PERMAFROST - Seventh International Conference (Proceedings),
Yellowknife (Canada), Collection Nordicana No 55, 1998

AIR AND SOIL TEMPERATURE RELATIONS ALONG AN ECOLOGICAL TRANSECT THROUGH THE PERMAFROST ZONES OF NORTHWESTERN CANADA

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Abstract

Summary air and soil temperatures are presented for six sites along a transect covering scattered discontinuous permafrost near Whitehorse, Y.T., to continuous permafrost north of Inuvik, N.W.T. Data were collected over 12 months from screen-height air temperatures and soil temperatures at 20, 50, 100, and 150 cm depths. Annual and monthly mean temperatures, accumulated freezing and thawing degree-days and n-factors have been calculated. Annual mean air temperatures at the sites range from -2.4°C in southern Yukon to -8.6°C north of Inuvik, while annual mean ground temperatures at 50 cm depth decrease from -0.6°C to -5.8°C over the transect. The thaw season n-factor (N_t) is relatively constant along the transect. The freezing season n-factors (N_f) are considerably higher (>0.50) in tundra soils than forested soils.

Introduction

This paper presents air and soil temperatures from six sites between 60º N and 70º N along a transect through the Boreal Cordillera, Taiga Cordillera, Taiga Plains and Southern Arctic ecozones of Yukon Territory and adjacent Mackenzie Delta area, Northwest Territories, Canada (Figure 1). The sites span the range of permafrost conditions encountered in the region, from sporadic discontinuous permafrost with near-surface ground temperatures above -1ºC, to relatively cold (-6ºC) continuous permafrost, north of tree line (Heginbottom, 1995; see Table 1). The southern portion of the Boreal Cordillera ecozone is underlain by scattered discontinuous permafrost, while the northern portion is underlain by extensive discontinuous permafrost. The other ecozones along the transect all lie within the continuous permafrost zone. The sites are part of a ground temperature network established in the 1980s to obtain baseline data for resource development and planning (Tarnocai and Kroetsch, 1990) and to monitor the impact of climate change on permafrost (Burn and Smith, 1988; Tarnocai et al., 1993; Nixon and Taylor, 1994).

The objectives of the paper are to: (1) document the variation in air and soil temperatures over the transect; (2) discuss the relations between these variables; and (3) investigate the mechanisms of heat transfer within the soil profile at the sites.

Methods

The six sites are located in mature vegetation representative of regional landscape conditions and soil development (Table 2). The boreal sites are characterized by closed forests of mixed spruce (*Picea mariana*, P. *glauca*), pine (*Pinus contorta*) and poplar (*Populus tremuloides*). The taiga (subarctic) forests are composed of open stands of black spruce (*Picea mariana*) and tamarack (*Larix laricina*). The arctic site is characterized by a cover of willow (*Salix* spp.) and birch (*Betula glandulosa*) shrubs. Air temperatures were collected at a height of 150 cm and soil temperatures were recorded at depths of 20, 50, 100 and 150 cm below the ground surface, in order to span the active layer and the top of permafrost.

Air and soil temperatures were measured by thermistors attached to a variety of single and multi-channel data loggers (Onset Computing HoboTM loggers,

Table 1. Environmental conditions along the monitoring transect and the deviation from normal of air temperature during the period used in this study

Site	Latitude	Ecozone	Permafrost zone[1]	AES station normal[2]	Record period	Record period deviation from normal (ºC)
Takhini	60º50'	Boreal Cordillera	Sporadic discontinuous	-2.5	1/95-12/95	+1.0
Mayo	63º37'	Boreal Cordillera	Extensive discontinuous	-3.6	1/91-12/91	+1.2
Dawson	64º03'	Boreal Cordillera	Extensive discontinuous	-4.4	8/93-7/94	+0.5
Eagle Plains	66º23'	Taiga Cordillera	Continuous	-6.7	8/91-7/92	-0.5
Inuvik	68º06'	Taiga Plains	Continuous	-9.5	1/93-12/93	+3.2
Parsons Lk	68º55'	Southern Arctic	Continuous	-10.0[3]	9/93-8/94	+1.5

1Heginbottom (1995).
2The 1961-90 mean annual temperature (ºC) from the Atmospheric Environment Service (AES) station closest to the monitoring site is presented where available (Environment Canada 1993). For Takhini and Eagle Plains, long-term means are presented. Sites are located within 5 km of the respective AES stations.
3 The site falls between Inuvik and Tuktoyaktuk AES stations and the value for station normal is interpolated from these records.

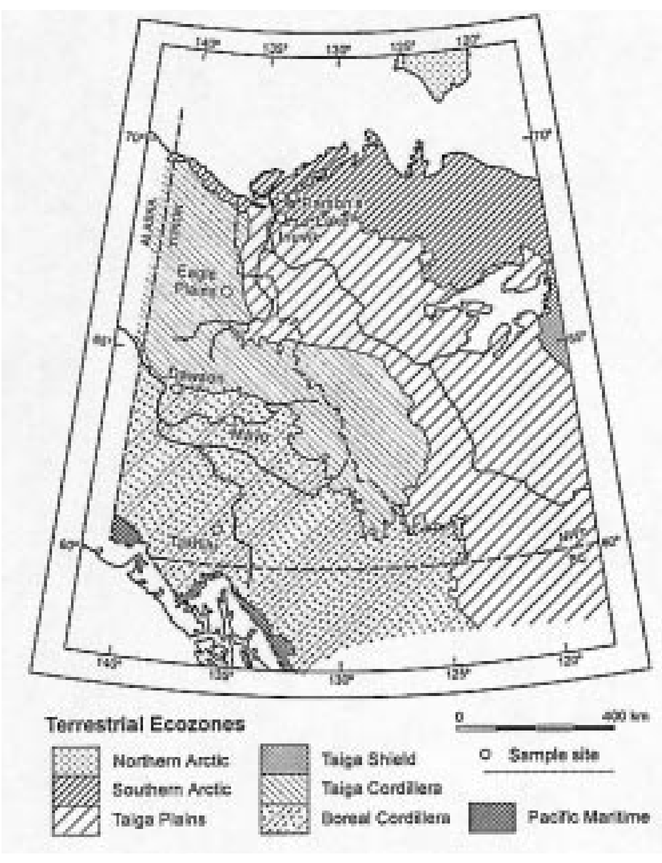

Figure 1. Ecozones of Yukon and adjacent Northwest Territories (after Ecological Stratification Working Group, 1995). The transect includes three sites in the Boreal Cordillera ecozone, and one site each in the Taiga Cordillera, Taiga Plains and Southern Arctic ecozones.

Brancker Research XL-800TM multi-channel loggers and Campbell Scientific CR10), except at the Takhini site where temperature values from the 50, 100 and 150 cm depths were recorded manually every 14 days. Daily values for these depths were interpolated using cubic spline (Press et al., 1989).

An uninterrupted 12 month time series was selected from the record collected at each site. Within this period (see Table 1), whose dates varied between sites, daily mean temperatures were calculated for the air and each soil depth. From these data, thawing degree-days (TDD), freezing degree-days (FDD), thawing n-factors (ratio of TDD at each soil depth to TDD in the air) and freezing n-factors (ratio of FDD at each soil depth to FDD in air) were calculated. These data were used to illustrate trends in air and soil temperatures over the transect. In addition, monthly mean temperatures were calculated and plotted for two sites on a series of phase-space diagrams (Beltrami, 1996), to illustrate the character of heat transfer and seasonal temperature relations between the air, the active layer and permafrost.

Results and discussion

Mean temperatures and calculated degree-day summaries are presented in Table 3. Except at Eagle Plains, the 12 month time series used for each site recorded air temperatures warmer than the 30-year normal or other long-term mean (Environment Canada, 1993, 1996). Based on the standard 50 cm depth, all of the soils monitored in this study have either very cold or pergelic

Table 2. Landscape and soil conditions at the sites along the transect

Site	Landscape position	Vegetation cover	Soil parent material	Soil drainage	Soil classification[1]
Takhini	valley bottom	closed mixed forest	Silty clay glaciolacustrine	moderately well	Orthic Eutric Brunisol
Mayo	valley bottom	closed spruce forest	Silty clay glaciolacustrine	imperfectly	Histic Eutric Turbic Cryosol
Dawson	valley bottom	closed spruce forest	Fine sandy alluvium	imperfectly	Histic Eutric Turbic Cryosol
Eagle Plains	upland ridge	open spruce woodland	Silty loess	Imperfectly	Orthic Eutric Turbic Cryosol
Inuvik	undulating plain	open spruce woodland	Sandy loam moraine	Imperfectly	Orthic Eutric Turbic Cryosol
Parsons Lake	undulating plain	shrub tundra	Sandy loam moraine	moderately well to imperfectly	Orthic Eutric Turbic Cryosol

[1]Canadian System of Soil Classification (Soil Classification Working Group 1998).

temperature regimes according to the Canadian and U.S. soil classification systems (Soil Survey Staff, 1996; Soil Classification Working Group, 1998). The annual mean air temperatures varied from -2.4° to -4°C at sites representative of boreal climatic conditions (Takhini, Mayo and Dawson), from -5.5° to -7.2°C at sites representative of taiga (subarctic) climatic conditions (Eagle Plains, Inuvik), and was -8.5°C at the site representative of southern arctic climatic conditions (Parsons Lake). Days with thawing were approximately equal to the number of days with freezing in the upper portion of the active layer at the southernmost site (Takhini), in scattered discontinuous permafrost, but declined to a ratio of 1:3 thawing to freezing days at the northernmost site (Parsons Lake), in the continuous permafrost of the Southern Arctic ecozone.

The air temperature at Inuvik for 1993 was 3.2°C warmer than the long-term mean annual value for that station and caused some scatter in data when plotting temperature trends over the transect (Figure 2). Nevertheless, ground temperatures cool slowly north-

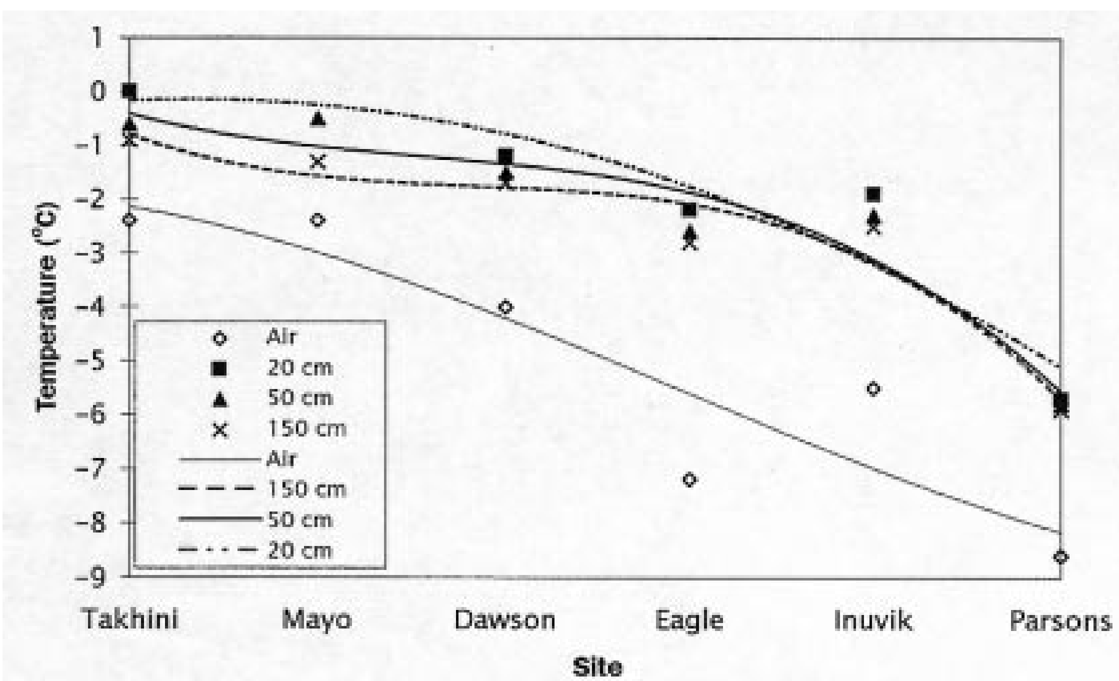

Figure 2. Trends in annual mean air and soil temperatures at six study sites in Yukon Territory and Mackenzie Delta area. Trend lines were fit by eye to each data series.

Table 3. Summary of soil and air temperatures (°C) for six sites along a ecological transect in NW Canada

	Temp (°C) Annual Mean	Amplitude	Summer Mean	Winter Mean	TDD[1]	FDD	DWT	DWF	N_t[2]	N_f
Takhini Valley, YT. 1/95-12/95. Soil surface temperature (estimated) 0.65°, thermal offset (20-100 cm) 1.01°C.										
Air (Takhini)	-2.4	60.0	12.6	-16.2	1799	2686	196	169		
Soil (20 cm)	0.0	18.9	6.8	-7.2	896	883	176	189	0.50	0.33
Soil (50 cm)	-0.6	10.1	3.7	-4.8	428	662	134	231	0.24	0.25
Soil (100 cm)	-1.0	5.2	0.2	-2.8	71	429	77	288	0.04	0.16
Soil (150 cm)	-0.9	3.4	-0.7	-1.6	0	325	0	365	0.00	0.12
Mayo, YT. 1/91-12/91. Soil surface temperature (estimated) 0.75°, thermal offset (20-100 cm) 1.2°C.										
Air (Mayo A.)	-2.4	69.3	14.1	-16.7	1975	2841	187	178		
Soil (20 cm)	nd[3]	nd	nd	nd	nd	nd	nd	nd	nd	nd
Soil (50 cm)	-0.5	9.0	2.8	-3.7	318	516	133	232	0.16	0.18
Soil (100 cm)	-1.2	3.7	-0.4	-2.9	1.5	441	38	327	0.00	0.15
Soil (150 cm)	-1.4	2.7	-1.0	-2.3	0	492	0	365	0.00	0.17
Dawson, YT. 8/93-7/94. Soil surface temperature (estimated) -0.7°, thermal offset (20-100 cm) 0.5°C.										
Air (site)	-4.0	67.6	13.4	-21.7	1742	3193	176	189		
Soil (20 cm)	-1.2	11.7	1.5	-5.2	169	608	103	262	0.1	0.19
Soil (50 cm)	-1.5	6.4	-0.5	-3.9	0	534	0	365	0.00	0.17
Soil (100 cm)	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Soil (150 cm)	-1.7	6.8	-1.2	-2.8	0	619	0	365	0.00	0.19
Eagle Plains, YT. 8/91-7/92. Soil surface temperature (estimated) -1.4°, thermal offset (20-100 cm) 0.63°C.										
Air (site)	-7.2	57.6	11.4	-20.3	1314	3952	139	225		
Soil (20 cm)	-2.2	16.4	3.4	-7.7	349	1136	113	253	0.27	0.29
Soil (50 cm)	-2.6	12.1	0.8	-7.0	105	1043	90	275	0.08	0.26
Soil (100 cm)	-2.8	7.8	-1.0	-5.8	0	1019	0	365	0.00	0.26
Soil (150 cm)	-2.8	7.3	-1.6	-4.8	0	1019	0	365	0.00	0.26
Inuvik, NWT. 1/93-12/93. Soil surface temperature (estimated) -1.7°, thermal offset (20-100 cm) 0.56°C.										
Air (Site)	-5.5	64.2	13.4	-20.2	1516	3511	142	222		
Soil (20cm)	-1.9	11.9	2.3	-6.7	246	949	104	259	0.16	0.27
Soil (50cm)	-2.3	7.6	0.1	-5.8	39	863	77	287	0.03	0.25
Soil (100cm)	-2.5	6.2	-1.0	-5.0	0	906	0	364	0.00	0.26
Soil (150cm)	-2.5	5.9	-1.6	-4.3	0	920	0	364	0.00	0.26
Parsons Lake, NWT. 9/93-8/94. Soil surface temp (estimated) -5.5°, thermal offset (20-100cm) 0.28°C.										
Air (site)	-8.6	64.0	11.9	-25.8	1216	4253	124	230		
Soil (20cm)	-5.7	30.8	4.7	-17.2	450	2457	97	257	0.37	0.58
Soil (50cm)	-5.8	23.5	1.4	-15.3	179	2245	72	282	0.15	0.53
Soil (100cm)	-6.0	15.8	-1.7	-12.6	0	2107	0	354	0.00	0.50
Soil (150cm)	-5.9	13.8	-2.9	-10.9	0	2099	0	354	0.00	0.49

[1] TDD - thawing degree-days, FDD - freezing degree-days, DWT - days with thawing, DWF - days with freezing
[2] N_t - ratio of TDD at soil depth to TDD in air, N_f - ratio of FDD at soil depth to FDD in air
[3] nd - value not determined or missing

wards south of the tree line and drop more rapidly north of tree line. Within the Boreal Cordillera ecozone, annual mean air temperatures remained about 2° to 2.5°C below soil temperatures at 50 cm, and about 1° to 2°C below soil temperatures at 150 cm. In the Taiga Cordillera and Taiga Plains ecozones this temperature difference increased to 3° to 4°C. Within the Southern Arctic ecozone (Parsons Lake), relatively uniform annual mean soil temperatures, about 2.5°C warmer than annual mean air temperature, were recorded throughout the profile.

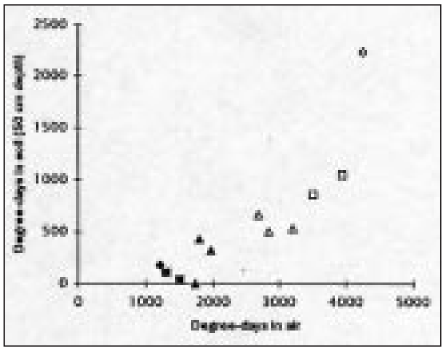

Figure 3. Scatterplot of seasonally-accumulated degree-days in the air and at 50 cm depth in the soil during thawing and freezing seasons. Open symbols are for FDD and closed symbols are for TDD. Sites from the boreal ecozone are represented by triangles, those from taiga ecozones by squares and from the arctic ecozone by diamonds.

The relation between freezing and thawing in the air and at 50 cm depth in the soil expressed as degree-days above or below 0ºC is illustrated in Figure 3. Very different relations exist for thawing degree-days (TDD) compared to freezing degree-days (FDD). The FDD vary through a wide range of soil and air degree-days. TDD appear as two adjacent clusters; the two southernmost boreal sites with deep active layers appear together, but separate from the more northerly sites that tend to accumulate few TDD. FDD values in both the soil and the air are greater than the TDD values, particularly at the Parsons Lake site where FDD in air are >4000 and FDD in soil at 50 cm are >2000. Interestingly, the coldest summer mean temperature at 50 cm is recorded at the Dawson site (-0.54ºC, with 0 TDD) where, under a thick, peaty forest floor, the active layer is only 40 cm deep.

N-factors are the ratios between soil and air TDD or FDD and are presented for each soil depth in Table 3. The n-factors are less than 1.0, indicating that vegetation and snow cover attenuate air temperatures within the soil. Values of the n-factors are controlled by site conditions such as vegetation cover, thickness of surface organic layers, moisture regime and aspect (Taylor, 1995). N-factors for the freezing season (Nf) are greater than those for the thawing season (Nt) except at the 20 cm depth at the Takhini site. At 50 cm depth, the difference between Nf and Nt tends to increase moving northwards. Nf ranges from 0.15 to 0.30 in forested terrain, but increases to >0.50 in the Southern Arctic ecozone. It is interesting to note that Nt in the arctic (Parsons Lake) is similar to Nt from other sites, indicating that the basic processes of energy exchange in summer are similar across the tree line.

"Phase-space" diagrams showing the relation between air and 50 cm depth soil temperature and between 50 cm and 150 cm soil temperatures are given for two sites in Fig. 4. The diagrams illustrate heat transfer between the air and the active layer, or between the active layer and permafrost. The air temperature vs. 50 cm soil temperature plots show a widening of the envelope due to a decrease in snow depth while moving from Boreal Cordillera (Takhini) to Southern Arctic (Parsons Lake) ecozones. Both sites show the same maximum summer air temperature (15ºC). Winter soil temperatures at 50 cm drop by less than 5ºC at the Takhini site but by over 15ºC at Parsons Lake.

Beltrami (1996) proposed that under a purely conductive regime, such plots might appear as ellipses.

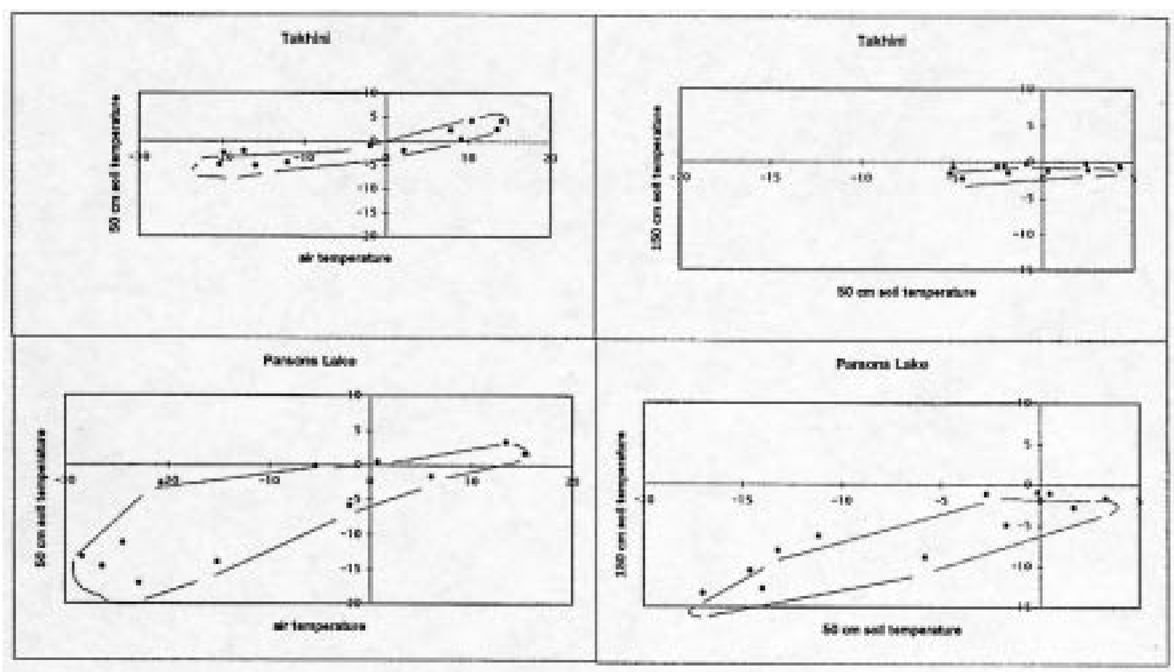

Figure 4. Phase-space diagrams for monthly mean temperatures in air versus the active-layer (50 cm depth) and the active layer versus permafrost (150 cm depth) (Beltrami 1996). Data from the Takhini and Parsons Lake sites are used to represent the Boreal Cordillera ecozone (scattered discontinuous permafrost) and the Southern Arctic ecozone (continuous permafrost) respectively.

Distortions to the ellipse may be attributed to the effects of heat transfer, including phase changes of soil water and transfer of heat by soil water movement (e.g. Hinkel and Outcalt, 1994). In each case, freezing and thawing of soil water within the active layers of the soils presented in Figure 4 cause distortions of the ellipses. The transition from heat transfer across a surface without snow to heat transfer through the snow pack, and the heat consumed by snow melt in the spring, further distort the ellipse. Irregularities are less evident in the heat transfer between the active layer and permafrost, because the energy exchange includes fewer convective effects. The ellipses produced in the 50 cm vs. 150 cm soil temperature diagrams show more regular and compacted form. Both the slope of the long axis of the ellipse, and the range of temperatures incorporated in the ellipse, tend to increase when moving from boreal to arctic conditions. In the more northerly environments, a greater temperature drop is observed within the upper portion of the permafrost in the winter. The thickness of the active layer at Parsons Lake is approximately 60 cm, while at Takhini the active layer is 145 cm thick. The result is that heat transfer between the 50 and 150 cm depths may be, in large measure, conduction through permafrost at Parsons Lake, while other processes may be more effective in the seasonally unfrozen soil at Takhini.

Conclusions

Temperature profiles from sites in the Boreal Cordillera, Taiga Cordillera and Taiga Plains ecozones show common depth trends and similar values. North of tree-line, soil temperatures decline markedly. This can be attributed to the lack of a deep, insulating snow cover over upland soils in the tundra environment. In addition, these soils remain frozen longer throughout the year. Thermal conductivity is greater in frozen soil than in thawed soil (Williams and Smith, 1989) allowing these soils to undergo long periods of effective cooling to achieve these much cooler temperatures. Winter conditions distinguish the arctic soil from the soil south of the tree line: TDD values in the active layers vary only marginally between sites along the transect, but FDD values in the arctic soil are more than double those of boreal and taiga soils, regardless of where they are located within the continuous or discontinuous permafrost zones. The amplitude of temperature variation through the year tends to increase from boreal to arctic environments. Plots of monthly air, active layer and permafrost temperatures show elliptical patterns that become wider in colder environments. Distortion of these ellipses implies non-conductive heat transfers occur in these soils.

Acknowledgments

The research has been supported by the Atmospheric Environment Service (AES), Environment Canada, the Research Branch of Agriculture and Agri-Food Canada and through grants to C.R. Burn from the National Science and Engineering Research Council and the Northern Research Institute, Yukon College. Field data collection at the Inuvik and Parsons Lake sites was supported by Indian and Northern Affairs Canada. The extent of field activities in Mayo would not be possible without the support of Joan Ramsay Burn and the hospitality of Jim and Shann Carmichael. Monitoring at the Dawson site is conducted with the support and cooperation of Jenny Kaisner and Mike Heydorff. We also wish to acknowledge the station volunteers at Takhini River Ranch and at Eagle Plains Lodge who provide AES with continuing weather observations that allow calculation of air temperature means for these sites.

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