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Ground Temperatures and Permafrost Warming from Forest to Tundra, Tuktoyaktuk Coastlands and Anderson Plain, NWT, Canada

S. V. Kokelj,[1]* *M. J. Palmer,*[2] *T. C. Lantz*[3] *and C. R. Burn*[4]

[1] Northwest Territories Geological Survey, Government of the Northwest Territories, Yellowknife, Canada
[2] Cumulative Impact Monitoring Program, Government of the Northwest Territories, Yellowknife, Canada
[3] School of Environmental Studies, University of Victoria, Victoria, British Columbia Canada
[4] Department of Geography and Environmental Studies, Carleton University, Ottawa, Ontario Canada

ABSTRACT

Annual mean ground temperatures (T_g) decline northward from approximately −3.0°C in the boreal forest to −7.0°C in dwarf-shrub tundra in the Tuktoyuktuk Coastlands and Anderson Plain, NWT, Canada. The latitudinal decrease in T_g from forest to tundra is accompanied by an increase in the range of values measured in the central, tall-shrub tundra zone. Field measurements from 124 sites across this ecotone indicate that in undisturbed terrain T_g may approach 0°C in the forest and −4°C in dwarf-shrub tundra. The greatest range of local variation in T_g (~7°C) was observed in the tall-shrub transition zone. Undisturbed terrain units with relatively high T_g include riparian areas and slopes with drifting snow, saturated soils in polygonal peatlands and areas near lakes. Across the region, the warmest permafrost is associated with disturbances such as thaw slumps, drained lakes, areas burned by wildfires, drilling-mud sumps and roadsides. Soil saturation following terrain subsidence may increase the latent heat content of the active layer, while increases in snow depth decrease the rate of ground heat loss in autumn and winter. Such disturbances increase freezeback duration and reduce the period of conductive ground cooling, resulting in higher T_g and, in some cases, permafrost thaw. The field measurements reported here confirm that minimum T_g values in the uppermost 10 m of permafrost have increased by ~2°C since the 1970s. The widespread occurrence of T_g above −3°C indicates warm permafrost exists in disturbed and undisturbed settings across the transition from forest to tundra.

KEY WORDS: active layer; climate change; ground temperature; Mackenzie Delta area; terrain disturbance; tree line

INTRODUCTION

Latitudinal tree line is a circumpolar ecotone close to the southern boundary of continuous permafrost (Bliss and Matveyeva, 1992; Timoney *et al*., 1992). In the rolling uplands to the east of the lower-lying Mackenzie Delta, an abrupt northward decline in mean annual ground temperature occurs across the transition from spruce forest to dwarf-shrub tundra in association with decreasing snow depths and mean annual air temperatures (Mackay, 1967, 1974). Annual mean ground temperatures (T_g) are approximately −3.0°C in the subarctic forest and −7.0°C in dwarf-shrub tundra near the Beaufort Sea coast (Burn and Kokelj, 2009; Palmer *et al*., 2012). Across this gradient, local heterogeneity in soils, vegetation, topography, hydrology and snow cover may produce variation in T_g on the order of a few degrees centigrade across distances of a few hundred metres (Mackay and MacKay, 1974; Smith, 1975). Higher T_g are encountered in riparian areas and wetlands, areas where snow accumulates due to topography or tall shrubs, and natural and anthropogenic disturbances (Burn *et al*., 2009; Kokelj *et al*., 2009, 2010, 2014; Lantz *et al*., 2009; Morse *et al*., 2012). Despite this local variation, the range of T_g in terrain across this ecological transition has not been quantitatively assessed.

Regional and local variability in ground thermal conditions may indicate permafrost sensitivity to changing climate or surface disturbance and inform the design and maintenance of northern infrastructure, including pipelines and roads (e.g. Burgess and Smith, 2000; Darrow, 2011).

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* Correspondence to: S.V. Kokelj, Northwest Territories Geological Survey, Government of the Northwest Territories, PO Box 1320, Yellowknife, NT, X1A 2L9, Canada. E-mail: steve_kokelj@gov.nt.ca

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The systematic studies of permafrost ground temperatures summarised by J. R. Mackay in the 1970s provide us with a regional baseline against which to evaluate present-day conditions and climate-induced change (Mackay, 1974). Here we present a large compilation of published and unpublished data to quantitatively describe the variability in ground temperatures across the transition from forest to tundra in the Tuktoyaktuk Coastlands and Anderson Plain physiographic regions east of the Mackenzie Delta (Figure 1). We also compare these data with the regional syntheses presented by Mackay (1974) and Burn and Kokelj (2009). Across the study area, wind redistribution of snow to vegetated topographic hollows, areas with tall shrubs or riparian zones may lead to greater spatial variability in surface ground temperatures than in the open-canopy boreal forest, where snow cover is thicker and less heterogeneous.

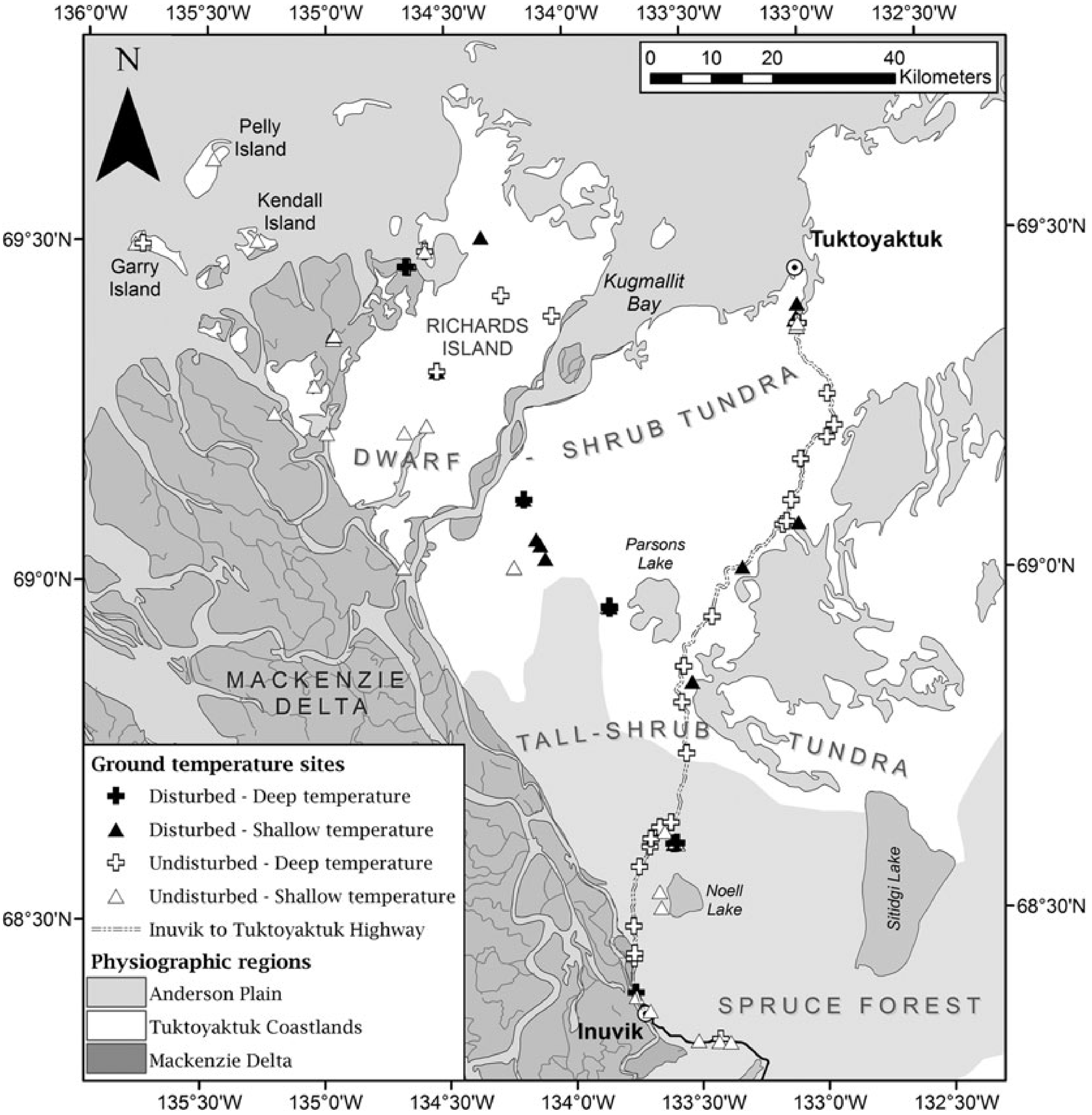

Figure 1 Study area in the Tuktoyaktuk Coastlands and Anderson Plain, Northwest Territories, Canada. The figure shows the location of 124 ground temperature monitoring sites reported in this study. Several sites are close to each other, and so the symbols overlap. The physiographic regions are from Rampton (1988).

On this basis, we hypothesise that a northward decrease in annual mean air temperatures and greater range of surface conditions, primarily variation in snow cover, increase the range in T_g through the transition from forest to tundra. To test this hypothesis we summarised ground temperatures from 124 sites in undisturbed terrain, and from natural and anthropogenic disturbances in upland terrain east of the Mackenzie Delta (Figure 1). To investigate the influence of winter surface conditions on variation in near-surface thermal regime across this region, we also examined relationships between the duration of active-layer freezeback and T_g. Our synthesis quantifies local and regional variability in permafrost ground temperatures in this ecologically and economically important region of the Canadian North.

STUDY AREA

This study is focused on the transition from forest to tundra within the western part of the Tuktoyaktuk Coastland and Anderson Plain physiographic regions (Figure 1) (Mackay, 1963; Rampton, 1988). The region was glaciated in the Late Wisconsinan and surficial materials are predominantly fine-grained and stony tills (Duk-Rodkin and Lemmen, 2000). Rolling, ice-rich hummocky moraine is interspersed with lacustrine plains that are locally dominant in the central and northern part of the study area (Aylsworth *et al*., 2000). These extensive, more poorly drained areas typically contain polygonal terrain and organic soils (Kokelj *et al*., 2014; Steedman *et al*., 2016). The entire study area is lake-rich and water bodies with depths that exceed about two-thirds of the winter ice thickness are underlain by taliks (Burn, 2002). Drainage of lakes causes permafrost to aggrade in the lake sediments (Mackay, 1992), and provides nutrient-rich soil surfaces for colonisation by shrubs (Marsh *et al*., 2009).

Terrestrial environments throughout the study area are underlain by thick, ice-rich permafrost (Burn and Kokelj, 2009). The depth of permafrost increases from about 100 m in the subarctic forest near Inuvik to more than 500 m in the northern part of the study area (Mackay, 1967; Judge *et al*., 1979). Near-surface segregated ice is common in the upper 2–3 m of the ground, above the early Holocene thaw unconformity (Burn, 1997; Kokelj and Burn, 2003). Ice wedges occur in organic deposits throughout the region, but wedge ice is only common north of the tall-shrub transition zone in tills (Mackay, 2000; Kokelj *et al*., 2014).

The region is characterised by a steep climatic gradient, with colder and drier conditions close to the coast and warmer and wetter conditions inland (Burn and Kokelj, 2009). Mean annual air temperatures for 1981–2010 at Tuktoyaktuk and Inuvik were −10.1 and −8.2°C, respectively (Environment Canada, 2015). The northern part of the study area receives less precipitation than inland areas: annual snowfall for 1981–2010 at Inuvik was 158.6 cm, and at Tuktoyaktuk was 103.1 cm. The vegetation in the study area transitions from open-canopy spruce forest in the southern part of the study area to dwarf-shrub tundra near the Beaufort Sea coast (Figure 1; Supplementary Figure S1;) (Timoney *et al*., 1992). The central part of the study area is dominated by a mosaic of tall-shrub, dwarf-shrub, and graminoid tundra and is referred to throughout the paper as the tall-shrub transition zone (Lantz *et al*., 2010). Regional variation in ground temperatures is strongly associated with these latitudinal gradients in climate and vegetation structure (Burn and Kokelj, 2009; Palmer *et al*., 2012).

Rising air temperatures since the 1970s have been associated with an increase in permafrost temperatures (Smith *et al*., 2005; Burn and Kokelj, 2009; Burn and Zhang, 2010), thermokarst disturbance (Lantz and Kokelj, 2008), and the increased size and abundance of tall shrubs (Lantz *et al*., 2013; Fraser *et al*., 2014; Moffatt *et al*., 2016). The study region includes the communities of Inuvik and Tuktoyaktuk, a growing network of roads, and numerous historical hydrocarbon exploration staging areas and drilling-mud sumps, which rely on permafrost as a foundation or for containment (Burn and Kokelj, 2009; Kokelj *et al*., 2010).

METHODS

This paper reports ground temperatures at 124 sites with mineral and organic soils in disturbed and undisturbed environments from the subarctic forest through tall-shrub tundra and dwarf-shrub tundra in the Tuktoyakuk Coastlands and Anderson Plain (Figure 1; Table 1). Site attributes and data sources are provided in Supplementary Table S1, and photographs and descriptions of the main site types are shown in Supplementary Figure S1. We stratified our sites by ecotype (forest, tall shrub and dwarf shrub), disturbance status and depth of temperature measurement. Undisturbed sites included hilltops, slopes, valley bottoms, riparian areas and polygonal peatlands. Natural disturbances included areas burned by wildfire, retrogressive thaw slumps and drained, revegetated lake-beds (Table 1). Anthropogenic disturbances included hydrocarbon drilling-mud sumps, aggregate quarries and roadsides. These perturbations described in Table 1 had a range of impacts, including: the destruction of organic material, alteration of drainage, increased soil moisture, and elevated snow cover due to changes in topography or shrub proliferation. The impact of surface disturbance on temperatures at depth is related to the intensity, spatial footprint and duration of the perturbation, with recent terrain disturbances resulting in disequilibrium between surface and subsurface conditions.

Installation techniques and measurement equipment varied among the different sites. Near-surface ground temperatures were typically reported at depths of 0.05 m (T_s) and 1.0 m (T_{ns}) below the ground surface. Sensors at 1.0 m depth were usually within permafrost in undisturbed terrain, but active-layer thicknesses commonly exceeded this depth at disturbed sites (Mackay, 1995; Kokelj *et al*., 2010). All data reported in this summary are from 2002 to 2015 and approximately 20 per cent of the sites have

Table 1 Study area environments and general site conditions.

Site type	Biological conditions	Physical conditions	References
Undisturbed	—	—	—
Flat terrain	Forest, tall-shrub, dwarf-shrub tundra	Variable snow, vegetation and hydrology. Fine-grained mineral to organic soils	Smith *et al.* (2005), Burn and Kokelj (2009), Palmer *et al.* (2012)
Valleys, side slopes and riparian bottoms	Side slopes and bottoms	High snow depths	Stevens *et al.* (2011)
Disturbed	—	—	—
Burned	Dense tall-shrub	Removal of O-layer, increased thaw depths, variable soil organic conditions	Mackay (1995), Palmer *et al.* (2012)
Drained lake	Dense tall-shrub	Mineral soils, moderately drained, medium to high snow depths	Mackay and Burn (2002), Marsh *et al.* (2009)
Thaw slump	Dense tall-shrub	Removal of O-layer, mineral soils, modified topography, increased snow and thaw depths	Kokelj *et al.* (2009), Lantz *et al.* (2009)
Anthropogenic disturbances (sumps, quarries, roadside sites)	Unvegetated to dense-tall shrub	Removal of O-layer, modified topography, impeded drainage, increased snow and thaw depths	Mackay *et al.* (1970), Burn *et al.* (2009), Kokelj *et al.* (2010)

multiple years of data (Supplementary Table S1). Measurements were made every 2–4 h with thermistors (model TMC6-HA, Onset Computer Corporation, Bourne, MA, USA) that were attached to two- or four-channel Onset HOBO data loggers (typically models H08–006-04, U23–001, U12–008, U10–003 or U12–003). These temperature sensors have a minimum range of −20 to 70°C, an accuracy of ±0.53°C or better and a precision of ±0.41°C or better at 0°C. Since we report mean ground temperatures for individual years, we refer to this estimate as an annual mean ground temperature (Palmer *et al.*, 2012). Annual mean ground temperatures (T_g) were based on T_{ns} and calculated using observations from 1 September to 31 August. Years with more than 10 days of missing data were excluded from the analyses.

Daily mean ground temperatures were used to estimate the duration of active-layer freezeback for all sites and in years with adequate data. The period of active-layer freezeback was defined as from the date that T_s dropped below 0°C for three consecutive days until the date, later, when T_{ns} declined and indicated closure of the zero curtain. The temperature drop for T_{ns} was identified as an abrupt decrease of more than 0.5°C from a stable freezing value. At some sites, the freezeback period extended through the entire winter and ended when T_s rose above 0°C.

At 48 of the 124 sites, deeper ground temperatures (T_d) were compiled from a range of environments across the region. T_d values are reported from a depth of at least 5 m below the ground surface, typically at 10-m depth, where annual variation in ground temperature is <0.5°C. If data were not available at 10-m depth, we estimated the temperature by linear interpolation between the temperature measurements that bracket the 10-m depth. Most T_d values reported in this paper are from ground temperature monitoring conducted by the Department of Transportation of the Government of the Northwest Territories along the Inuvik to Tuktoyaktuk Highway alignment, and Indigenous and Northern Affairs Canada and Natural Resources Canada data that were collected along the proposed Mackenzie Gas Pipeline corridor (Kokelj *et al.*, 2009; Stevens *et al.*, 2011), and regulatory monitoring of drilling-mud sumps and adjacent undisturbed terrain. Measurements by the Department of Transportation are manual readings obtained biannually before construction of the Inuvik to Tuktoyaktuk Highway. At sites instrumented by Indigenous and Northern Affairs Canada, and Natural Resources Canada, ground temperatures were recorded at 8-h intervals using eight-channel data loggers (Branker XR-420-T8). These thermistors (YSI 46004) have an accuracy of ±0.1°C or better, and a precision of ±0.01°C or better at 0°C.

To show the range of snow conditions across the study region we compiled late winter snow survey data obtained between 2004 and 2015. Site means were calculated for each year of available data.

RESULTS

Regional Variation in Ground Temperatures

The lowest T_g at measurement sites decline northward across the transition from spruce forest to dwarf-shrub

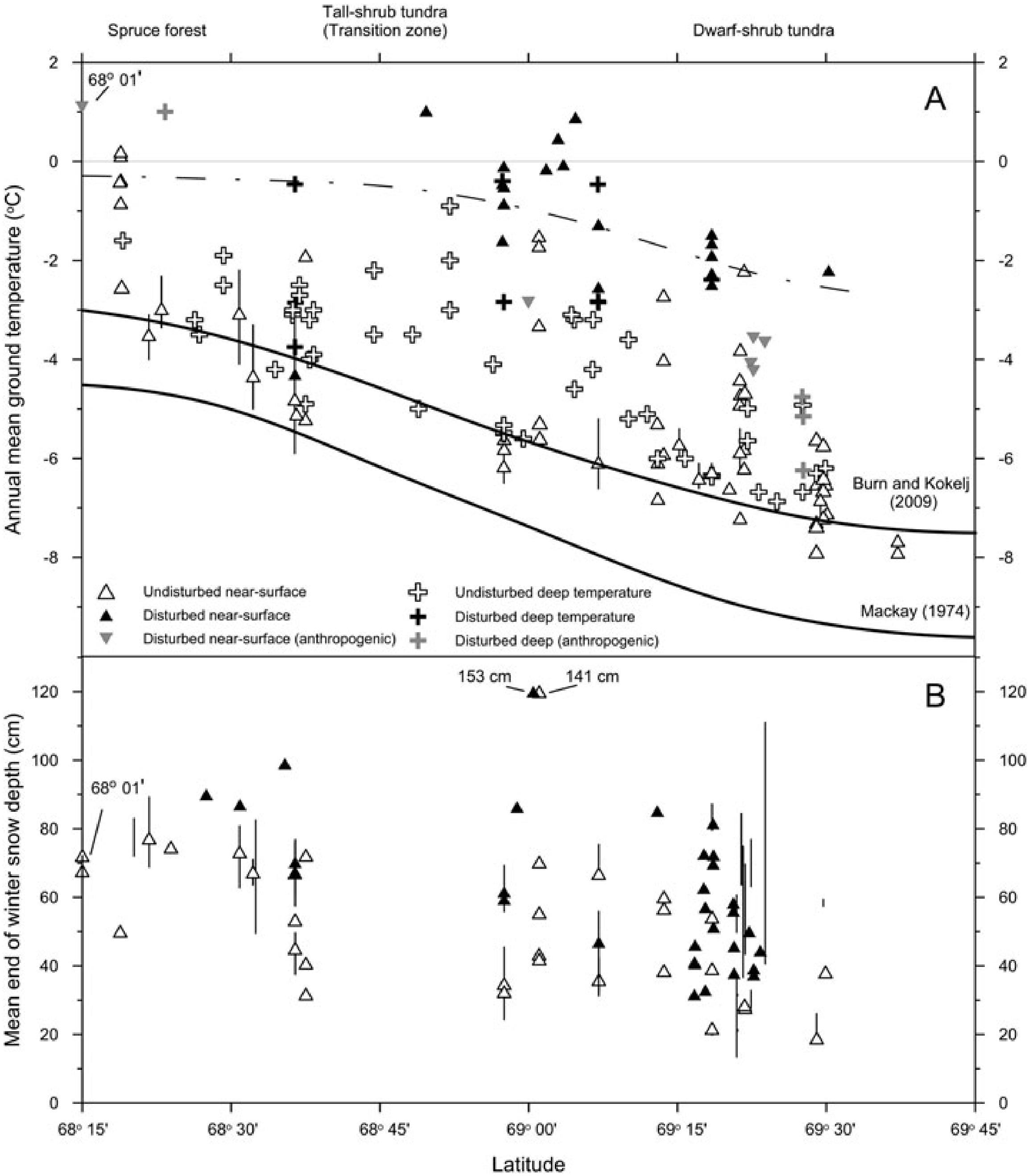

Figure 2 Ground temperature and snow conditions across the transition from forest to tundra, Tuktoyaktuk Coastlands and Anderson Plain. (a) Annual mean ground temperatures at 124 sites in disturbed and undisturbed terrain from forest to dwarf-shrub tundra. The triangles indicate sites with near-surface temperatures (1 m) (T_{ns}) and the crosses indicate sites with data from 10-m depth. Vertical bars show the range of annual mean values when two or more years of data were available and the point along the bars shows the average annual mean value with three or more years of data. The dashed line approximates the highest mean ground temperatures reported from undisturbed terrain. The upper solid line shows the lowest mean ground temperatures interpolated from a regional map based on data from 2003 to 2007 compiled by Burn and Kokelj (2009). The bottom line shows lowest mean ground temperatures from a similar regional map from the 1960s and 1970s (Mackay, 1974), in addition to data for the Inuvik region from Brown (1966) and Mackay (1967). (b) Mean snow thickness at 70 sites in disturbed and undisturbed terrain from forest to dwarf-shrub tundra. Mean values are plotted for each site. Vertical bars show the range of annual mean values when two or more years of data were available and the point along the bar shows the average mean value with three or more years of data. Data are from 2004 to 2015. Disturbed and undisturbed sites are distinguished using the symbols in (a).

tundra (Figure 2a). The lowest T_g values are reasonably bounded by a curve derived from the regional ground temperature map for 2003–07 presented by Burn and Kokelj (2009). The lowest T_{ns} in the forest was about −3.5°C and decreased to about −8°C in the dwarf-shrub tundra close to the coast (Figure 2a). T_d falls within the range of T_{ns}

and minimum values decrease northward from about −2.0°C in forest near Inuvik to −7.0°C in the dwarf-shrub tundra near the Beaufort Sea coast (Figure 2a).

Annual mean T_{ns} from all environments sampled varied by 4.0–5.0°C in the forest and dwarf-shrub tundra zones and by at least 7.0°C in the tall-shrub tundra (Figure 2a). Most of the sites across the region have T_g higher than those indicated by the isocline in Burn and Kokelj (2009, figure 11), although there is a notable cluster of T_{ns} and T_d at the southern extent of the tall-shrub tundra zone with lower ground temperatures. The hatched line in Figure 2a shows that the upper range of ground temperatures from undisturbed terrain is 3–6°C higher than the lowest mean temperatures and the greatest range of variation is in the tall-shrub zone. The highest T_g are about 0°C in undisturbed forested areas, −1 to −2°C in the tall-shrub tundra, and −2 to −4°C in the dwarf-shrub tundra. The highest T_d reported in dwarf-shrub tundra is typically a few degrees centigrade lower than the highest T_{ns} (Figure 2a). Undisturbed terrain with high T_g includes riparian areas, slopes with drifting snow, saturated organic soils in polygonal terrain and areas proximal to lakes.

The range of snow thicknesses also increases northwards across the transition from forest to tundra. Figure 2b shows that snow thicknesses in the forest are typically greater, but less variable, than on the tundra. Tundra sites typically have thin snow cover, but areas with upright shrubs, and natural hollows or infrastructure such as road embankments can accumulate snow drifts, causing site-specific snow thicknesses and the range of local variability to exceed those in the forest.

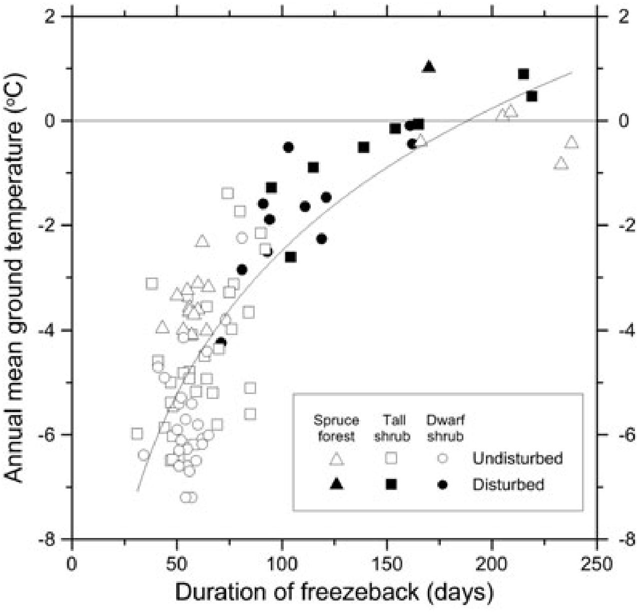

Figure 3 Scatter plot of T_{ns} versus the duration of freezeback for all sites and all years with available data. Sites are symbolised according to ecotype and disturbance status. The linear relationship between T_{ns} and log-transformed duration of freezeback is $y = 9.05(\ln x) - 20.59$; $r^2 = 0.70$; $n = 98$. The slope and y-intercept are significant at $P < 0.001$ (Slope: $t_{1,97} = 14.84$; Intercept: $F_{1,97} = 220.29$).

The warmest permafrost across the region was associated with natural and anthropogenic disturbances, where T_g was commonly above −2°C. In these environments, disturbances to the surface organic cover, a deep snow pack and saturated soils may result in T_{ns} above 0°C, even in the tall-shrub transition zone (Lantz *et al*., 2009; Kokelj *et al*., 2010). Disturbances such as drilling-mud sumps or thaw slumps in the dwarf-shrub tundra that did not lead to increases in snow accumulation had lower ground temperatures. Natural disturbances such as fire, thaw slumps or drained lakes modify surface conditions, which over varying time scales shift towards the local undisturbed condition (Mackay, 1995). However, disturbances such as road embankments or sumps represent a longer term alteration of surface boundary conditions and departure from local, undisturbed ground temperatures (Kokelj *et al*., 2010; Gill *et al*., 2014).

Active-Layer freezeback and T_{ns}

The duration of active-layer freezeback showed a positive, non-linear association with T_{ns} for all sites with available data from the study area (Figure 3). Most of the undisturbed sites typically refreeze within 75 days of sub-zero T_s and have T_g that range from about −3.0 to −7.0°C. The large range in T_g where the active layer rapidly freezes can be attributed to inter-annual variation in snow and air temperatures, and to differences in soil thermal properties and the rates and magnitude of snow accumulation throughout winter among sites. For example, the duration of freezeback at undisturbed forest sites is only slightly longer than that at the tundra sites, but T_g in the forest is several degrees higher than on the tundra (Figure 3). This difference is caused by the deeper snow in mid- to late winter at forest and many transition zone sites, which reduces ground heat loss (Figure 2b) (Palmer *et al*., 2012).

The high variability in snow conditions among sites contributes to the greater range of T_g in the tall-shrub transition zone (Figure 3). At sites where freezeback exceeds 80–90 days, regardless of vegetation zone, T_g is typically above −3°C, and increases gradually with freezeback duration (Figure 3). Sites with a prolonged freezeback typically have deep snow, thick active layers and saturated soils (Table 1) (Burn *et al*., 2009; Kokelj *et al*., 2009, 2010, 2014). Environments with these conditions include thaw slump scars, revegetated drained lake basins, some ice-wedge troughs, drilling-mud sumps and road embankments (Table 1). Since the extended freezeback duration limits the period of conductive heat loss from permafrost, some disturbed sites may have T_g that approach or exceed 0°C.

Climate Change and Ground Temperatures

The regional mean ground temperature curve based on Burn and Kokelj (2009, figure 11) approximates a lower boundary for present-day T_g across the forest–tundra transition (Figure 2a). The few recent ground temperature observations below this upper line, and the fact that all T_d values were well above the bottom curve, which approximates the regional ground temperatures for the late 1960s and early 1970s (Brown, 1966; Mackay, 1967, 1974), confirm that T_g values have increased by about 2°C since the 1970s (Burn & Zhang, 2010). The presence of warm, undisturbed permafrost throughout the transition from forest to tundra highlights the thermal sensitivity of terrain in this region to disturbance or climate change.

DISCUSSION

There is a northward decrease in minimum T_g across the transition from subarctic forest to dwarf-shrub tundra (Figure 2a). This regional ground temperature gradient is associated with an increased range of T_g through the tall-shrub transition zone. The background variation in soils, vegetation, snow conditions and proximity to water bodies may account for up to about 5°C of local variation in mean ground temperatures in the study region (Figure 2) (Kanigan *et al*., 2008; Burn and Zhang, 2009). In the tall-shrub and dwarf-shrub tundra, deep snow on hillslopes or areas with tall shrubs and elevated snow and soil moisture in riparian zones may result in T_g several degrees higher than in surrounding terrain (Kokelj *et al*., 2014). As a result, many low Arctic environments north of the tree line have ground thermal conditions that are comparable with those in the boreal forest (Figures 2a and 3).

Figures 2(a) and 3 show that terrain disturbance across the study area can lead to permafrost degradation. Removal of surface organic cover, development of a dense shrub cover, or topographic changes that alter snow accumulation or soil moisture can modify soil thermal properties, surface conditions and ground heat flux. Such disturbances may prolong the duration of active-layer freezeback and decrease the annual period of conductive ground cooling (Figure 3) (Romanovsky and Osterkamp, 1995; Kokelj *et al*., 2010, 2014). Many natural disturbances revert back to an undisturbed condition, albeit over varying time scales (Mackay, 1970, 1995; Mackay and Burn, 2002; Lantz *et al*., 2009). However, anthropogenic disturbances such as road embankments and sumps can result in the longer term alteration of soil, drainage and snow conditions. While disturbance and localised alteration of surface conditions can significantly increase T_{ns}, in dwarf-shrub tundra environments the thermal effects are typically dampened with depth due to the influence of lateral heat transfer with the surrounding cold permafrost (Figure 2a).

The wide range of surface boundary conditions and ground temperatures encountered across the transition from forest to tundra (Figure 2) suggests that permafrost in this ecotone is thermally sensitive to further disturbances or climate change. Our data also suggest that an increase in natural or anthropogenic disturbance or a northward shift in the tall-shrub tundra zone will compound climate-driven increases in low Arctic ground temperatures. While at most undisturbed sites across this region T_g values remain several degrees below 0°C, patches of the terrain have ‘warm’ permafrost and surface disturbances and thick snow can result in thermal degradation (Figure 2a). Together, these observations are of relevance to the planning and maintenance of infrastructure that utilises permafrost as a foundation (Hayley and Horne, 2008) or containment medium (Kokelj *et al*., 2010), and for anticipating the thermal consequences of future disturbance, climate warming and regional shrub proliferation (Lantz *et al*., 2013; Moffat *et al*., 2016).

CONCLUSIONS

Based on the analyses and interpretation of this regional ground temperature dataset we draw the following conclusions:

1. The northward decrease in minimum T_g from about −3.0 to −7.0°C across the transition from subarctic forest to dwarf-shrub tundra is accompanied by an increase in the range of T_g in the tall-shrub transition zone.
2. The greater range in T_g through the tall-shrub tundra is associated with areas of deep snow or areas of increased snow and soil moisture. In these locations T_g can be several degrees higher than in surrounding terrain and similar to conditions in the forest.
3. Natural or anthropogenic disturbances that alter snow cover or soil thermal properties can prolong active-layer freezeback and increase T_{ns}, causing permafrost thaw at sites across the transition from forest to tundra.
4. Annual mean ground temperatures at undisturbed sites in the study area have increased by as much as 2°C since the 1970s due to climate warming.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web site.

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