OBSERVATIONS ON THE THERMAL RESPONSE OF DISCONTINUOUS PERMAFROST TERRAIN TO DEVELOPMENT AND CLIMATE CHANGE -AN 800 KM TRANSECT ALONG THE NORMAN WELLS PIPELINE

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Abstract

Ground temperature instrumentation is installed at 23 study sites along the buried Norman Wells oil pipeline right-of-way as part of a government-industry Permafrost and Terrain Research and Monitoring Program. The pipeline, forming an 869 km transect through the discontinuous permafrost zone of northwestern Canada, was designed to limit energy exchange with the surrounding thaw- sensitive soils. Data collected at the study sites during the first 3.5 years of pipeline operation (April 1985 - October 1988) reveal that: 1) mean annual external pipe temperatures are greater than 0 °C and show a continuous warming trend (average increase 1.5 K over the observation period), 2) mean annual ground temperatures several metres away from the pipe, on the right-of-way and at the depth of pipe burial, also show a gradual warming trend at most sites (average increase 1.2 K over the observation period), 3) mean annual ground temperatures at a similar depth off the right-of-way showed no warming trend until 1988 (average increase 0.6 K). Non-permafrost locations show the most rapid changes in mean annual temperatures. The pattern of change off the right-of-way suggests that the ground temperature there is responding to a recent increase in air temperature (about 3 K from 1985 to 1988) at a rate controlled by the initial ground thermal conditions.

Résumé

L'examen des conditions thermiques du sol se poursuit à 23 sites de mesure situés le long de l'oléoduc de Norman Wells. L'étude fait partie d'un programme de recherche et d'observation du pergélisol et du terrain, projet conjoint entre le gouvernement et l'industrie. L'oléoduc enfoui qui traverse 869 km de la zone de pergélisol discontinu du nord-ouest canadien a été conçu pour minimiser le transfert d'énergie au terrain sensible au dégel. L'analyse des données recueillies durant les premières 3.5 années d'exploitation du pipeline (avril 1985 - octobre 1988) révèle que: 1) les températures annuelles moyennes sur l'extérieur de la conduite sont supérieures à 0 °C et ont augmenté de façon continue (en moyenne de 1.5 K pendant cette intervalle), 2) les températures annuelles moyennes du sol sur le droit de passage, à une profondeur comparable à celle du pipeline, ont aussi augmenté de façon continue à la plupart des sites (augmentation moyenne de 1.2 K), 3) les températures annuelles moyennes du sol à la même profondeur en dehors du droit de passage n'ont demontré un réchauffement qu'en 1988 (moyenne de 0.6 K). Les sites non pergélisolés ont subi les changements les plus rapides des températures annuelles moyennes. Le patron des variations observées en dehors du droit de passage suggère que la température de ces sols change en fonction d'une augmentation récente de la température annuelle moyenne de l'air (3 K de 1985 à 1988) et à un taux déterminé par les conditions thermiques initiales.

Introduction

The 869 km Norman Wells pipeline is the first completely buried oil pipeline in the discontinuous permafrost zone of northwestern Canada. Instrumentation was installed at 23 study sites along the pipeline route as part of a government-industry multidisciplinary Permafrost and Terrain Research and Monitoring Program designed to improve on impact evaluation and mitigation on the Norman Wells pipeline and future projects. This paper examines trends in the pipe thermal regime and the ground thermal regime since operation began in April 1985 through to October 1988. The analysis of ground temperatures is focused on trends at the depth of pipe burial.

A detailed review of the Norman Wells pipeline design and construction, the regional environmental framework (climate, permafrost and terrain), and the research and monitoring program appears in MacInnes *et al.* (1989). A brief description of this background material follows.

PIPELINE PROJECT

The Norman Wells pipeline is owned by Interprovincial Pipe Line (NW) Ltd and carries oil from ESSO Resources Norman Wells, N.W.T., oil field south to Zama, Alberta. The permafrost and terrain encountered along the route (Kay *et al.* 1983) necessitated special design features and mitigative approaches to minimize terrain disturbance and ensure pipe safety under possible conditions of thaw settlement, frost heave and slope instability. Features selected to limit thermal disturbance of the terrain and reduce energy exchange of the uninsulated pipe with surrounding soils are outlined in Nixon *et al.* (1984), Hanna and McRoberts (1988) and Wishart (1988), and included: 1) pre-construction winter right-of-way (ROW) clearance, maximizing the use of previous cutlines, 2) winter construction using temporary roads, 3) shallow burial depth (average 1 m), 4) small diameter (324 mm) pipe, 5) chilling of the oil to near 0°C before pumping at Norman Wells for pipeline operation at "ambient" ground temperature, and 6) wood chip insulation of thaw-sensitive slopes. Main construction was completed in the winters of 1983-1984 and 1984-1985. The pipeline has a design capacity of 4800 m³/day and an expected life of 25-30 years.

Permafrost and terrain research and monitoring program (PTRM)

The Permafrost and Terrain Research and Monitoring Program involves several multidisciplinary studies. The major project, undertaken by the Geological Survey of Canada and Indian and Northern Affairs Canada, consists of the quantification of changes in the geothermal regime and geomorphic conditions at instrumented monitoring sites. The main sites, listed in Table 1 by kilometrepost distance from the start of the pipeline in Norman Wells, were selected to represent major soil types and ground thermal conditions (both frozen and unfrozen). Information on the establishment of each site, including borehole lithology and visual ice logs, aerial and ground photos is contained in Pilon *et al.* (1989).

Table 1. Site Descriptions

SITE	km	DESCRIPTION (at time of establishment)
84-1	0.02	Ice-rich silty clay, widespread permafrost
84-2		**(Previously cleared cutline)**
A	19.0	Low-ice till in widespread permafrost
B	19.3	East-facing pf slope, 1 m wood chip cover
C	19.6	West-facing pf slope, uninsulated section
84-3		**(Joint IPL site with thaw-sensitive slope)**
A	79.2	Complex ice-rich alluvial terrace deposits
B	79.4	Lacustrine deposits, low-ice, aeolian veneer
85-7		**(Joint IPL site with thaw-sensitive slopes)**
A	271.2	Ice-rich lacustrine plain (old seismic line)
B	272.0	Ice-rich lacustrine plain (helipad clearing)
C	272.3	Ice-rich lacustrine plain
84-4		**(Unfrozen terrain after long frozen stretch)**
A	478.0	Saturated sands and silts in dune hollow
B	478.1	Dry sands and silts in dune crest
85-8		**(Rapidly changing permafrost conditions)**
A	557.8	Thin peat, thick (10 m) permafrost
B	558.2	Thick peat (2.7 m), thin (1 m) permafrost
C	558.3	Thin peat (1 m), thin (1 m) permafrost
85-9		**(Pipe previously traversed frozen section)**
	583.3	Unfrozen granular soils
85-10		**(Unfrozen/frozen interface)**
A	588.3	Recent helipad clearing in unfrozen terrain
B	588.7	Thin permafrost (3 m) with 2 m peat cover
85-11	597.4	**Thin permafrost (4 m) in recent helipad**
85-12		**(Unfrozen/frozen interface)**
A	608.6	Thin unfrozen peat
B	608.7	Thick ice-rich peat plateau; 4 m permafrost
84-5		**(Degrading peat plateau)**
A	783.0	Ice-rich peat (3.5 m); 15-18 m permafrost
B	783.3	Very thick icy peat (7 m); 12 m permafrost
84-6		**(Peat plateau preceded by unfrozen fen)**
	819.5	Thick (5 m) ice-rich peat; 7 m permafrost

Note: Unless otherwise indicated sites are located in newly cleared level terrain. pf = permafrost

Thermal instrumentation

There are 12 principal monitoring locations (fig. 1) where thermal instrumentation has been installed in one or more cross-sectional arrangements called "thermal fences"; there are a total of 23 fences. The experimental design of a fence is as follows: 1) 5 thermistor sensors are located on the outside of the pipe (one on the top, one on the bottom and 3 on the side), 2) two 5 m multithermistor cables are located within 3 m of the pipe, 3) two 20 m multithermistor cables are installed: one on the ROW generally within 10 m of the pipe, and the other off the ROW. Further information on the accuracy of the temperature sensors, the installation procedure, the actual cable lengths and sensor spacing at each borehole, and the field measurement procedure is discussed by Burgess and Naufal (1989) and Pilon *et al.* (1989).

During 1985 to 1988, data were collected at most thermal fences during monthly helicopter-supported field trips. Listings of monthly measurements are published annually as GSC Open Files (e.g. Burgess and Naufal, 1990 and previous volumes listed therein). The manual measurement program has been supplemented at 7 select fences with 64 channel automatic data acquisition systems (Seadata model 1250) recording 3 times/day.

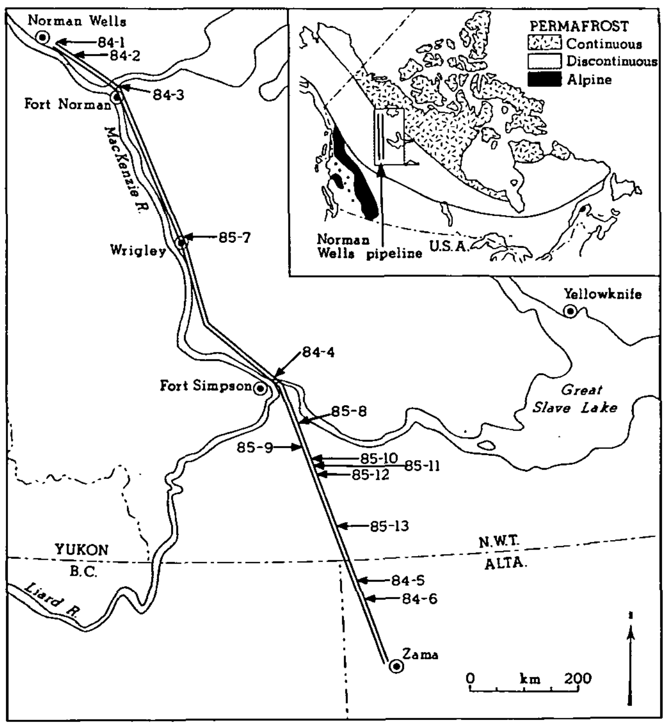

Figure 1. Location of the Norman Wells pipeline study sites and relation to discontinuous permafrost zone.

Analytical procedures

The ground temperature data allow the characterization of the annual temperature wave, the ground temperature envelope and the approximate active layer thickness for a given cable. Variations in ground temperature across the right-of-way and over time are also examined. Since seasonal fluctuations may mask a more general long term trend, mean annual and running mean annual temperatures are calculated in order to assess the spatial and temporal changes. The discussions of the pipe thermal regime and ground thermal regime in this paper are largely based on the analysis of such mean annual temperatures.

The techniques used to calculate mean and running mean annual temperatures are described in Burgess and Riseborough (1989) and Riseborough *et al.* (1988). Briefly, since the data acquired manually constitute an irregular time series, with occasional gaps of 1-2 months, an interpolation program (cubic spline) is used to generate more regularly and closely spaced temperatures. For the calculations on the data collected to October 1988 (Riseborough, 1989), smooth temperature curve values were interpolated at 5 day intervals. For each sensor, the first mean annual temperature was obtained as the average of the first 73 five-day values; this mean was assigned to the midpoint of the first year of data. The mean annual was updated at 5 day intervals to obtain running mean annual temperatures.

Climate during observation period

The Atmospheric Environment Service (AES) of Environment Canada operates meteorological stations with uninterrupted data collection at Norman Wells and Fort Simpson along the pipeline route in the N.W.T., and at High Level, Alberta (the nearest station to the southern terminus of the pipeline). Monthly mean air temperatures for these three stations are shown in Figure 2a for the period 1984 to October 1988. These were used to obtain running mean annual air temperatures (i.e. 12 month running means), shown in Figure 2b.

Monthly average air temperatures change smoothly throughout the spring summer and fall. In winter however, monthly average temperatures along the pipeline corridor change abruptly, reflecting positions in the Arctic front and the stalling of high pressure systems in February (Burns, 1973). These variations are reflected as mid-year interruptions in the running mean trend, as unusually warm or cold winter months are added or dropped from the averaging interval. Trends in running means are roughly similar at all three stations: after a short, moderate cooling period (6 months to 1 year), the mean annual temperature rises continuously to mid-1987 (as noted before this represents the mean for the 12 months extending 6 months on either side of mid-1987). From Figure 2a, it can be seen that the warming trend is due primarily to warmer winter temperatures. A short cooling trend follows, with recovery to higher temperatures at Norman Wells. The rise in mean annual temperature from mid-1985 to mid-1987 at the three stations is on the order of 3 K.

The full effect of the warmer winter air temperatures may or may not be felt at the ground surface depending especially on the trend in snow accumulation. In most years, snow cover at Fort Simpson and High Level is at least twice as deep as at Norman Wells. There is no obvious increasing or decreasing trend in the snow cover from 1984 to 1988 either at Fort Simpson or High Level, whereas Norman Wells airport data show progressively less snow cover from 1985 to 1988. However, measurements at snow stakes installed both on and off ROW at thermal fences 84-1 and 84-2 in the vicinity of Norman Wells do not show a similar trend. These snow stakes also document the spatial variability of the snow cover, as does a snow depth sensor at an automatic climate station at site 84-2 (Dave Etkin, AES, pers. comm.).

Summer precipitation records from the AES stations are not representative of diverse physiographic conditions along the pipeline route, particularly with regard to frequency and distribution of summer storm events. For example in June 1986 a major storm occurred in the Wrigley area with 56 mm of rainfall recorded in 24 hours at the territorial government's

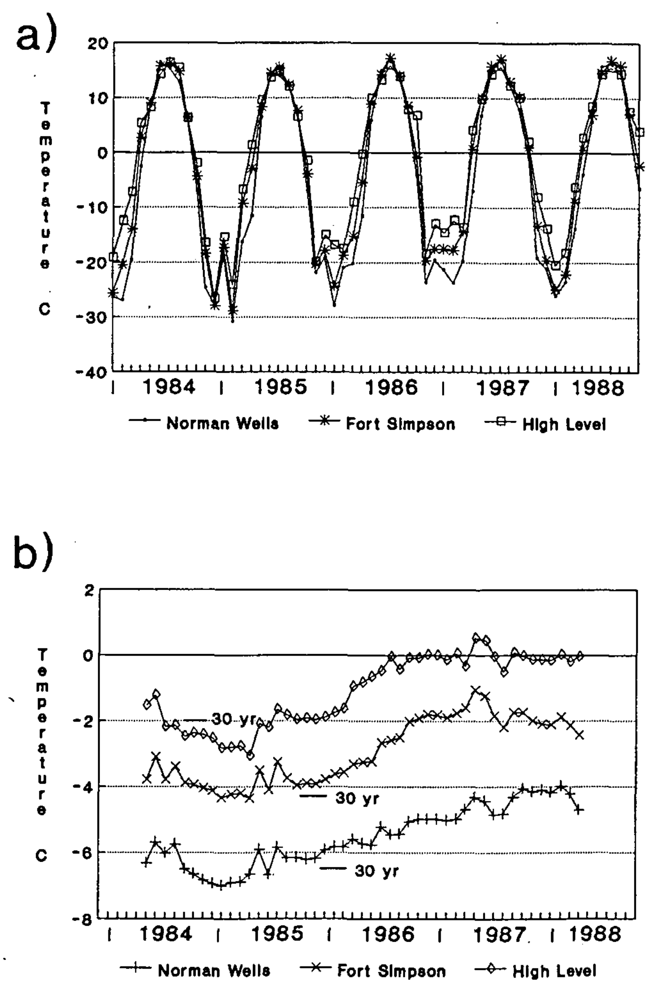

Figure 2. Air temperature data from Norman Wells, Fort Simpson and High Level AES meteorological stations. a) Monthly means b) Running mean annual air temperatures based on monthly means. The 30-year (1951-1980) climate normal mean annual temperature is also shown for each station.

fire tower seasonal meteorological station (MacInnes *et al.*, 1989). No similar storm was observed at the Fort Simpson or Norman Wells AES weather stations. Data from the AES and local fire tower weather stations indicate that summer precipitation was significantly higher than normal in 1988 all along the pipeline corridor, with record breaking rainfalls (storms) at the end of June/beginning of July. Visual observations showed that the ground surface on and off-ROW was wet during the summer of 1988.

Trends in pipe temperature

Trends in running mean annual pipe temperature observed through October 1987 are given in Burgess and Harry (1988). Observations are updated here through October 1988. Plots of interpolated and running mean annual temperatures, averaging the 5 sensors at each site are available in Riseborough (1989). Since pipeline operation began through October 1988, a general increase in mean annual pipe temperature has been observed at 20 of 23 sites (examples shown in fig. 3); on average an increase of 1.5 K. Those sites not showing this general trend are within 20 km of Norman Wells. The average daily throughput of oil increased from about 3400 m³/day in 1985 to 4500 m³/day in 1988, while oil delivery temperature at Norman Wells dropped from -2 to -5 °C . Trends observed in the last year of data show that warming continued at 70 % of the sites.

The only site experiencing a prolonged cooling trend is that at km 0.02, Norman Wells, where the oil is chilled by ESSO prior to pumping by Interprovincial Pipe Lines. This site is also the only site showing mean annual pipe temperatures below 0 °C (-1.5 °C after 3.5 years). The cooling trend at Norman Wells likely reflects the drop in oil delivery temperature. Elsewhere the mean annual pipe temperature, after 3.5 years of operation, ranges from 0.2 to 5.5 °C .

Many sites experienced exceptionally high summer pipe temperatures in 1986 causing a "hump" in the running mean for that year (e.g. fig. 3c) followed by a short period of cooling before recovery to a warming trend. Sites showing the hump are those located between km 478 and 597. As noted in the above discussion of climate, major storms that affected parts of the right-of-way were not recorded at AES stations in June 1986. Visual observations during data collection trips indicate that the ground surface was wet in the summer of 1986 at most of the sites between km 478 and 598, suggesting the hump may be related to summer precipitation.

Trends in ground temperature on and off the right-of-way

On right-of-way

Analyses of shallow ground temperatures have focused on an examination of data from the "1 m" sensor (nominal depth at the time of cable installation). This sensor depth most closely corresponds to the initial depth of pipe burial (1 m) and is subject to change in subsequent years as surface settlement occurs but the cable remains fixed in the borehole. For comparison to pipe temperatures, data from the deep cable on-ROW have been used; this cable, the furthest from the pipe on ROW, was selected in order to examine ROW trends away from the influence of the pipe. As with the pipe temperatures, since pipeline operation began, most (3/4) of the sites show an increase in mean annual ground

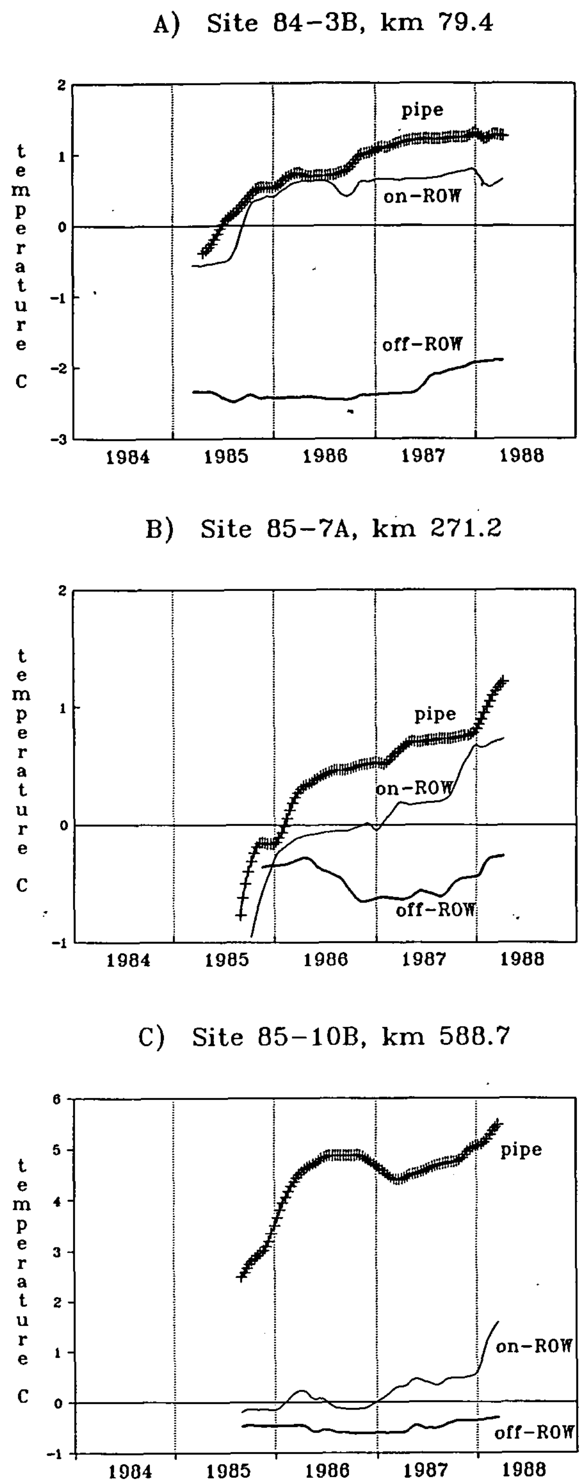

Figure 3. Running mean annual pipe and ground temperatures at nominal 1 m depth (see text). a) Site 84-3B, b) Site 85-7A, and c) Site 85-10B.

temperature on-ROW, though less consistently than for the pipe (see example of running mean annual plots in Figure 3). The average increase in mean annual "1 m" ground temperature has been 1.2 K over the observation period. An examination of the interpolated temperature curves showed that the warming trend is most apparent in the summer. The only site experiencing a small but gradual cooling trend is the wood chip insulated slope at km 19.3, suggesting that thermal conditions in the wood chip layer are stabilizing following an initial self-heating of the chips.

Surface settlement has occurred on the right-of-way, both within and outside the trench area. Results from level surveys conducted from 1984-1987 are discussed in Burgess and Harry (1988). This settlement has decreased the absolute depth of many sensors. Such a decrease, under a stable ground thermal regime, may result in an apparent increase in the mean annual ground temperature due to the "thermal rectification effect" (Goodrich, 1982). This effect, arises from the difference between frozen and thawed thermal conductivities, and results in a curvature towards higher mean annual temperatures in the active layer (or seasonal frost zone). The magnitude of the effect depends on the ratio of frozen to thawed conductivities as well as on the depth of the active zone.

When the ground surface is warming and settling, the change in sensor depth might thus lead to an apparently greater rate of temperature rise being recorded at the "1 m" sensor, because of the thermal rectification effect. Settlement and change in sensor depth at each site are discussed in Burgess and Naufal (1990). Half the sites show little to no surface settlement (2A/C, 3B, 4A/B, 8A, 9, 10A/B, 11, 12A; located either in non-permafrost terrain or underlain by thaw-stable soils), and therefore little to no thermal rectification effect, yet "1 m" warming ranging from 1 to 3 K is observed. This would suggest that thermal rectification is not the principal source of the temperature rise (ranging from 0.2 to 2.4 K) observed at the remaining sites undergoing settlement.

A few of the sites between km 478 and 597 also show the hump in 1986 on-ROW temperatures. They are all non-permafrost sites with near surface granular mineral soils (sands, gravels). The geotherm plot for the deep ROW cable at km 597 in Figure 4, shows that the thermal wave generated by the hump was not limited to the surface, but penetrated to a depth of 6 m. (The geotherm plot represents lines of equal mean annual temperature on a plot of depth versus time; e.g. 9/85 represents mid-point of year of initial mean annual profile. The depth of penetration of the hump is indicated on the plot.) The 1986 hump was thus not experienced exclusively at the pipe, and therefore cannot be attributed solely to an effect of the pipe. The hump may be related to an effect which is enhanced by the presence of the pipe such as increased soil moisture in the trench area, and/or the occurrence of unfrozen ground or a thaw bulb.

Off right-of-way

The off-ROW trends in "1 m" ground temperature had, until October 1987, been variable throughout the period of observation. The 1986 "hump" was, with the exception of

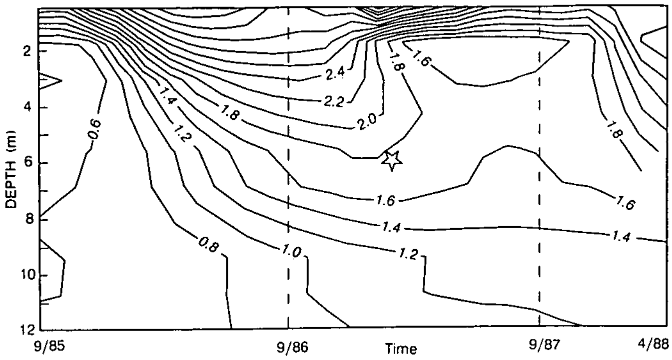

Figure 4. Mean annual geotherms for cable T3 (on-ROW) at site 85-11, km 597. Dashed lines are 1 year apart. Time on x-axis represents mid point of year for a given mean annual temperature. Plot runs from Sept. 1985 to April 1988. Star denotes depth of penetration of 1986 "hump".

site 84-4A, not observed in the off-ROW running means. Attempts were made to minimize disturbance to the buffering surface organic layer while drilling the off-ROW borehole, whereas on ROW some scraping or removal of the organic layer occurred at all sites during winter construction. In the 12 months prior to October 1988, more sites off-ROW experienced rapid warming for the first time than in any previous periods (70 % of sites). Ground temperatures on average rose by 0.5 K in this period, compared to an average of 0.6 rise over the whole record.

Relationships: pipe and ground temperature

The relationships previously noted (Burgess, 1988; Burgess and Harry, 1988) continue to prevail. In summary, at most sites, mean annual pipe temperatures remain greater than "1 m" mean annual temperature in the deep cable on-ROW, and these on ROW temperatures are in turn warmer than those off-ROW.

Thermal behaviour near zero

The off-ROW temperature trends illustrate the thermal behaviour of soils near 0 °C in response to a surface warming, as demonstrated by the geothermal simulations presented by Riseborough (this volume). These simulations showed the importance of the initial ground thermal condition (cold, warm, or non permafrost) and of the release or absorption of latent heat, in determining the rate and timing of ground temperature change in response to a surface temperature increase. The off-ROW thermal behaviour is shown in Figure 5a which plots, for each thermal fence showing warming, the rise in "1 m" mean annual temperature since pipeline operation began through October 1988 as a function of the initial mean annual temperature. Off-ROW sites with mean annual temperatures below 0 °C show a small temperature rise (<0.5 K) with the amount of the rise decreasing as the 0 °C threshold is approached. The Norman Wells off-ROW mean annual ground temperatures have shown a greater increase when the initial mean annual temperature is above zero; the higher the initial temperature, the greater the observed increase. The consistency of an off-ROW temperature rise despite distance between the sites, differences in soil materials and permafrost conditions, differences in actual sensor depths (with absolute depths varying with surface settlement), suggests that a gradual rise in mean annual ground surface temperature off-ROW may be occurring in response to the recorded rise in mean annual air temperature at the AES stations.

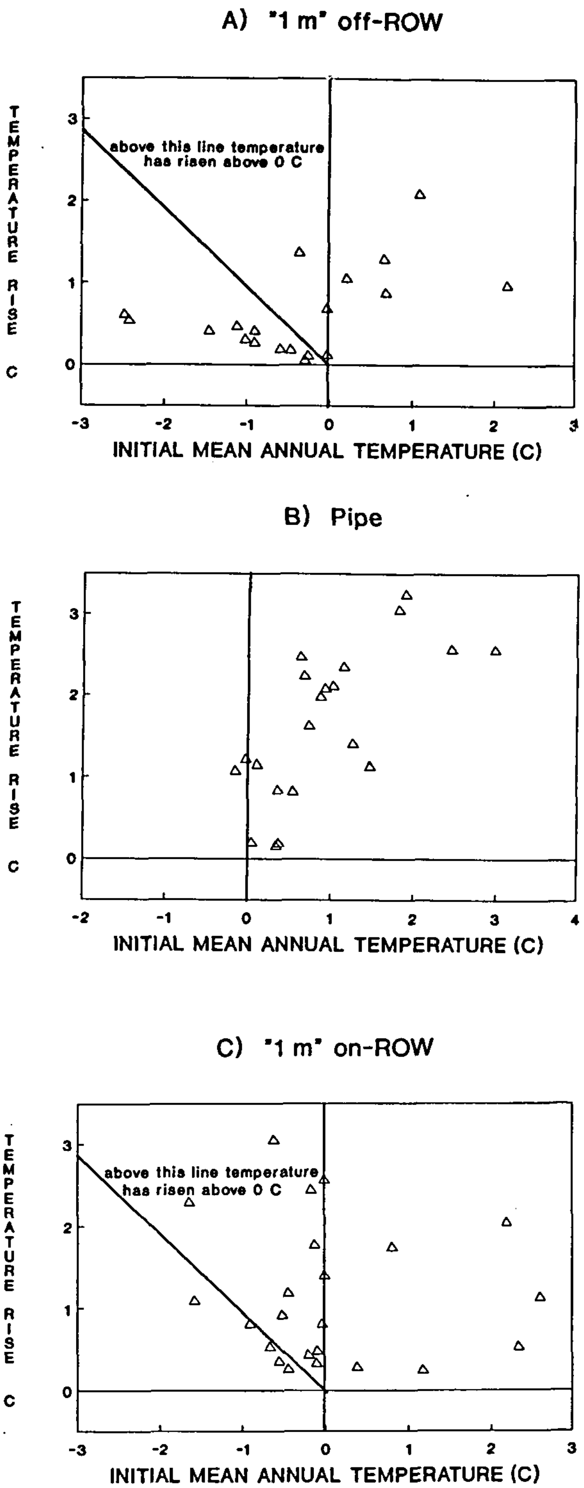

Figure 5. Thermal response (change in mean annual temperature over observation period for sites showing warming) as a function of initial mean annual temperatures: a) "1 m" off-ROW, b) pipe, and c) "1 m" on ROW.

A similar plot for the pipe temperatures (fig. 5b) suggests that the trends may also in part be related to initial mean annual temperature. Most of mean annual pipe temperatures were initially above 0 °C ; the higher the initial temperature, the greater the observed temperature rise. Although the pipe temperature trend may appear to correlate directly to the air temperature trend, the thermal regime of the pipe is also governed by changes in the operating conditions (oil temperature and flow rates) as well as the changes in physical, moisture and permafrost conditions in the vicinity of the trench.

A plot for the "1 m" ROW data (fig. 5c) shows little correlation. On-ROW, too many effects combine to produce a response based on initial temperature alone. These effects include new micro-climatic conditions following ROW clearance (tree removal) or widening, blading or reducing of the surface organic layer, revegetation, settlement, and changes to snow cover accumulation, as well as the warming air temperature trend. Disturbance or removal of vegetation and surface cover of itself, is well known to result in degradation of permafrost (Linell, 1973 ; Brown and Pewe, 1973 ; Lawson, 1986).

Summary

1. From the start of pipeline operation in 1985 through October 1988, the mean annual temperature has increased on average by 1.5 °C at the pipe, 1.2 °C at the "1 m" depth on-ROW furthest from the pipe, and 0.6 °C at the "1 m" depth off-ROW. These increases have been consistent over an 800 km north-south transect through the discontinuous permafrost zone.
2. A "hump" in mean annual temperatures was noted in 1986 at all pipe sensor cables between km 478 and 598 (all these sites have a thaw bulb around the pipe) and at the on-ROW cables of the non-permafrost sites between km 478 and 598 but generally not in the off-ROW. Analysis of this "hump" suggests that presence of unfrozen conditions may be common to the rapid temperatures changes. However, the combination of unfrozen conditions and high soil moisture contents (as are often found in the trench, and as were noted on the ROW in the summer of 1986) may also be important.
3. Mean annual air temperatures recorded at AES stations in the vicinity of the pipeline corridor (Norman Wells, Fort Simpson, High Level) showed an increase of about 3 K during the 1985-1988 monitoring period. The warming was concentrated in the winter months.
4. The pattern of "1 m" mean annual temperature warming off-ROW suggests that the ground temperature off-ROW all along the pipeline route is responding to the short term increase in air temperature noted above, at a rate primarily controlled by the initial ground thermal conditions. These observations although taken over an interval of only a few years, provide some insight into the response of discontinuous permafrost terrain to climate warming.

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