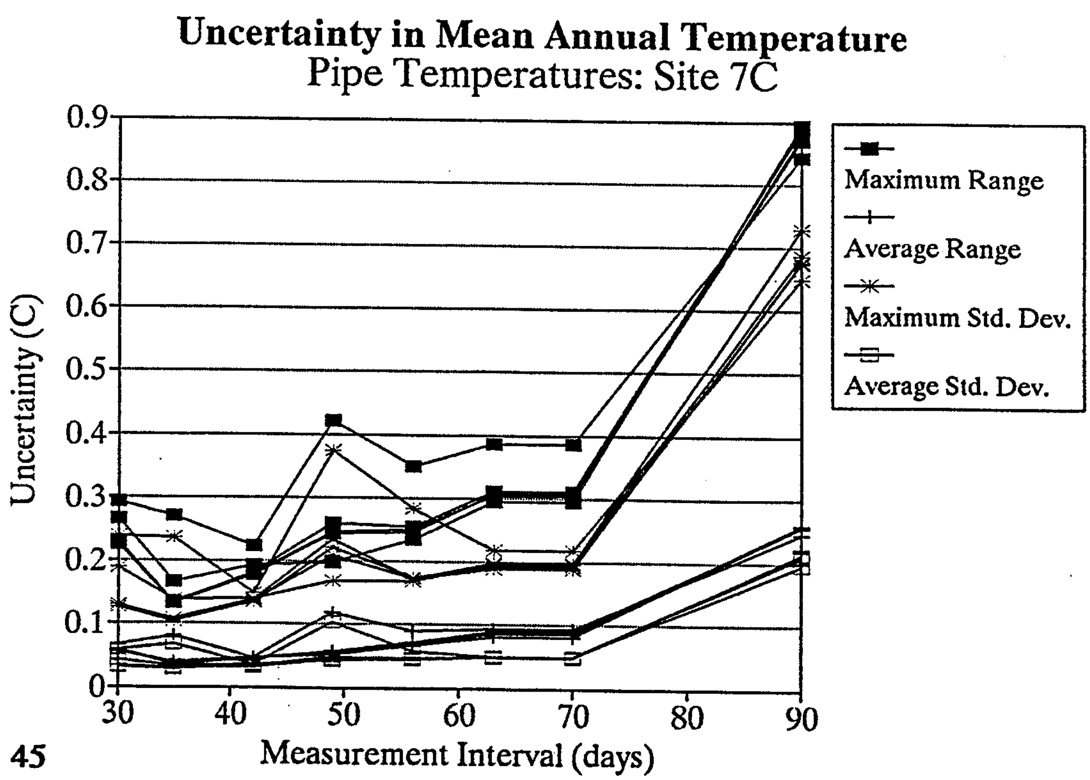


Figure 45

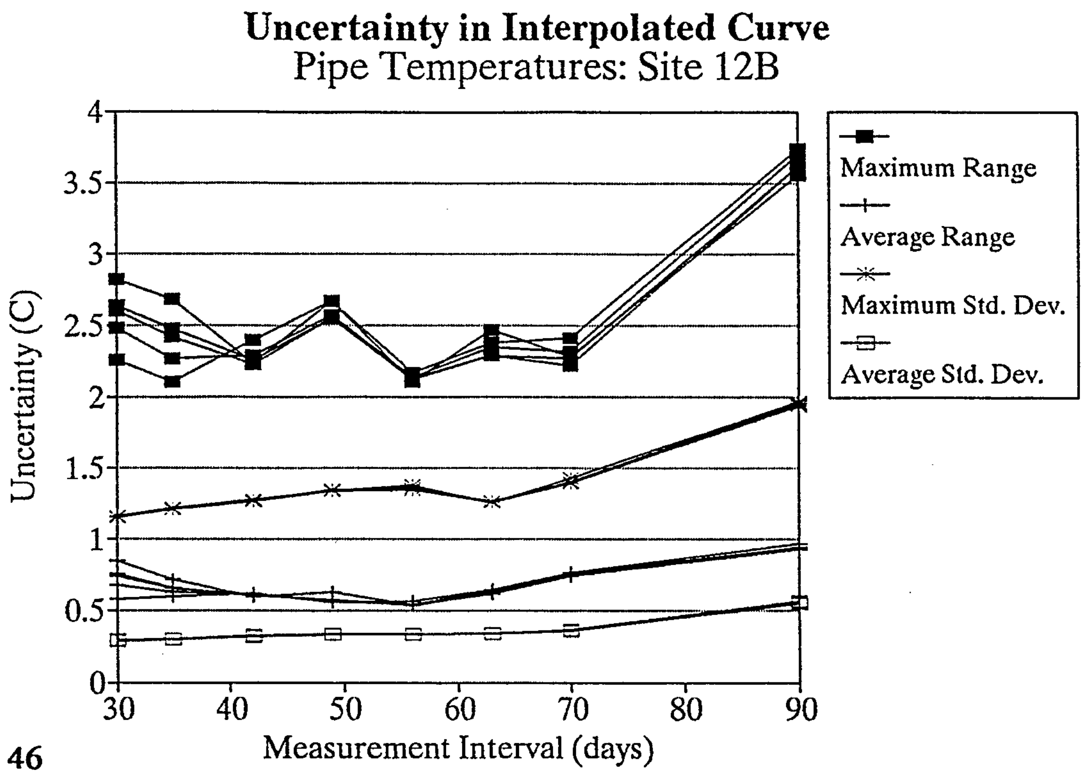


Figure 46

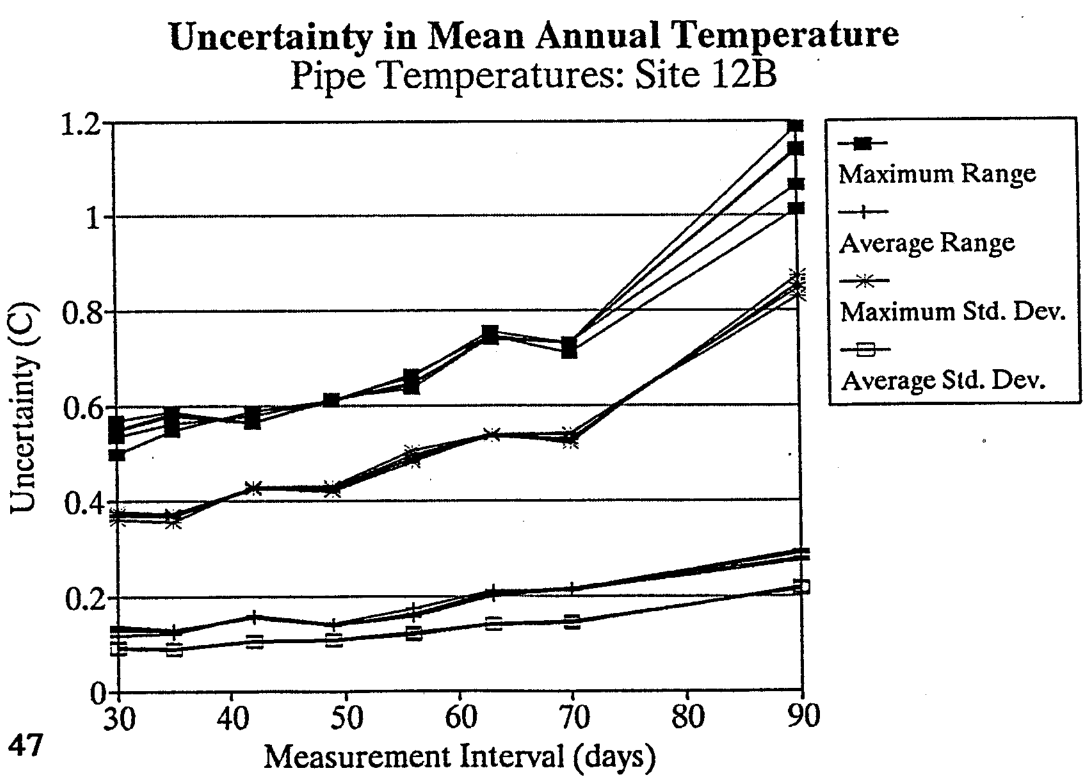


Figure 47

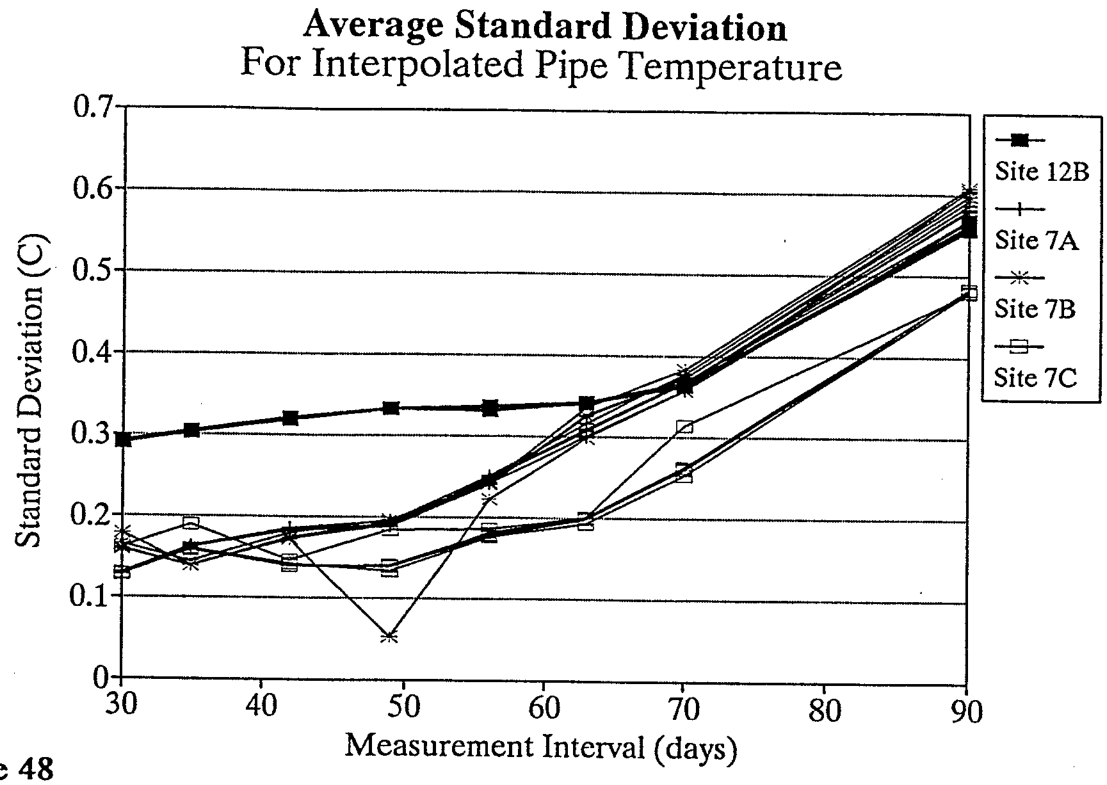


Figure 48

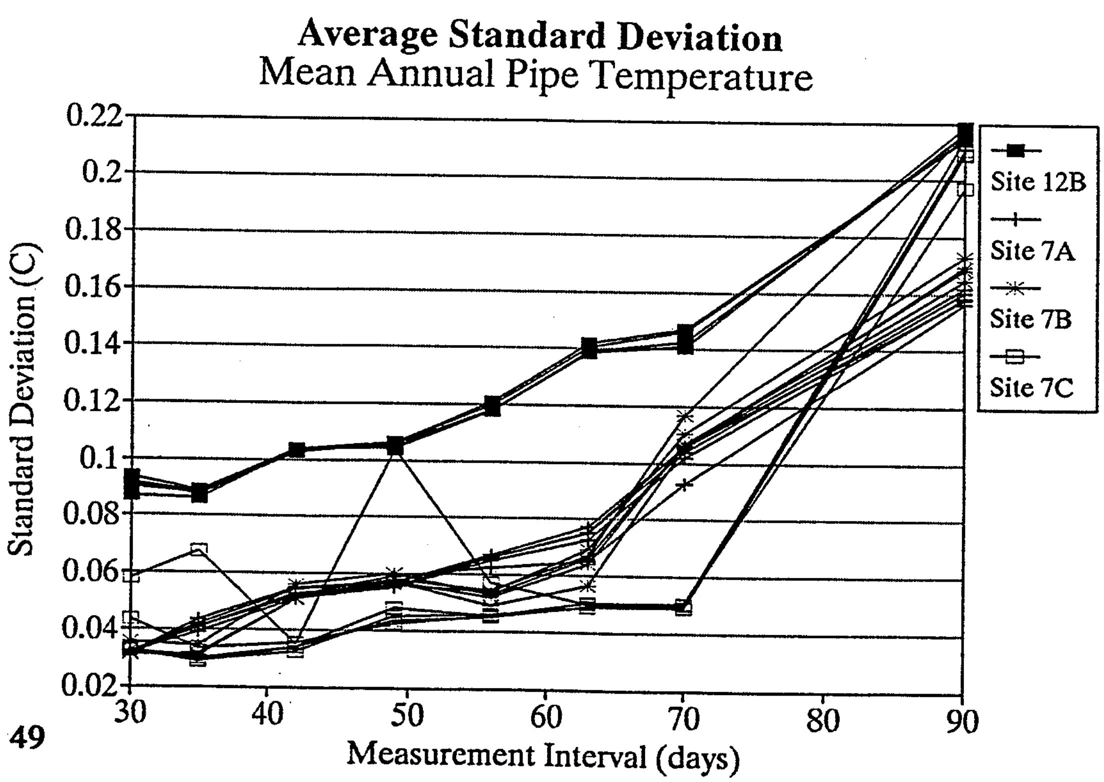


Figure 49

interval longer than the frequency of the short term fluctuation.

Pipe Shutdowns

At any point along the pipeline, oil flowing in the pipe is at a temperature which is controlled primarily by the temperature of the soil surrounding the pipe *upstream* of the measurement point, by its initial temperature on entering the pipe from a pump station, and some frictional heating due to flow. When oil stops flowing in the pipe, the oil begins to assume the temperature of the immediately adjacent soil. An oil flow shutdown can cause a significant change in temperature measured at monitoring sites, depending on the difference between flowing oil temperature and the temperature of the surrounding soil.

The thermal effect of shutdowns was examined to evaluate:

1. The magnitude of their influence on mean annual pipe temperature; and

2. Their importance in the manual temperature record, specifically whether temperatures taken during a shutdown should be excluded when evaluating the thermal regime of the site via spline interpolation.

At site 12B, shutdowns in August 1990 and May 1992 were examined (Figures 50 and 51). Only the August 1990 shutdown was examined at site 7A (Figure 52), since the May 1992 shutdown left no clearly definable temperature signature at this site.

Figures 53 to 55 show the magnitude of the temperature anomalies in each instance, by subtracting sensor temperatures at the start of shutdown from the temperature during and following the shutdown. During a shutdown, the thermal response follows a classic pattern of rapid early change in temperature, with the rate of temperature change declining with time. As oil flow is resumed, a similar early rapid temperature change declining with time is apparent as the pipe returns to its normal thermal condition. During the shutdown of August 1990 all sensors at 12B cooled by different amounts. In May 1992, however, all sensors cool by approximately the same amount over time. At site 7A, most sensors cool to varying degrees, while one sensor became warmer during the shutdown. These differences in behaviour reflect the different ground thermal regimes in spring versus late summer (i.e. small versus large temperature gradients through the ground around the pipe), as well as the particular regimes at the two sites.

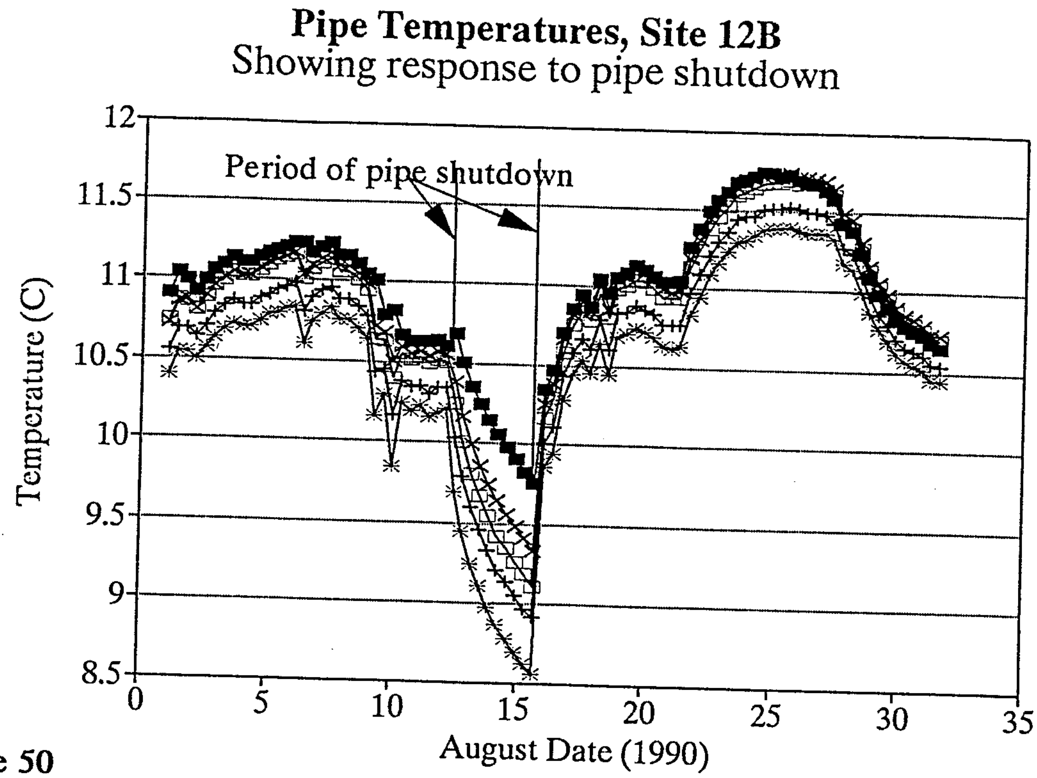


Figure 50

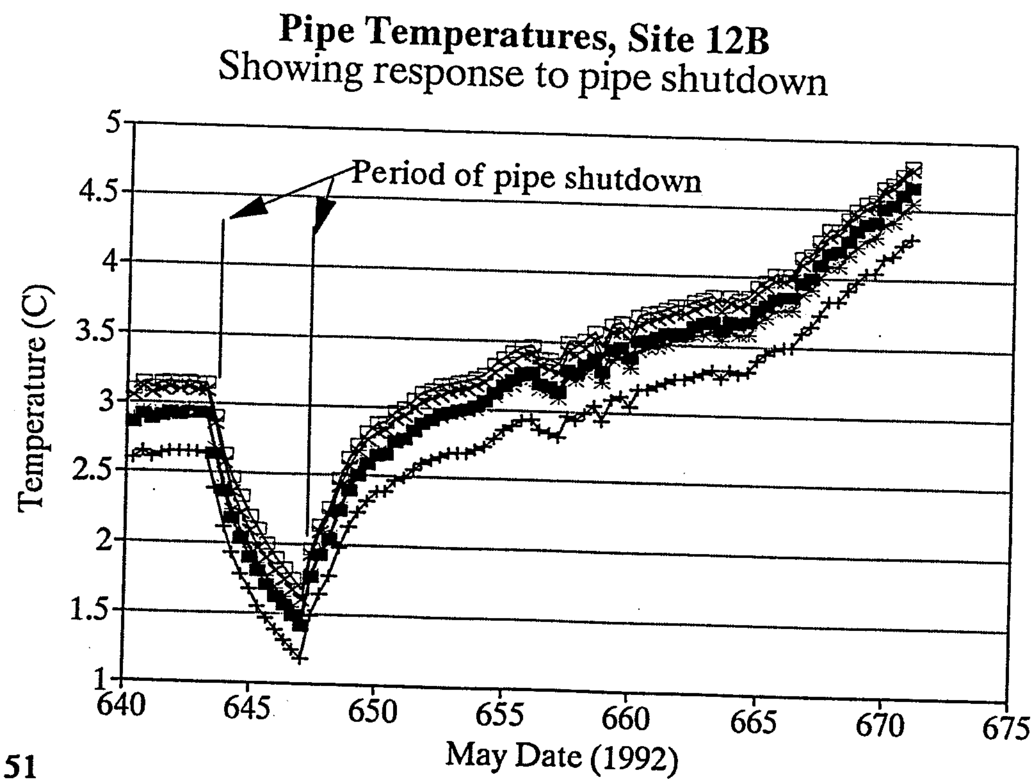


Figure 51

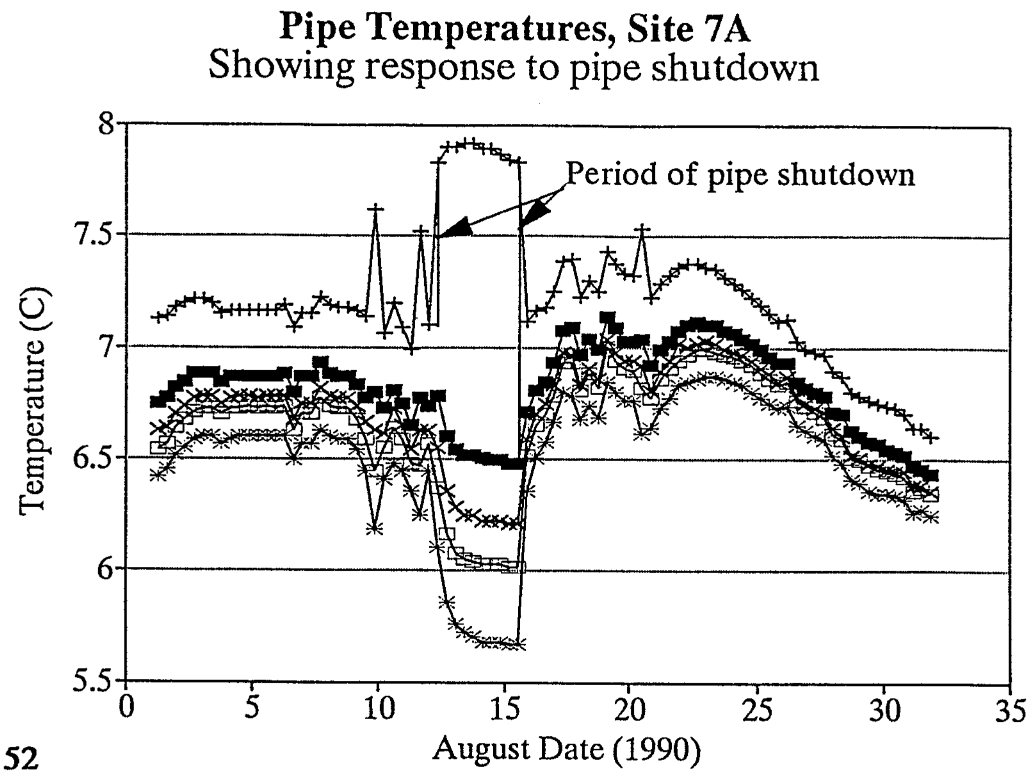


Figure 52

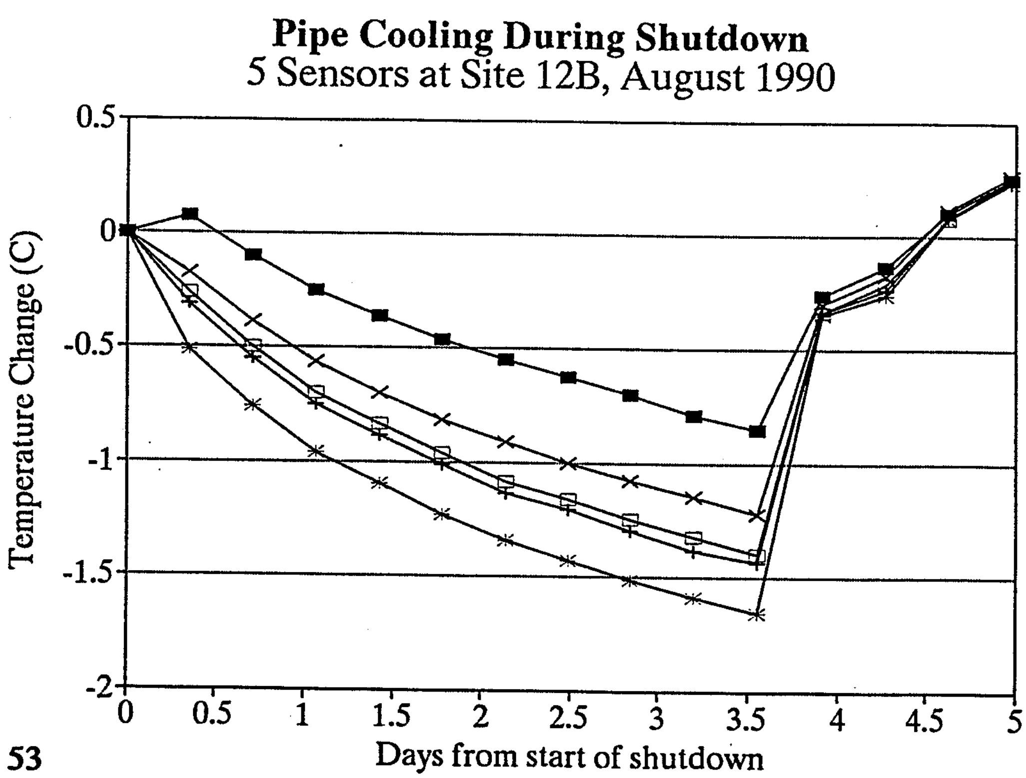


Figure 53

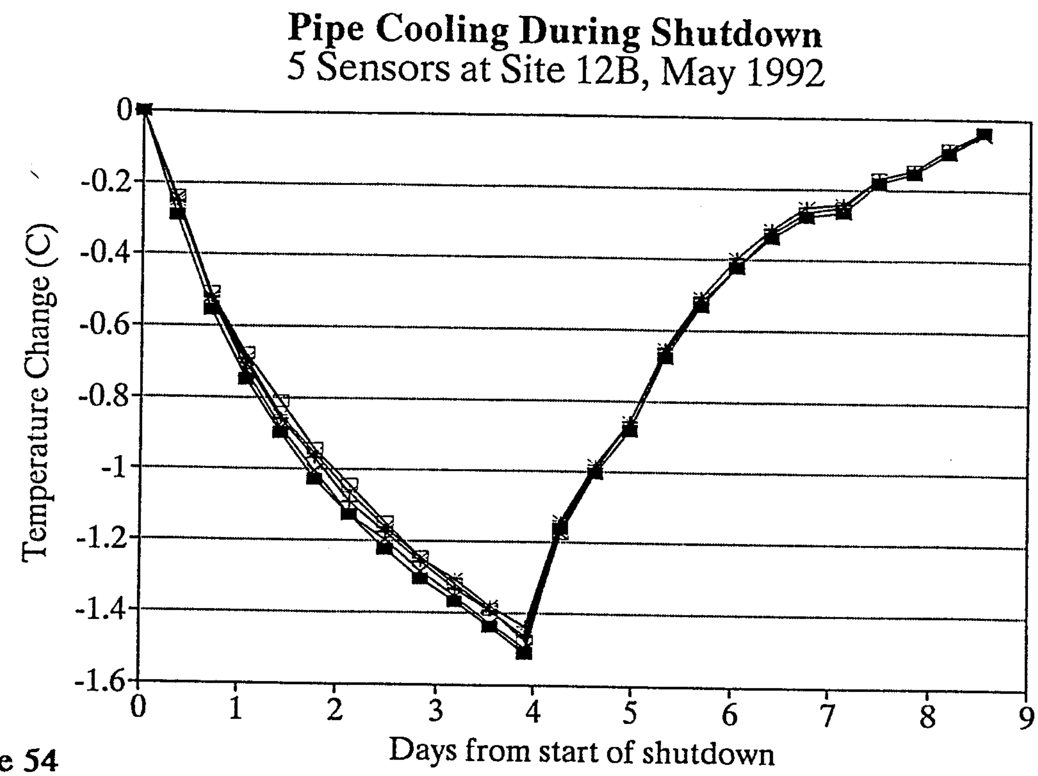


Figure 54

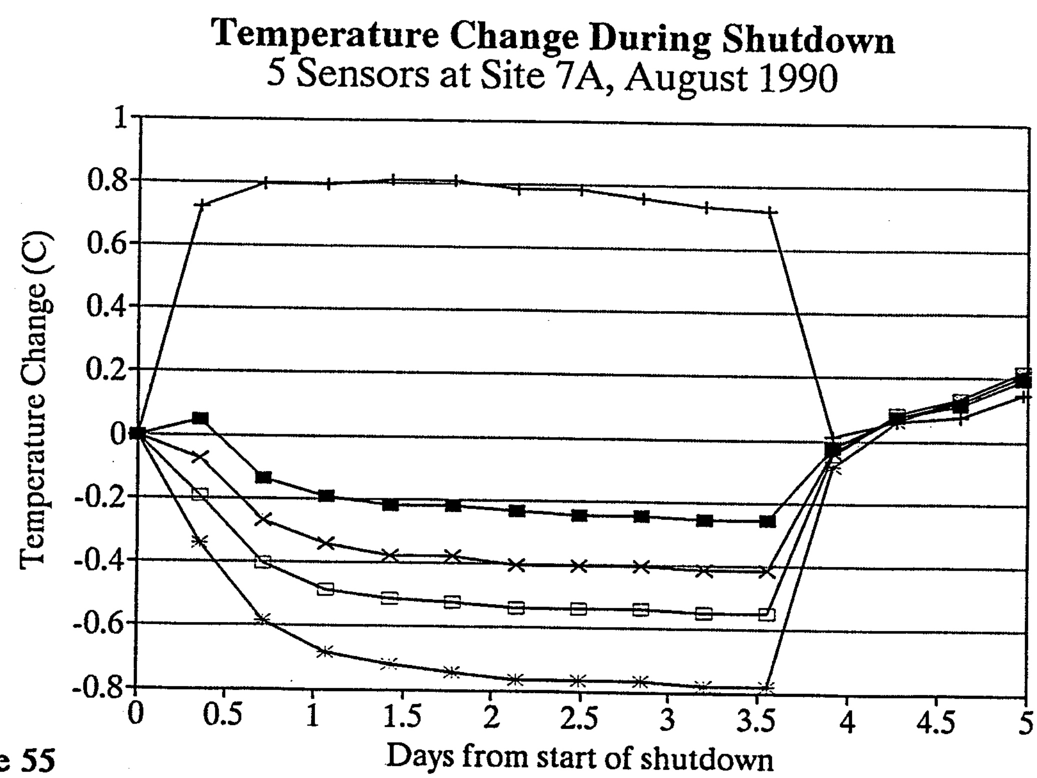


Figure 55

The effect of each shutdown-related thermal anomaly on the thermal regime can be calculated by integrating the temperature change over time. This results in a degree-day value which can be used directly to calculate the effect on the annual or monthly mean temperature. Each degree-day of the anomaly will contribute 1/365th of 1°C toward the annual mean temperature, or 0.00274°C. The corresponding value for the monthly mean is 0.0333°C. The cumulative degree-day values for each of the shutdown cases studied are shown in Figures 56 to 58. The greatest anomaly produced by these shutdowns is about 6 degree days, which corresponds to an influence on the mean annual temperature of 0.016°C, or 0.2°C for the monthly mean temperature.

To examine the effect of including data from a shutdown on the interpolation procedure, the standard procedure for evaluating interpolation uncertainty outlined in the introduction (p. 3) was repeated using a data file for site 12B which had the August 1990 shutdown edited out of the datalogger file. The uncertainty envelop for the original file (including the shutdown in the logger file) and the edited file are shown in Figure 59 for the 30 day measurement interval. The additional uncertainty near the time of the shutdown is apparent as a lower minimum temperature on the envelop for the data set with the shutdown data included. Figure 60 compares the minima of the two envelops for the period close to the shutdown. The difference between these curves represents the added uncertainty due to the inclusion of the shutdown data in the manual measurement data. A degree-day integration of this difference (Figure 61) yields a value of about 22 degree days, corresponding to an added uncertainty of 0.060°C in the mean annual temperature.

Given that the error resulting from the inclusion of the data is about 3.5 times greater than the error resulting from its exclusion, manual temperature measurements known to have been taken during periods when oil is not flowing in the pipe should be removed from the record prior to subsequent analysis.

"Attached" versus "Unattached" Pipe Sensors

Additional pipe temperature sensors were added at some sites in order to supplement the record available from sensors attached to the pipe at the time of pipe placement. These have been intalled at several sites starting in 1988, usually with only a single "unattached" sensor per site,attached to Branker TL100 dataloggers. Because the pipe was already buried, these additional sensors were installed at the pipe surface but not

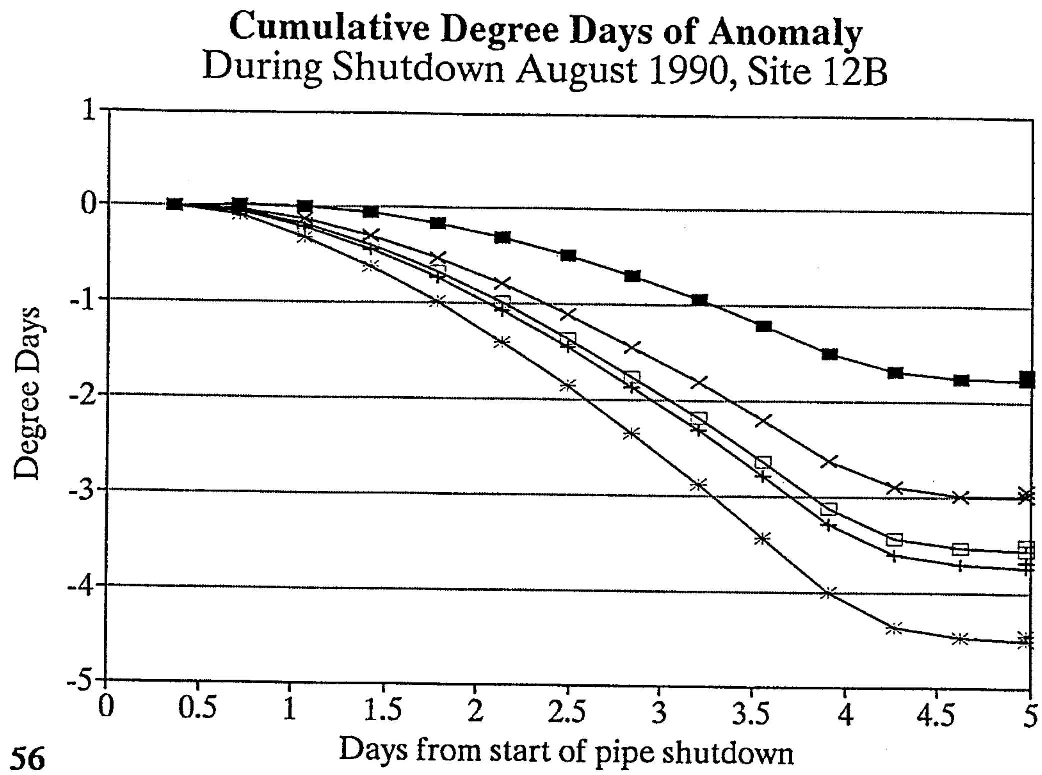


Figure 56

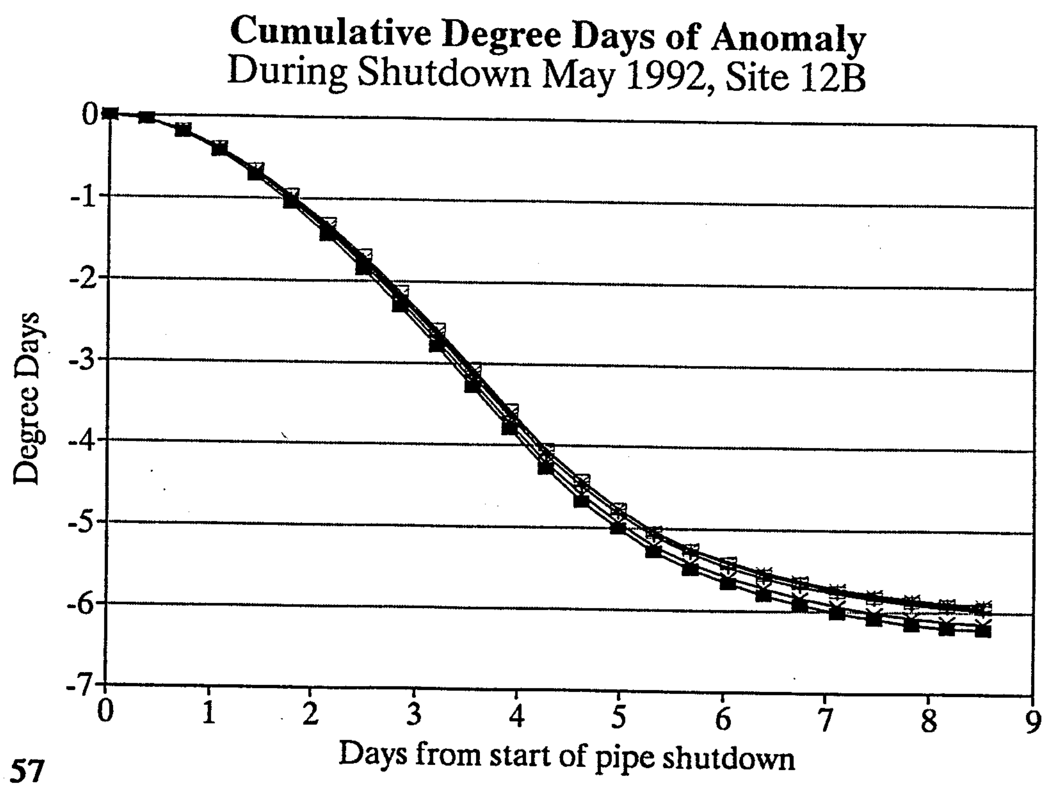


Figure 57

Cumulative Degree Days of Anomaly
During Shutdown August 1990, Site ~~12B~~ 7A

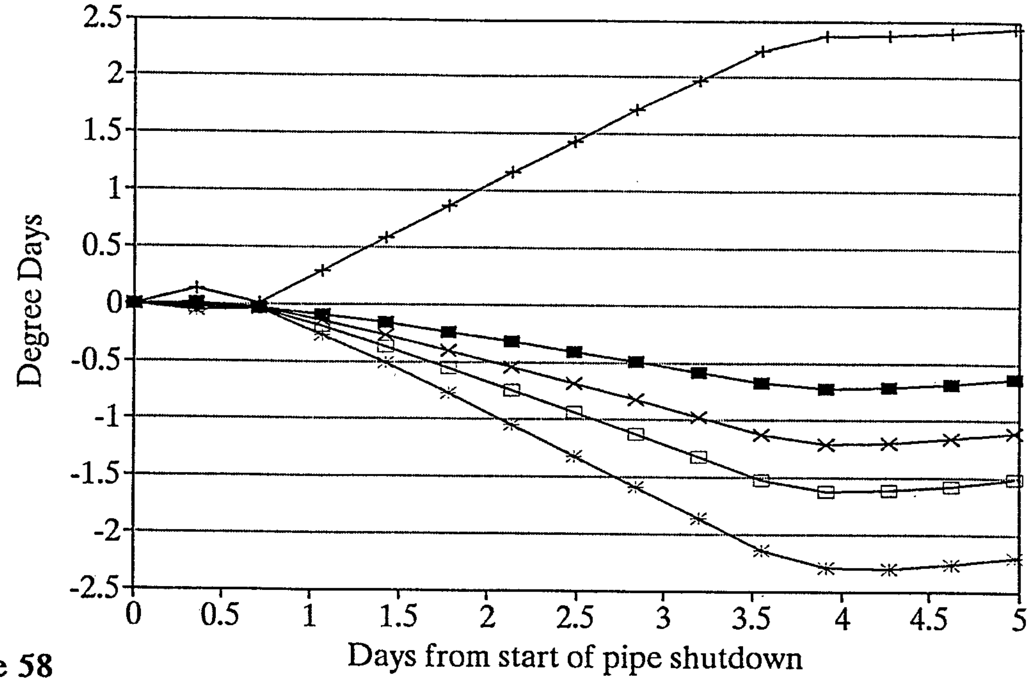


Figure 58

Temperature Uncertainty with 30 Day Interval
With / without August shutdown in data

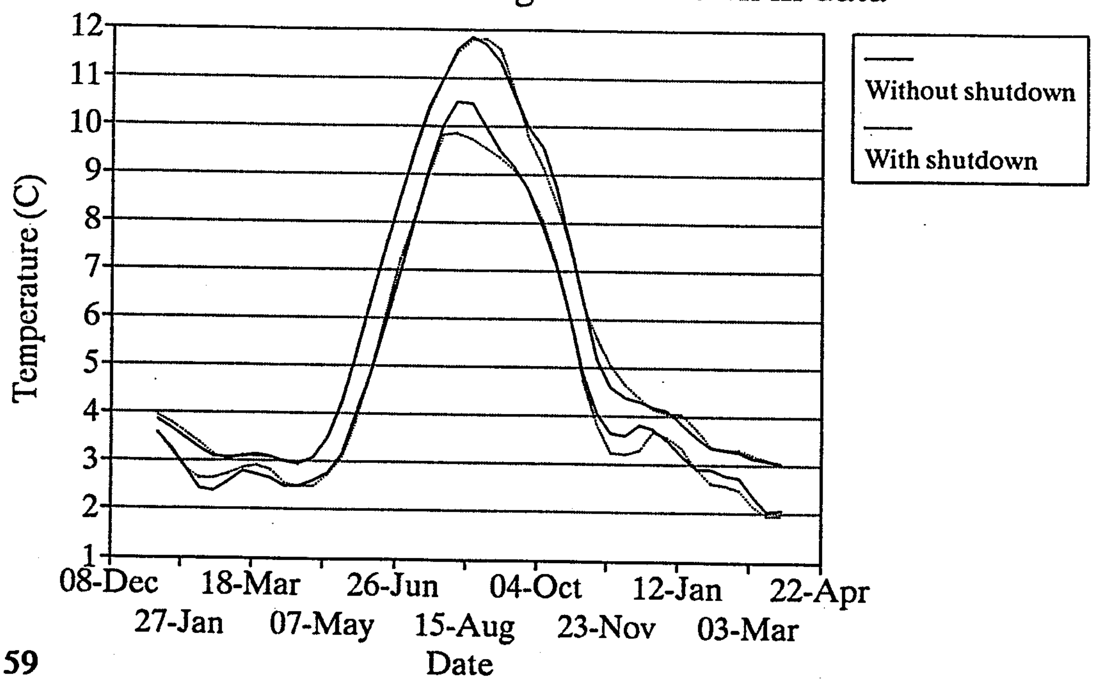


Figure 59

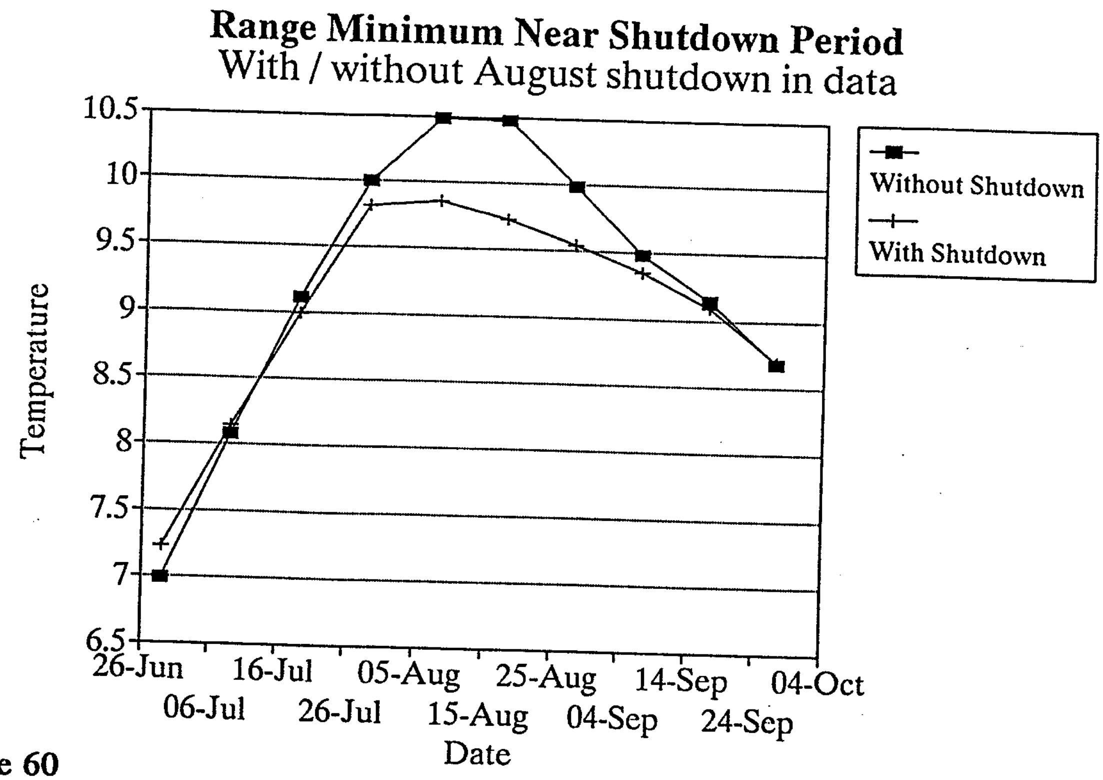


Figure 60

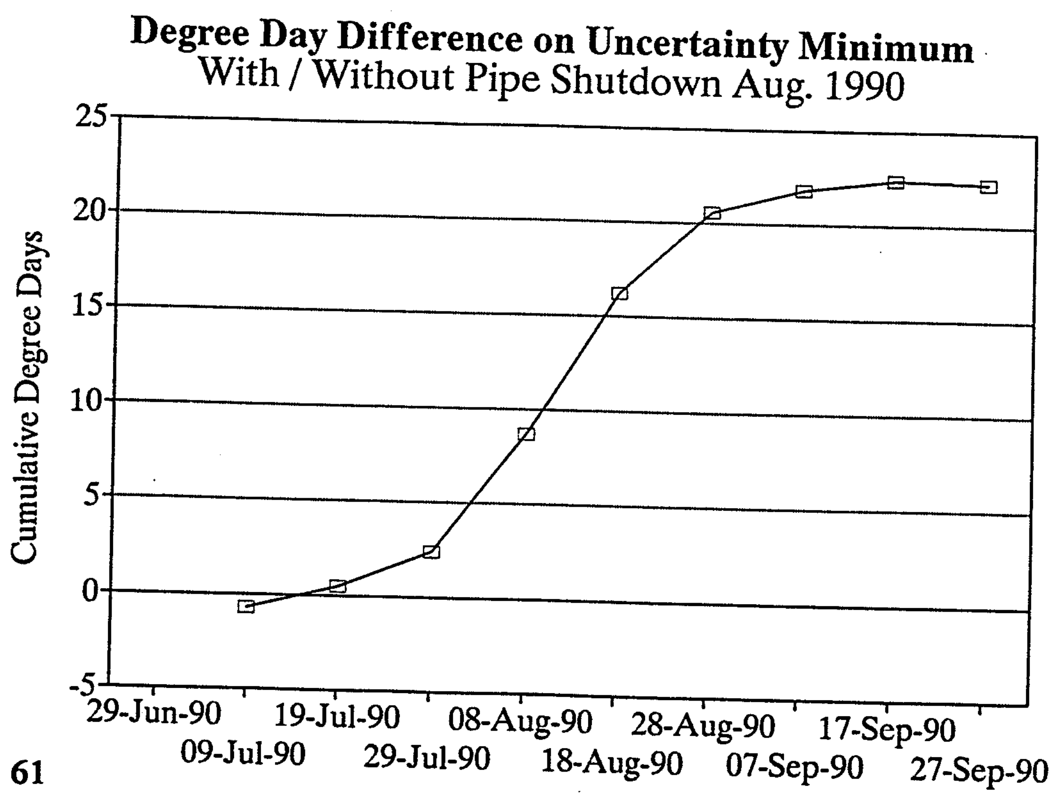


Figure 61

attached to it. There is evidence that the unattached sensors can move away from the pipe, making it difficult to use these sensors to monitor long term behaviour.

Figure 62 compares the long term temperature record for one of the attached sensors and the unattached sensor at site 12B. Two features are apparent. First, the unattached sensor shows the same short term temperature variations as the attached sensor. This indicates unequivocally that these are due to actual pipe temperature variation rather than datalogger noise, since the attached and unattached sensors are connected by different data acquisition systems. Second, the unattached sensor drifts continuously to lower temperatures with time.

Figure 63 shows the difference between attached and unattached pipe sensor temperatures over time. The temperature change is characterised by periodic intervals of relatively rapid change followed by intervals in which the difference does not change significantly. Comparison with Figure 62 shows that the periods of most rapid change in the temperature difference correspond to rising limb of the summer temperature wave. This indicates that the source of temperature drift in the unattached sensors is differential settlement between the sensor and the pipe.

This behaviour makes it difficult to analyze the long term behaviour of the pipe using data from the unattached sensors when differential settlement may be occuring. The record for these sensors would be useful in cases where there are gaps of several months in the adjacent manual or datalogger records, in which case the unattached sensor record could substitute with an appropriate offset calibration.

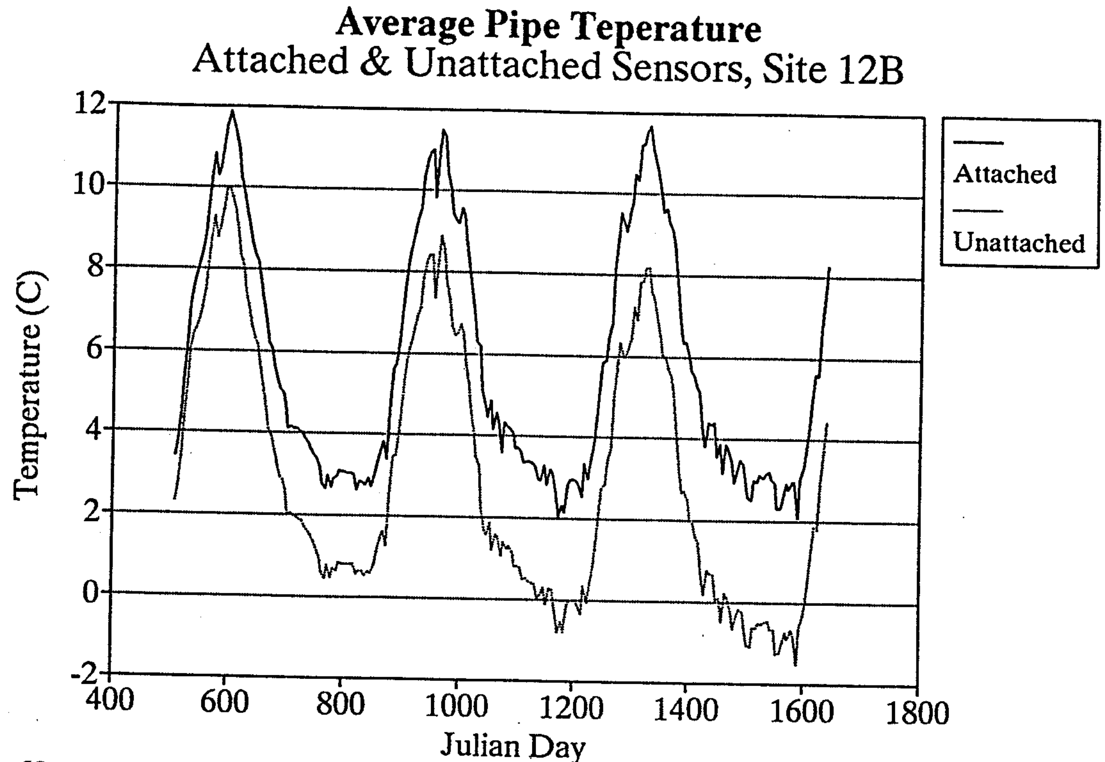


Figure 62

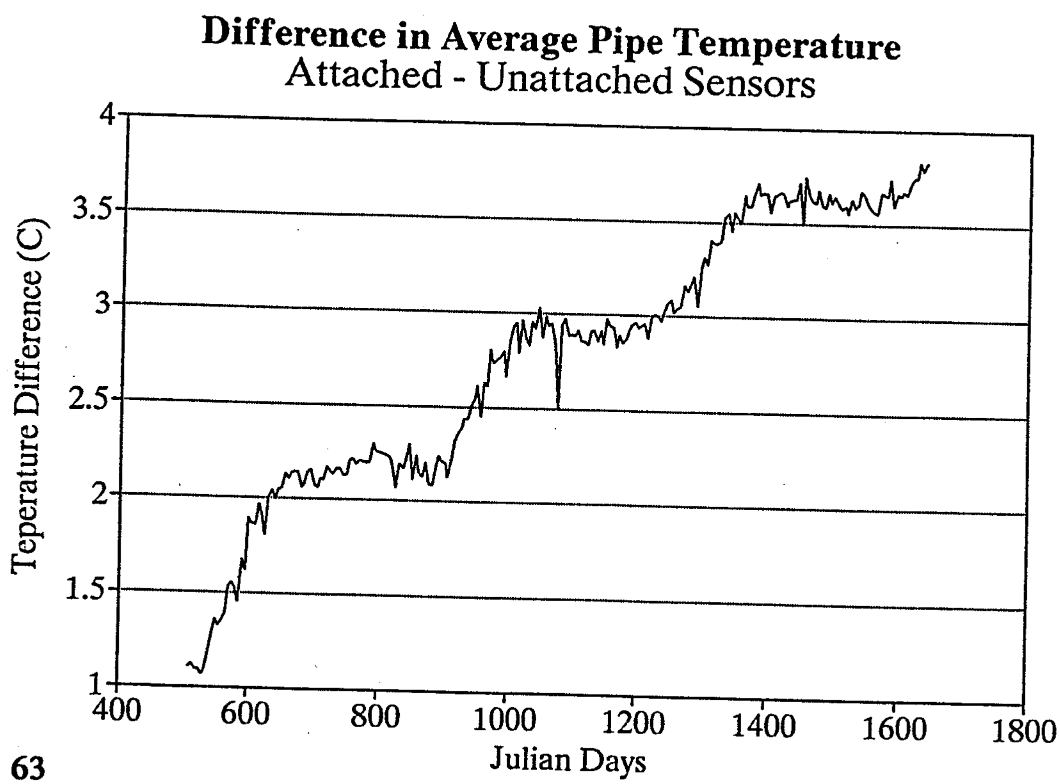


Figure 63

Conclusions

1. No specific recommendations can be made about a preferred interval between measurements. Results show that the relationship between the measurement interval and uncertainty concerning the thermal behaviour of the pipe or ground is consistent and fairly predictable. To repeat:
For the interpolated temperature curve:

$$\overline{\sigma_z}=0.0041R_z m \quad (4)$$

and for the mean annual temperature:

$$\overline{\sigma_z}=0.00085R_z m \quad (5)$$

where

$\overline{\sigma_z}$ = average standard deviation at depth z
m = measurement interval (days)
R_z = Temperature range at depth z (twice the annual amplitude)

These relationships make it possible to establish the degree of certainty that can be obtained with a given interval. Conversely, if a particular level of accuracy is desired, then the measurement interval required to achieve it for a particular depth in the ground can be established.

2. While the most extreme measurement errors in the datalogger records could be and were edited out before the present analysis was undertaken, results were influenced by the presence of small but clearly spurious temperature fluctuations. Any routine analysis of the datalogger records (to obtain mean annual temperatures or other derived statistics about the thermal regime) should include some method of prior filtering of these fluctuations.

3. The short term pipe temperature variations at site 12B reduce the accuracy of the interpolated temperatures and mean annual temperature estimates, since the measurement program cannot sample pipe temperatures often enough to characterize them. This identifies sites near pump stations as preferred candidates for the installation of data acquisition systems.

4. Pipe shutdowns of up to 4 days have a relatively small influence on the annual pipe thermal regime. Because of the much larger effect that they have on interpolated temperature curves, manual temperature measurements known to have been taken during periods when oil is not flowing in the pipe should be removed from the record prior to subsequent analysis.

5. The analysis presented for one site indicates that "unattached" pipe sensors are problematic for long term temperature monitoring due to the effect of differential settlement between pipe and sensor on the temperature record. The record for these sensors would be useful in cases where the gaps of several months are present in adjacent manual or datalogger temperature records, in which case the unattached sensor record could substitute with an appropriate offset calibration.

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