Topoclimatic controls on active-layer thickness, Alaskan Coastal Plain

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GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
Although many studies of active layer development address spatial variations in soil thermal properties and moisture conditions, few have attempted to isolate topoclimatic influences on active-layer thickness. Observed patterns of thaw depth on various facets of an anthropogenic thermokarst landform near Prudhoe Bay, Alaska show systematic variation with slope orientation. This study demonstrates that aspect has a strong control on active-layer thickness, even at 70°N latitude, with south-facing slopes thawing to greater depth than north-facing slopes and northern exposure compensating even for the absence of an insulating layer of vegetation.

RÉSUMÉ
Bien que de nombreuses études sur le développement de la couche active traitent de la variabilité spatiale dans les caractéristiques thermiques du sol et les conditions d'humidité, seulement quelques-unes ont tenté d'isoler les influences topoclimatiques sur l'épaisseur de la couche active. Les profondeurs de dégel mesurées sur une forme thermokarstique anthropique près de Prudhoe Bay, en Alaska démontrent une relation systématique entre l'épaisseur de la couche active et l'orientation de la pente. Cette étude prouve que l'orientation a un grand contrôle sur l'épaisseur de la couche active, même à 70°N de latitude. Par exemple, la couche active sur les pentes exposées au sud dégèle à une plus grande profondeur que celles exposées au nord, de même que l'exposition au nord qui sert d'alternative à l'absence d'une couche de végétation isolante.

1 INTRODUCTION

Topography exerts substantial controls over local climate, creating pronounced differences in climatic parameters over short lateral distances. These climatic contrasts, in turn, affect the rates at which geomorphic processes operate, and ultimately the form of the land surface. These effects can be particularly pronounced in permafrost landscapes, which are highly susceptible to climatic influences where underlain by ice-rich sediments.

The term "topoclimatology," introduced by C.W. Thornthwaite (1954), is a shorthand reference to the study of the influence of Earth's surface terrain on micro- and meso-scale climate. Topoclimatic studies encompass diverse scientific disciplines, including plant ecology, habitat suitability modeling, energy balances, hydrology, soil and ground water processes, geomorphology, agriculture, and urban climate. Topoclimatic relations are a key element in simulation studies of permafrost distribution in mountainous areas.

Surprisingly little empirical research has been completed in mapping geographic variations in active-layer thickness (ALT) on hillslopes. Robust statistical data are necessary to validate modeling efforts. Nelson *et al*. (1997) mapped active-layer thickness in the Kuparuk region of Alaska's North Slope using a computational algorithm that included a topoclimatic index to control for aspect-induced differences. The data set used to calibrate topoclimatic parameterizations in that study is described in detail in this paper.

2 STUDY AREA AND DEVELOPMENT HISTORY

Field investigations were undertaken during the summer of 1981 on an abandoned road constructed during the early stages of oilfield development at Prudhoe Bay, Alaska. The portion of the road investigated lies adjacent to the Deadhorse Airport, the main public air-transport facility servicing the Prudhoe Bay oilfield (Figure 1). Nelson and Outcalt (1982) provided a description of the road and a preliminary analysis of data collected from it.

The Prudhoe Bay oilfield is located on the northern edge of Alaska's Arctic Coastal Plain physiographic region (Wahrhaftig 1965), an extensive area of low relief with tundra vegetation, shallow thaw lakes, drained lake basins, and anastomosing rivers. Much of the landscape is saturated with water during the short summer season. The marine silts underlying the region contain relatively large volumes of ice, mostly in the upper 5 to 10 m. Areas of low-centered ice-wedge polygons are typical of the Prudhoe Bay region. A comprehensive description of the region was provided by Walker *et al*. (1980), and the cumulative impacts of oil field activities have been described and analyzed by Walker *et al*. (1986) and Raynolds *et al*. (2014).

The discovery of large oil reserves at Prudhoe Bay in 1968 necessitated development of a means to transport matériel to the North Slope. This major oil and gas discovery initiated strong pressure to develop overland transport facilities. During the winter of 1968-69, the State of Alaska constructed a 735 km road to transport materials to the North Slope. From Livengood to Bettles the road followed an existing winter trail used by tractor trains when the airfield at Bettles was built in the early 1940s. The road from Bettles, south of the Brooks Range, to Prudhoe Bay on the coast of the Beaufort Sea, was new (Figure 1). The oil companies built and operated a winter road from Sagwon to the Prudhoe Bay oilfield. This section of road was built between December 1968 and March 1969, at a cost of US$766,000 (Anonymous, 1970).

To create a relatively level surface in hummocky and polygonal terrain, a rectangular 7 x 4 m steel frame with a two-ton (1818 kg) crossbar was dragged across the surface (Anonymous, 1970). In wet areas requiring more than surface leveling, two parallel strips of tundra were bulldozed and the mats stacked atop each other (Nelson and Outcalt, 1982). The result was an elevated berm on which vehicles could operate. The mode of construction resulted in the berm containing a triple layer of organic material. Excavation of the road surface indicated that 10-20 cm of the bladed organic layer was removed from each section now occupied by thermokarst troughs. Drainage patterns have been severely disrupted by subsidence in these parallel troughs, creating a local base level for running water in the surrounding area and eroding the tops of adjacent ice wedges.

At the time of construction, the road was the longest of its type ever built in Alaska (Anonymous, 1969). Spring thaw forced closure of the road only one month after its completion in the year of construction (Johns, 1969). The road caused extensive damage to the tundra insulation by removing the protective mat of vegetation and snow. Thermokarst processes transformed the damaged areas into deep ruts, necessitating creation of new roadbeds around eroded segments (Haynes, 1972).

A decade after construction, the road's morphology consisted of two parallel trenches separated by a relatively stable berm (Figure 2). Areas where the insulating tundra vegetation was removed were eroded deeply within two years of the disturbance (Haynes, 1972). Only ten years after the initial disturbance, two meters of subsidence had occurred in some areas adjacent to the road's flanks (Nelson and Outcalt, 1982). Thermal erosion generated by running water in the bladed sections removed sediment, annually exposing new layers of ice-rich permafrost and resulting in further settlement.

The road surface, underlain by three layers of organics, is a dry and compacted microenvironment on which less vegetation grows than the surrounding tundra. Permafrost aggradation has occurred within the road berm, owing to the insulating effects of the organic layers, and only shallow thawing occurs on the road surface. The road has been modified primarily by erosion along its flanks through slumping of organic-rich blocks and by water flowing in the adjacent troughs. Examination of sequential photographs demonstrates that slope angles on the thermokarst road have relaxed over the several decades since our initial observations. Troughs are gradually filling in with material sloughed off the road's flanks. In winter, snow drifts into the troughs, filling them completely. The effect of deep snow cover protects the troughs from the full brunt of low winter temperatures.

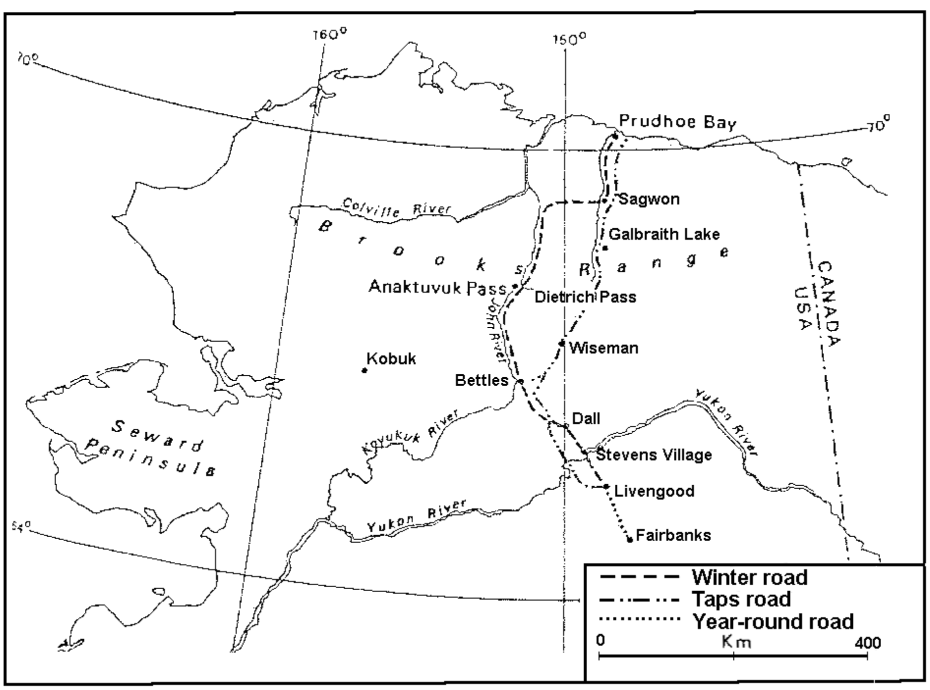


Figure 1. Map of winter haul road in northern Alaska, Adapted from Anonymous (1970).

In spring, the troughs collect warm meltwater from the tundra, quickly melting and suspending any snow remaining in them. The transition of troughs from snow catchment areas to running meltwater can occur in less than two days (Nelson and Outcalt, 1982).

Figure 2. Well-preserved section of the thermokarst road south of Deadhorse airport during the summer of 1980. View is to west.

3 METHODOLOGY

3.1 Sampling procedures

The study area contains an east-west and a north-south section of the 1969 road between the Sagavanirktok River and Beechey Point (70°11.4' N 148°28.9' W), providing a rectilinear surface facing each of the cardinal directions. The east- and west-facing segments of road where data were collected lie northwest of the Deadhorse airfield, while the north- and south-facing segments are south of the airfield.

To obtain an accurate characterization of slope steepness, 50 measurements of slope inclination were made with a Brunton compass at equal intervals of distance along each inclined facet of the road (Table 1).

Table 1. Slope inclination and orientation on thermokarst road. All values are expressed in degrees.

Facet	min	max	mean	std dev	orientation
North	17.0	57.0	29.9	7.6	000
South	11.0	51.0	24.7	8.4	180
East	11.5	41.0	22.4	6.6	080
West	12.0	38.5	21.6	6.0	260

Measurements of thaw progression on various facets of the road were recorded throughout the summer of 1981 by mechanical probing of the active layer. Thaw depth was determined using a standard 1 cm diameter Cold Regions Research and Engineering Laboratory (CRREL) calibrated steel probe. The data set consists of thaw-depth measurements taken throughout the summer on the road surface, a trough bottom paralleling the road, north- and south-facing slopes, undisturbed tundra paralleling the road, and (on alternate sampling dates) east- and west-facing slopes. Measurements were recorded on five occasions during the course of the 1981 summer: 2 July, 14 July, 2 August, 19 August, and 1 September. Each sample was comprised of 50 replications of thaw depth over the same marked section of the road used to make slope-angle measurements.

Validation of the mechanical probing methodology was carried out on several dates during the thaw season, using a YSI 419 thermistor probe and a Wheatstone bridge measuring resistance to locate the level at which temperature in the substrate was 0.0°C (cf. Mackay 1977). Calibration was achieved using an ice bath prior to field work each day. The thermal probe was pushed into the substrate in 5 cm increments, allowing sufficient time for temperature to reach equilibrium. A very high degree of agreement was found between the mechanical and thermal probed values, except on the final day of sampling (September 2), by which time freezeback from the top of permafrost had been sufficient to cause large differences between the two procedures (Figure 3). Ice bonding of refreezing sediment at the base of the active layer had progressed far enough by this date that upfreezing (Mackay 1979, 1984) was detected, even in the mechanically probed samples. The trough bottom was the sole exception, owing to the presence of ponded water at some sampling points along this transect.

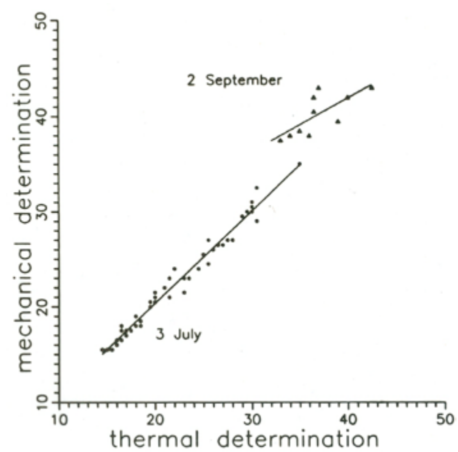


Figure 3. Comparative results from mechanical and thermal probing.

Daily air temperatures for the 1981 summer season were obtained from weather observations made atop the air traffic control tower at the Deadhorse airport. Because the airport and the site are in close proximity, air temperature measurements were assumed to be representative of the site's location. Hourly measurements were only recorded at the air traffic control tower during the time period 1400 to 0200 (local time) for the duration of the summer season. Mean daily temperature was calculated by averaging the temperatures recorded at 0200 and 1400 so as not to bias the results toward the time of day when temperatures were recorded. The cumulative degree days of thaw (DDT) was computed by summing mean daily temperatures from June 1 through September 2.

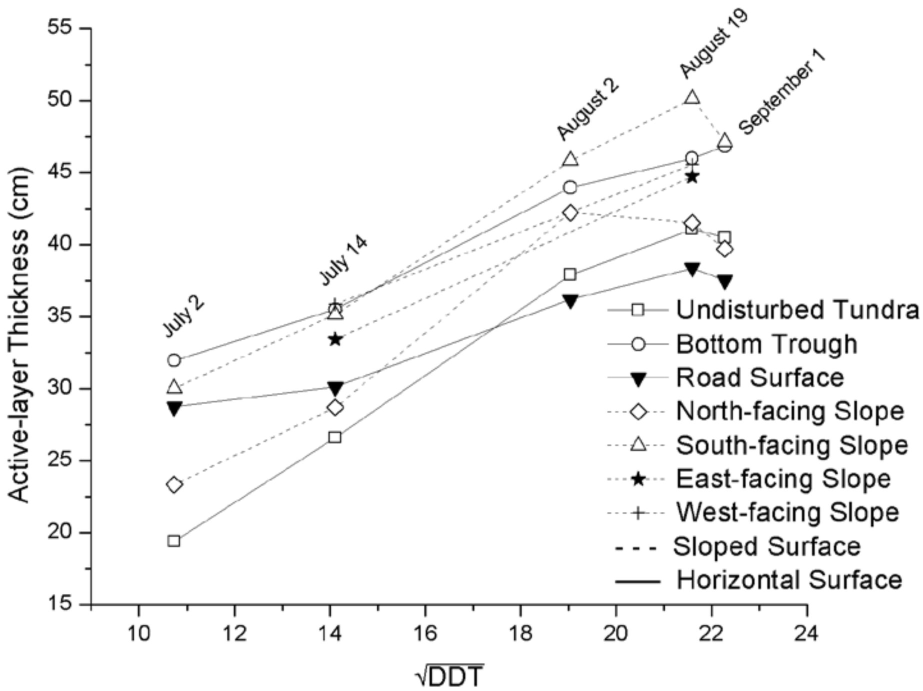


Figure 4. Thaw progression versus the square root of thawing degree-day sums (DDT) on various topographic elements of the thermokarst road throughout the summer of 1981.

3.2 Statistical analysis

Descriptive statistics were computed for all data sets. The Lilliefors (1967) test was used to examine the conformity of sample frequency distributions with the normal (Gaussian) probability density function. Four of the samples from July, when the active layer was in an early stage of development, showed minor departures from normality at the 0.1 level.

Sets of samples for each measurement date were analyzed using one-way analysis of variance (ANOVA). Because ANOVA is robust with respect to slight departures from normality and heterogeneity of variance when equal sample sizes are employed (Kirk, 1982, p.78), the samples were deemed appropriate for ANOVA procedures. Computed F values are significant at the 0.01 level for all sampling dates.

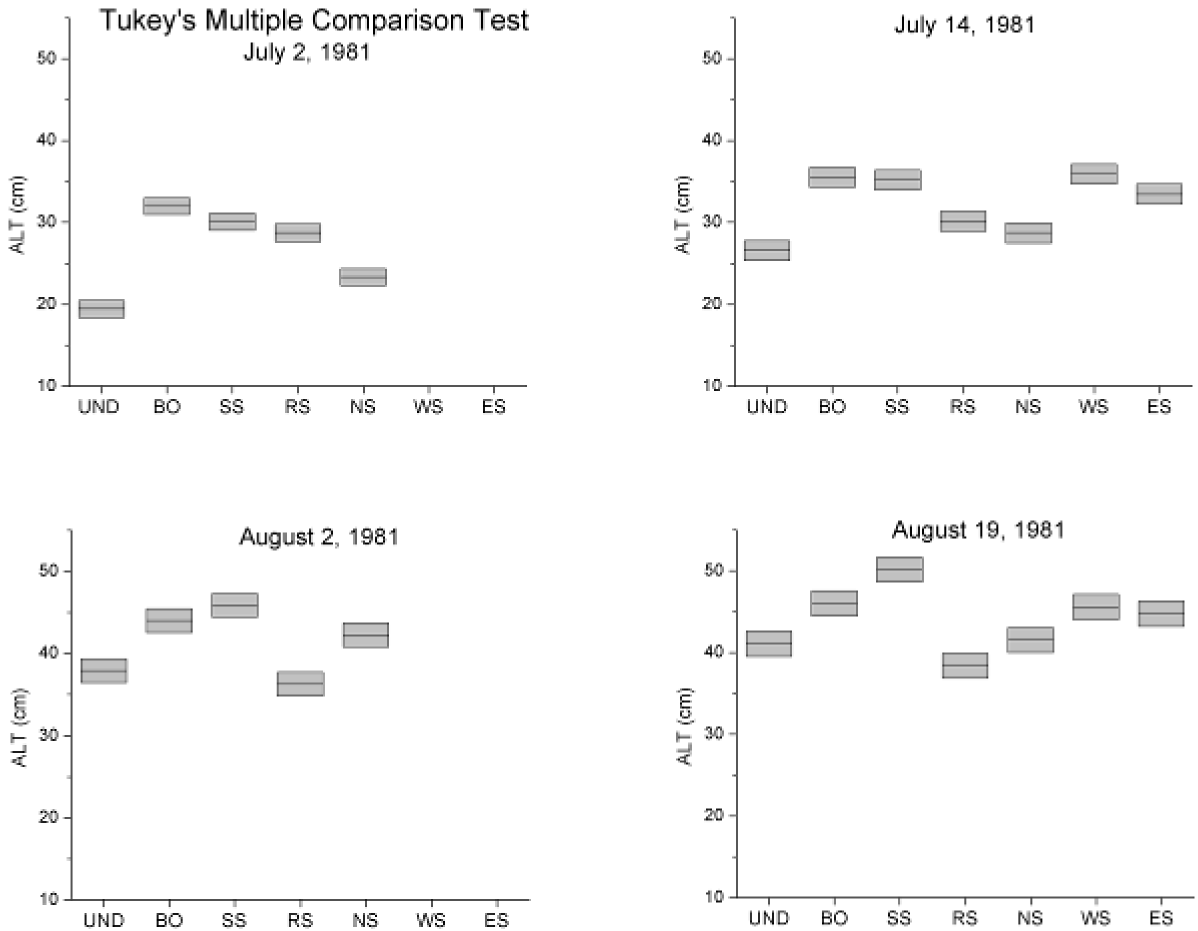
To determine which pairs of samples differ from one another, each sample was compared with all others from the same measurement date using Tukey's "honestly significant difference" (HSD; Tukey 1991; Hsu 1996) multiple comparison procedure (MCP). Comparisons were also made using Dunnett's MCP (Kirk, 1982, 112-118) to compare sample means against a control, in this case samples obtained from the undisturbed tundra.

4 RESULTS

Figure 4 shows the "Stefan relation" for the 1981 data set, i.e., thaw progression versus the square root of thawing degree-day sums on each facet of the road during the summer of 1981. At locations with relatively simple ground cover and homogeneous soil columns, the Stefan relation shows thaw penetration progressing as a linear function of the square root of accumulated degree-days. Figure 4 reflects the diverse orientations and material properties of the thaw-depth samples collected from and adjacent to the thermokarst road. Thaw progressed at divergent rates in different parts of the road, and several of the data traces cross during the summer. A pronounced decrease in the depth of thaw is also apparent between the last two sampling dates, indicating that freezeback from the top of the permafrost table (Mackay, 1979, 1984) affected most sampling locations.

Comparative analysis of mean values and assessment of their statistical significance can be achieved efficiently using box plots (Andrews *et al*., 1980). Figures 5 and 6 illustrate which facets of the thermokarst road experienced significantly different values of thaw depth at approximately two-week intervals over the summer of 1981.

Tukey's HSD (Figure 5) procedure compares each sample with all others to determine if differences exist between topographic facets. Pronounced differences in thaw depth are apparent on slopes facing various



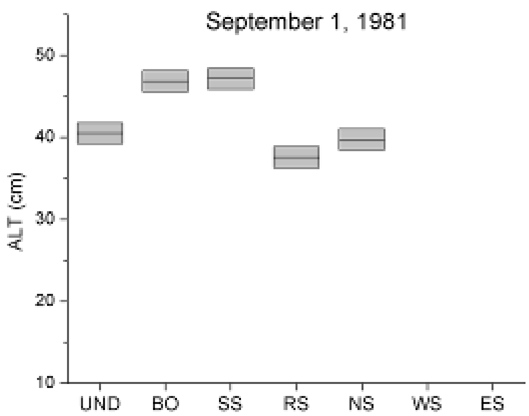


Figure 5. Summer 1981 box plots from Tukey's multiple comparison procedure, 0.05 significance level. Sample means are compared to all other sample means. Confidence intervals for each sample are displayed as the upper and lower bounds of each box, and the line through the middle of the box represents the sample mean. When any portion of the box falls into the same area on the vertical scale as another box the two are not significantly different. If the upper and lower limits of two boxes do not overlap, the corresponding samples are considered to be significantly different.

UND = undisturbed tundra

BO = bottom of "outer" (south) trough

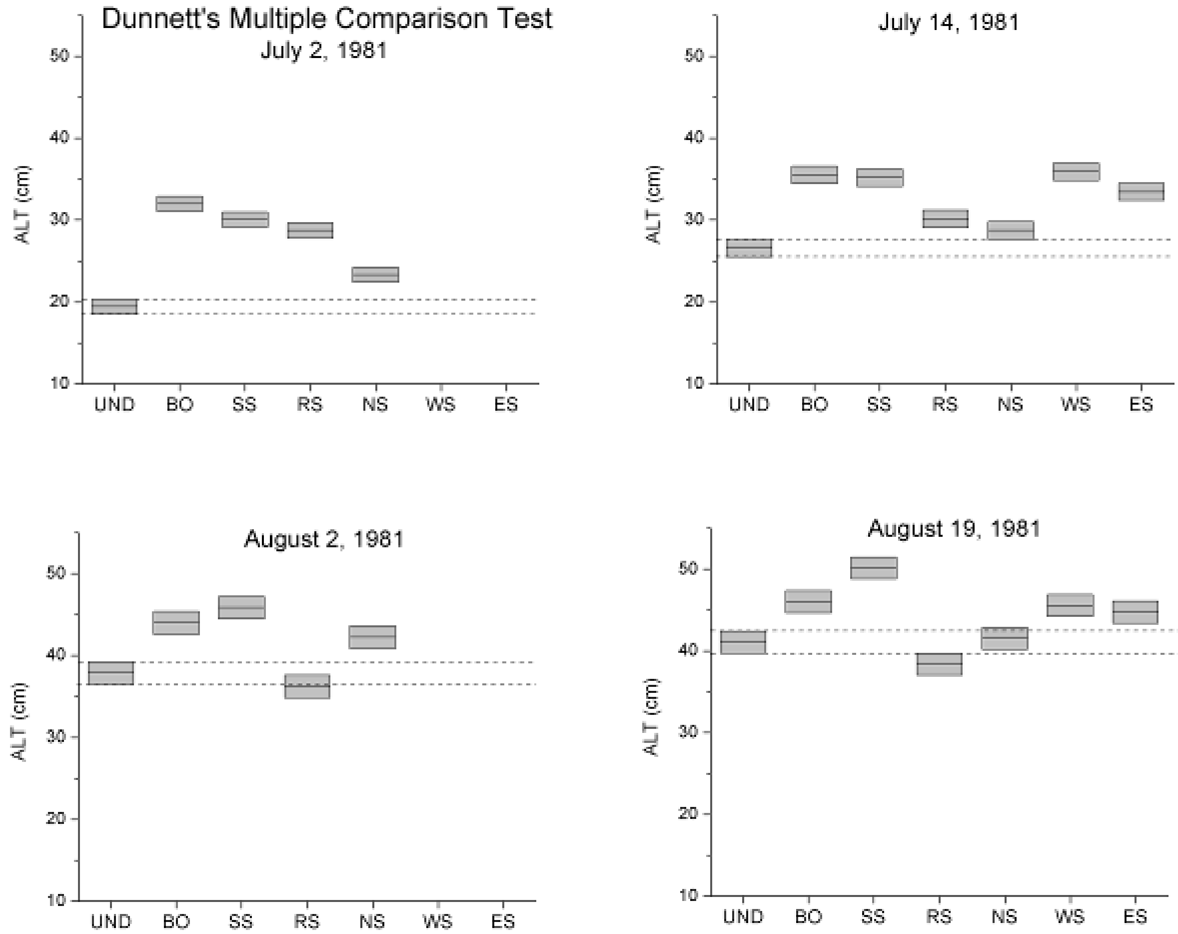
SS = south-facing slope

RS = road surface

NS = north-facing slope

WS= west-facing slope

ES = east-facing slope



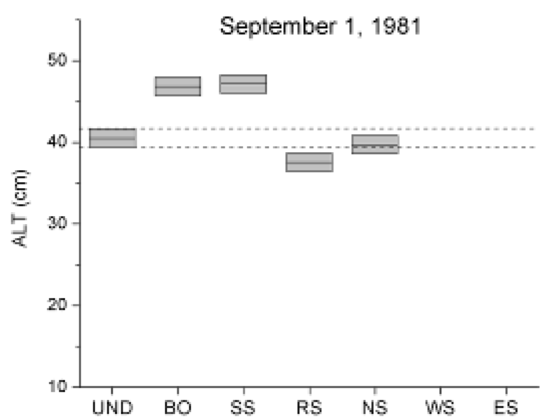


Figure 6. Box plots showing thermokarst road directional facets relative to undisturbed tundra. These figures are graphical representations of results from Dunnett's multiple comparison test, 0.05 level of significance. This procedure compares sample means to a control only; other samples cannot be compared to each other. Undisturbed tundra serves as the control and dotted lines are the bounds of the confidence interval.

UND = undisturbed tundra

BO = bottom of "outer" (south) trough

SS = south-facing slope

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directions, and rankings change over the course of the thaw season.

Dunnett's test (Figure 6) uses the undisturbed tundra as a "control," i.e., as the basis for comparison with thaw depth on other slope facets. Dashed lines show the calculated confidence interval for the undisturbed tundra. Any sample that does not intersect the confidence interval of the undisturbed tundra can be considered significantly different than undisturbed tundra.

Results from MCPs for the thaw-depth data show that on 2 July the undisturbed tundra had experienced significantly shallower thaw than all other samples. By 2 August, the undisturbed tundra and the road surface were not significantly different, having a similarly thin active layer, while the north-facing slope had significantly greater thaw than the undisturbed tundra. Maximum thaw values were recorded on 19 August. The south-facing slope had the greatest average thaw on this date. Tukey's HSD shows the depth of thaw on the south-facing exposure to be significantly greater than on all other slopes. The 19 August and 1 September graphs for Dunnett's procedure show that thaw depth on the road surface was significantly less than that of the undisturbed tundra and north-facing slope, which are not significantly different. The triple organic layer on the road surface acts to insulate the underlying permafrost, even though this surface begins to thaw before the others in late spring, owing to its greater exposure to deflation of snow by wind.

The ALT data demonstrate that, for road facets with similar material properties, north-facing slopes experience minimal end-of-season thaw and south-facing slopes experience the greatest thaw. The similarity of the samples from undisturbed tundra and north-facing slope, in particular, is remarkable. Even at 70^{o}N, a north-facing exposure compensates for the absence of insulation provided by a vegetation cover and organic layer.

5 CONCLUSIONS

Active-layer thickness is modified by topoclimatic processes and parameters at the surface, including air and soil temperature on each exposure, solar radiation, surface cover, and slope angle.

This study demonstrates that slope aspect exerts a strong control over active-layer thickness, even at high latitudes, with south-facing slopes thawing to greater depth than north-facing slopes and northern exposure compensating for the lack of an insulating layer of vegetation.

When 1981 averages are compared to those from 1995, 2006, and 2007 (Nelson and Schimek, unpublished data), ALT is 10-15 cm greater in the latter years.

The triple organic layer beneath the road surface acts as an insulator, resulting in decreased active-layer thickness values even though this surface begins thawing sooner, owing to its earlier emergence from snow cover. The rate of thaw on the road surface decreases significantly when the thawing front contacts the buried organic layers.

Although features such as the road investigated in this study impart great damage in permafrost environments, they provide interesting opportunities for geomorphological and topoclimatic field experiments in areas of otherwise homogeneous terrain.

ACKNOWLEDGEMENTS

FEN extends thanks to Cecil Goodwin, Jeanne Makihara, Jim Akerman, and Therese Spies for collaborative assistance along the very long road leading to this report.

REFERENCES

Andrews, H. P., Snee, R. D., and Sarner, M. H. 1980. Graphical display of means. *The American Statistician* , 34(4): 195-199.

Anonymous. 1969. Alaskans built 400-mile road to North Slope in one season. *Contractors & Engineers Magazine,* 66(4): 42-43.

Anonymous. 1970. Winter road in northern Alaska, 1969-70. *The Polar Record,* 15(96): 352-355.

Haynes, J.B. 1972. North Slope oil: physical and political problems. *The Professional Geographer,* 24(1): 17-22.

Hsu, J.C. 1996. *Multiple Comparisons: Theory and Methods*. Chapman & Hall, New York, NY, USA, 277 pp.

Johns, G.E. 1969. A winter road. *The Northern Engineer*. 1(3): 12-13.

Kirk, R.E. 1982. *Experimental Design: Procedures for the Behavioral Sciences*. Wadsworth, Inc., Belmont, CA, USA: 911 pp.

Lilliefors, H. W. 1967. On the Kolmogorov-Smirnov test for normality with mean and variance unknown. *Journal of the American Statistical Association,* 62(318): 399-402.

Mackay, J.R. 1977. Probing for the bottom of the active layer. *Geological Survey of Canada Paper 77-1A*, 327-328.

Mackay, J.R. 1979. Uplift of objects by an upfreezing surface. *Canadian Geotechnical Journal*, 16: 609-613.

Mackay, J.R. 1984. The frost heave of stones in the active layer above permafrost with downward and upward freezing. *Arctic and Alpine Research*, 16: 439-446.

Nelson, F. E., and Outcalt, S. I. 1982. Anthropogenic geomorphology in northern Alaska. *Physical Geography* , 3 (1): 17-48.

Nelson, F.E., Shiklomanov, N.I., Mueller, G.R., Hinkel, K.M., Walker, D.A., and Bockheim, J.G. (1997). Estimating active-layer thickness over a large region: Kuparuk River basin, Alaska, U.S.A. *Arctic and Alpine Research,* 29(4): 367-378.

Raynolds, M.K., Walker, D.A., Ambrosius, K.J., Brown, J., Everett, K.R., Kanevskiy, M., Kofinas, G.P., Romanovsky, V.E., Shur, Y., and Webber, P.J. 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay

Oilfield, Alaska. *Global Change Biology*, 20(4): 1211-1224.

Thornthwaite, C. W. 1954. Topoclimatology. In T. W. Wormell et al. (Ed.), *Proceedings of the Toronto Meteorological Conference 1953*. Royal Meteorological Society , London, UK, 227-232.

Tukey, J. W. 1991. The philosophy of multiple comparisons. *Statistical Science,* 6(1): 100-116.

Wahrhaftig, C. 1965. Physiographic Divisions of Alaska. *U.S. Geological Survey Professional Paper 482*, 52 pp. + maps, appendices.

Walker, D.A., Everett, K.R., Webber, P.J., and Brown, J. 1980. Geobotanical Atlas of the Prudhoe Bay Region, Alaska. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA, *CRREL Report 80-14*, 69 pp.

Walker, D.A., Webber, P.J., Binnian, E.F., Everett, K.R., Lederer, N.D., Nordstrand, E.A., and Walker, M.D. 1987. Cumulative impacts of oil fields on northern Alaskan landscapes. *Science*, 238(4828): 757-761.