Sensitivity of active-layer development to winter conditions north of treeline, Mackenzie delta area, western Arctic coast

GEO2010 CALGARY, ALBERTA in the New West

C. R. Burn & Y. Zhang
Department of Geography and Environmental Studies – Carleton University, Ottawa, Ontario, Canada

ABSTRACT
A simulation of the ground thermal regime in undisturbed tundra near the western Arctic coast has been validated by reproducing changes in ground temperatures between 1970 and 2009 to 53-m depth. The model has been used to determine the response of ground temperatures and active-layer thickness to potential climate warming up to 2100. The majority of the warming is in autumn and winter. Permafrost is sustained under this climate scenario, but a considerable increase in active-layer thickness may occur, because ground cooling is reduced in winter.

RÉSUMÉ
Une simulation du régime thermique du sol, dans une toundra non-remaniée près de la côte de l'arctique de l'ouest, a été validé en reproduisant les changements de températures du sol, jusqu'à profondeur de 53 mètres entre 1970 et 2009. Le modèle utilisé a déterminé la réaction des températures du sol, et l'épaisseur de la couche active, au réchauffement climatique possible jusqu'en 2100. La majeure partie du réchauffement dans le scenario survient en automne et en hiver. Le pergélisol est conservé sous ce climat, mais une augmentation considérable de l'épaisseur de la couche active est possible, parce que le refroidissement du sol pendant l'hiver est réduit.

1 INTRODUCTION

The response of permafrost to climate change is of considerable scientific and engineering interest (Osterkamp 2007; Hayley and Horne 2008). There are several initiatives coordinated by the Geological Survey of Canada to monitor and document the increases in ground temperature currently observed throughout northern Canada (Smith et al. 2010). Climate is the single most important influence on ground temperatures, but ground surface conditions and soil properties create considerable local variation in the ground thermal regime (Smith et al. 2008; Burn and Zhang 2009). These factors also influence the depth of the seasonally thawed active layer (Smith et al. 2009).

The majority of ground temperature series from permafrost terrain published in Canada comprise, at most, about 20 years of data (Smith et al. 2005, 2010). Two recent contributions provide a longer record concerning conditions near the western Arctic coast. First, in the Mackenzie Delta area it has been possible to summarize the regional response to climate change in a range of terrain units due to the benchmark summary of regional ground temperatures for the late 1960s and early 1970s published by J.R. Mackay (1974). Burn and Kokelj (2009, Figs. 10 & 11) present a comparison of the mean annual ground temperatures reported by Mackay (1974) with measurements for 2002-08 at over 60 sites in the area. They record warming of 2° to 3°C in tundra environments of the Tuktoyaktuk Coastlands, and 1° to 1.5°C in the boreal forest. Second, Burn and Zhang (2009) have reconciled climate warming over the 20th century at Herschel Island with the ground thermal regime in permafrost using a numerical simulation.

Deepening of the active-layer has important ecological, geomorphic, and geotechnical consequences due to thawing of the ice-rich zone at the top of permafrost (Mackay 1970; Pullman et al. 2007). Climate warming may lead to increases in both ground temperature and the thickness of the active layer (Burn and Kokelj 2009). While temperature is readily recognized as a function of climate year-round, active-layer thickness is predominantly associated, in practice, with thaw-season climate alone, and is characteristically modeled as a function of accumulated thawing degree-days using the Stefan solution (e.g., Andersland and Ladanyi 1994; Mackay 1995; Smith et al. 2009). The importance of variation in winter conditions for active-layer development is not commonly recognized (Burn 1997; Mackay and Burn 2002). In this paper, we demonstrate the sensitivity of thaw depth to conditions during the freezing season by projecting the impact of potential future climate change on active-layer thickness. We use a calibrated and validated simulation of the response of permafrost to climate change in the outer Mackenzie delta area driven by a scenario of climate warming for 2011-2100.

2 ILLISARVIK

2.1 Illisarvik and Richards Island, NWT.

The Illisarvik drained-lake experiment is the world's longest-running field experiment in permafrost terrain (Mackay 1997). It was established in 1978 to study the geophysical and geotechnical effects of permafrost aggradation *ab initio*. The site also allows year-round investigation of conditions in the undisturbed tundra surrounding the drained lake basin (e.g., Mackay and Burn 2002).

Illisarvik is on the West Point of Richards Island in the outer Mackenzie Delta area (Fig. 1). The ground has a veneer of till, approximately 2-3 m thick, on top of ice-bonded sand. The surface is hummocky, and supports low-shrub tundra vegetation. Most of the willows on the tundra are less than 30 cm high, but taller alder shrubs have established themselves on slopes where snow drifts accumulate. The conditions are representative of northern Richards Island, where several deep exploration wells were drilled in the 1960s and 1970s. Ground temperature profiles to hundreds of metres depth are published from some of these holes (e.g., Taylor et al. 1982).

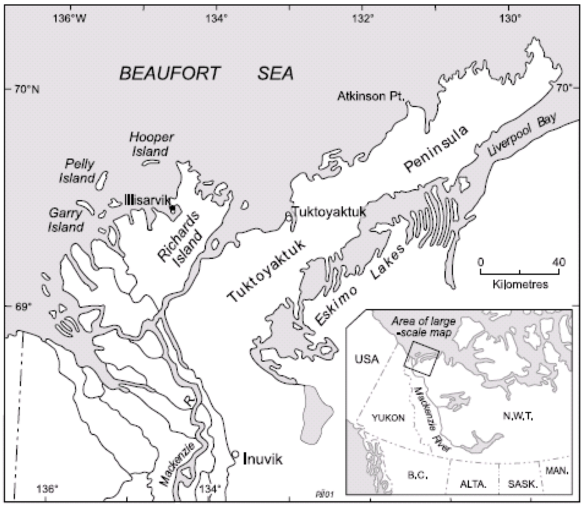

Figure 1. Location of Illisarvik (Mackay & Burn 2002, Fig. 1, reproduced with permission of NRC Research Press)

2.2 Climate Change at Illisarvik

The closest climate station to Illisarvik is at Tuktoyaktuk, approximately 60 km to the east. A climate record from Tuktoyaktuk is available since 1948, but there are gaps in the record and the station has been moved several times. However, the data are sufficient to obtain correlations with other stations in the region, principally at Inuvik and Aklavik, but also Fort McPherson (Burn and Kokelj 2009, Table 1).

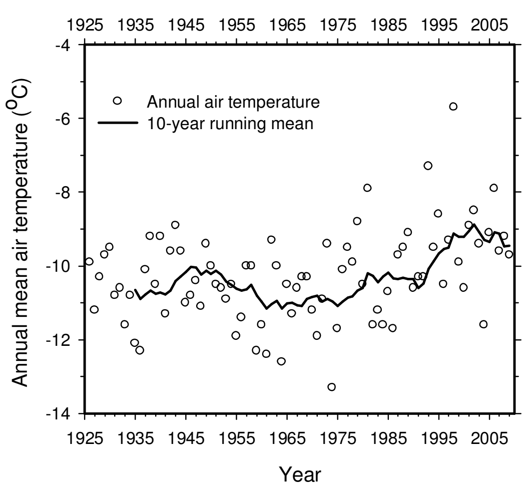

Figure 2. Annual mean air temperature and running mean for the previous 10 years at Tuktoyaktuk, N.W.T., 1926-2009.

Figure 2 presents a reconstruction of annual mean air temperatures for the Tuktoyaktuk area using the extant records from the stations at Tuktoyaktuk, with gaps filled through monthly transfer functions from the other stations. The record shows a relatively stable series for 1926-1970, and a progressive increase in temperature, of about 2°C since then. The majority of this warming has been in autumn and winter, as at Herschel Island (Burn and Zhang 2009).

We have measured air temperature at Illisarvik since 2004 using a miniature data logger placed in a radiation shield. This logger has recorded air temperature five times each day, and daily means have been computed for the series. Figure 3 presents a scatter plot of the daily means measured at Illisarvik and Tuktoyaktuk for 2004-2007. The data from these sites are sufficiently well related that we may consider the long-term climate record from Tuktoyaktuk to be representative also of climate change at Illisarvik.

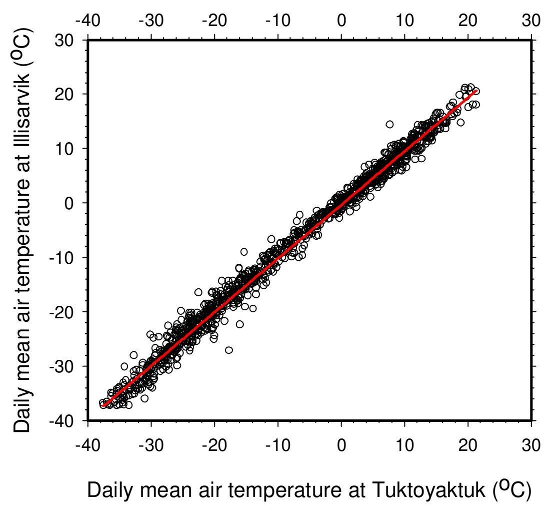

Figure 3: Correlation between daily mean air temperatures observed at Illisarvik and Tuktoyaktuk during 2004-2007. The equation of the least-squares linear regression line is T(Illi) = 0.99 T(Tuk) – 0.4. The coefficient of determination is 0.99.

2.3 Field Observations

Two holes, one to 50-m depth and the other to 53-m depth were drilled in August 2006 and July 2008 in the tundra near Illisarvik to obtain thermal evidence of the response of permafrost to recent climate change. The sites are about 0.8 km apart, and are both in level terrain, although one is near the top of a short slope. The holes were drilled by water jet, and 1-inch steel pipe was installed in the holes as casing for the thermistor

cable. The holes were full of water at the termination of drilling. Calibrated thermistor beads (BetaTHERM 2.2K3A1A) were spaced at 5-m intervals to the base of each hole. The steel casings were filled with non-convective fluid to ensure contact between the sensors and the surrounding ground. Temperature profiles were obtained manually in April and late August 2009. The temperatures obtained
from these holes are uniformly separated by 0.5°C and present very similar gradients throughout the profile. As a result, we only present data from the deeper hole in this paper.

In 2006, a hole to 6-m depth was drilled close to the 50-m profile in order to obtain the annual ground temperature cycle at the site by data logger. The hole was also cased with steel pipe. Ground temperatures at this site have been recorded by an Onsett Corp. HOBO H8 series data logger using Onsett TMC20-HD sensors. In 2008, a thermistor cable (TMC6-HD) was installed at 1-m depth at the site in a hole drilled with a hand-held CRREL drill, and backfilled with native soil. Data from these near-surface sensors have been used to calibrate a ground thermal simulation for the area.

3 MODELLING

The response of permafrost at Illisarvik to climate change since 1926 has been examined using a one-dimensional heat conduction model developed from the simulations presented in Zhang et al. (2008) and Burn and Zhang (2009). The model has 120 soil layers with a node spacing of 0.05 m near the surface progressively increasing to 10 m at the maximum depth (508 m). In winter, the model adds dynamic snow layers with spacing of 0.05 - 0.1 m. A linear snow development function controlled by four critical dates (Start of accumulation, maximum thickness, initiation of melt, and end of snow cover) and maximum snow depth was prescribed for each snow season. The four dates in 1955-2009 were obtained from observations each year at Tuktoyaktuk and Aklavik. The mean for each date was used for years without such data. Maximum snow depths for 1983-1988 and 1996-2009 were observed from a snow course at Illisarvik. Their mean value (20 cm) was used for all other years.

The soil was saturated quartz sand with a porosity of 0.30. A 10-cm thick organic layer with porosity of 0.9 was simulated on top of the mineral soil. An excess-ice content of 30% was prescribed between 1 and 3 m depth. Soil thermal properties were determined from its components (organic and mineral material, air, water and ice) by De Vries's method (Farouki, 1986). The model was driven by daily snow or soil surface temperatures derived from air temperature series. Snow surface temperature was assumed to be the same as air temperature, and soil surface temperature during the snow-free period was assigned with an n-factor of 0.8. The geothermal flux at the bottom of the profile (508 m) was 0.05 W m^{-2} (Majorowicz et al. 1990).

The model was calibrated to simulate near-surface temperatures at 1-m and 5-m depths, as recorded for 2007-09 in the two holes (Fig. 4). The calibration involved small adjustments to soil mineral conductivity, excess ice content, water content of the organic layer, and organic-layer thickness. It was spun up to equilibrate deep temperatures using mean conditions for air temperature and snow cover from the climate record for 1926-1970. Figure 5a illustrates the equilibrium simulation and equilibrium ground temperatures to 325-m depth presented by Taylor et al. (1982) for the Kilagmiotak F-48 well on central Richards Island (Earth Physics Branch record 165), 17 km from Illisarvik. The coincidence of model equilibrium profile and field data validates the thermal properties and geothermal flux in the simulation. When the climate recorded for the area for 1926-2009 was applied to the equilibrium state, current ground temperatures at Illisarvik to 53-m depth were reproduced (Fig. 5b), validating the surface modeling in the simulation.

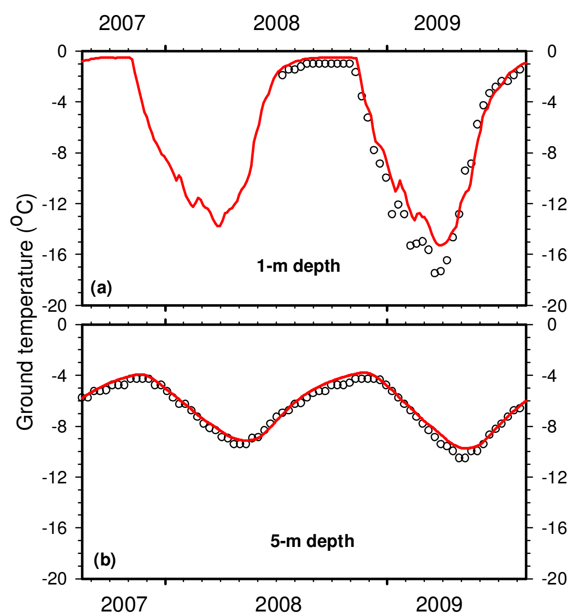

Figure 4: Calibration of model using observed upper ground temperatures at Illisarvik from Aug. 2007 to Aug. 2009. Observations (open circles) are plotted every 10 days for clarity.

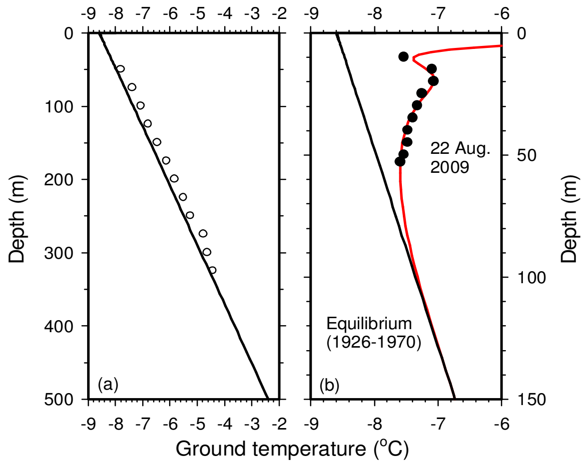

Figure 5: Validation of simulation. (a) Ground temperatures to 325-m depth from Kilagmiotak F-48 (open circles) and simulated profile at equilibrium with mean climate of 1926-70; (b) Near-surface ground temperatures from Illisarvik on 22 Aug. 2009 (closed circles) with profile simulated following climate of 1926-22 Aug. 2009. Note the different scales of the two figures.

4 CLIMATE CHANGE

Climate change scenarios for various parts of northern Canada have been produced by Environment Canada's Climate Change Scenarios Network (CCCSN). Table 1 presents projections of changes in future mean seasonal temperature for the western Arctic during the twenty-first century under a moderate emissions scenario. The changes represent increases from the 1971-2000 baseline. The projections were obtained from an ensemble mean of four global climate models (GCMs) that best reproduced the baseline climate for the region selected from a suite of GCMs used by the international community (see www.cccsn.ca). The projections suggest that the greatest change in seasonal temperatures will be in autumn and winter, with relatively little change in summer.

Table 1. Future air temperature increases (°C) above 1971-2000 baseline for western Arctic Canada, 65°N to 70°N, as projected by CCCSN ensemble mean under a moderate emissions scenario (CSA 2010).

Period	Winter	Spring	Summer	Fall	Annual
2011-2040	1.4	1.0	0.5	1.4	1.1
2041-2070	3.8	2.5	1.6	4.0	3.0
2071-2100	6.6	3.7	2.7	5.3	4.6

A projection of annual mean temperatures for the outer Mackenzie Delta area has been made using these scenarios. The changes projected in Table 1 have been modeled on a seasonal basis as a linear increase for each 30-year period. The increase in Table 1 appears at the mid point of each 30 year interval. These annual changes have been applied to the record from 1971-2000 in order to simulate climate variation. On a daily basis, the synthetic series of this future climate included (Fig. 6): the record for 1980-2009; data for 2009 repeated for 2010; ramped seasonal changes, simulated as a linear trend over each thirty-year interval, 2011-40, 2041-70, and 2071-2100.

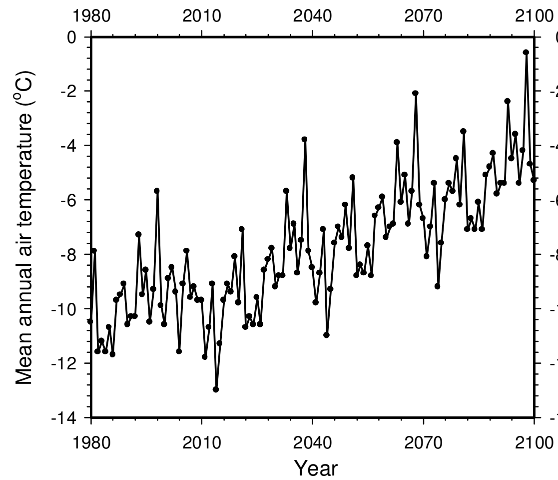

Figure 6: Annual mean air temperature for the western Arctic coast over the 21st century using CCCSN ensemble models with a moderate emissions scenario.

5 THE ACTIVE LAYER

5.1 Active-layer Development at Illisarvik

Active-layer deepening is a key response of permafrost terrain to climate warming, and is monitored internationally through the CALM program (Brown et al. 2000). The longest continuous measurements of active-layer thickness in Canada are from Illisarvik, both in the drained lake basin and along a 12-point course on the adjacent tundra (Mackay and Burn 2002). The mean depth along the tundra course for 1983-2009 is presented in Fig. 7. These data are determined from the mean of five measurements in the top of hummocks at each site along the course. Inter-annual variability is only partially (27 per cent) explained by variation in summer temperature for this series (Burn and Kokelj 2009). Since 1983, active-layer thickness has increased along this transect.

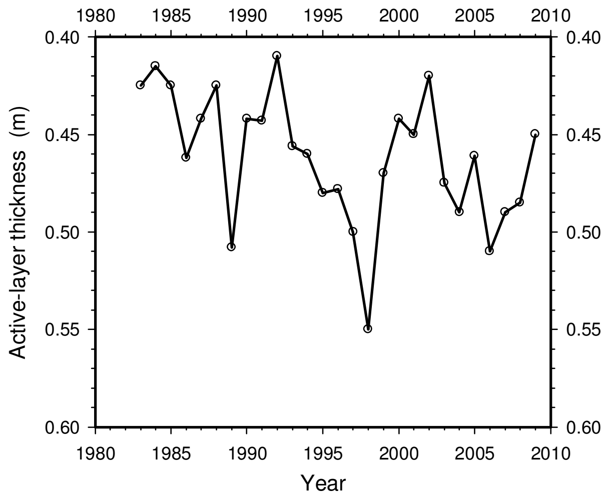

Figure 7: Mean active-layer thickness at 12 sites along the tundra course at Illisarvik (1983-2009).

Active-layer thickness may be obtained from the simulations described in this paper, by determining the annual depth of penetration of the 0℃ isotherm. This depth will not be precisely the value displayed in Fig. 7, because: (1) the field determinations are made by probing and likely penetrate into ground below 0℃ (Mackay 1977, Burn 1998); (2) the field data are mean values of twelve sites in hummocky ground, each with a unique stratigraphy, vegetation, and snow cover (Mackay and Burn 2002), while the simulation is of an ideal site without microrelief; and (3) the simulation does not include consolidation due to thawing of excess ice. The latter means that, in the simulation, the active layer is reset annually, while, in the field, degradation of near-surface permafrost proceeds more rapidly as water released by thaw of permafrost is removed (Mackay 1970). Nevertheless, Fig. 8 shows the correspondence between the field index of active-layer thickness and the simulated values. Figure 8 also displays the relation between measured active-layer depth and a calculation of depth with the Stefan solution, using the same thermal properties as in the simulation. The Stefan solution does not compute the heat required to warm the ground to 0℃ or the sensible heat supplied in summer to raise the temperature of the active layer above 0℃, instead all heat is used to melt ice. Hence the measured depth and the depth calculated by numerical simulation are less than the estimate with the Stefan method.

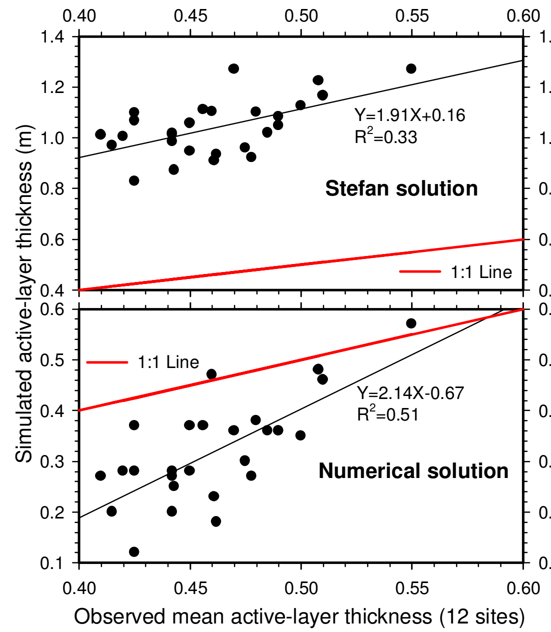

Figure 8: Regressions between mean active-layer thickness along the tundra course at Illisarvik and depths derived by the Stefan solution and from the numerical solution, 1983-2009.

5.2 Active-layer Development With Climate Change

Figure 9 shows the active-layer depth calculated by the numerical simulation of the ground thermal regime at Illisarvik under the climate scenario shown in Fig. 6. As discussed elsewhere (Burn and Zhang 2010), the model does not predict that the mean annual ground temperature will rise above 0℃ for the tundra at Illisarvik, but it does predict a substantial increase in active-layer depth, even though the warming is dominantly in autumn and winter. Table 2 presents the mean active-layer depths simulated by Stefan and numerical methods during the period with observations and for the three future intervals. The results show that active-layer thickness more than doubles under the numerical simulation, with climate warming year-round. The calculated increase is only 25% with the Stefan method, partly because active-layer thickness is overestimated at present by this method, and therefore a small change in summer temperature will have little effect on thaw depth.

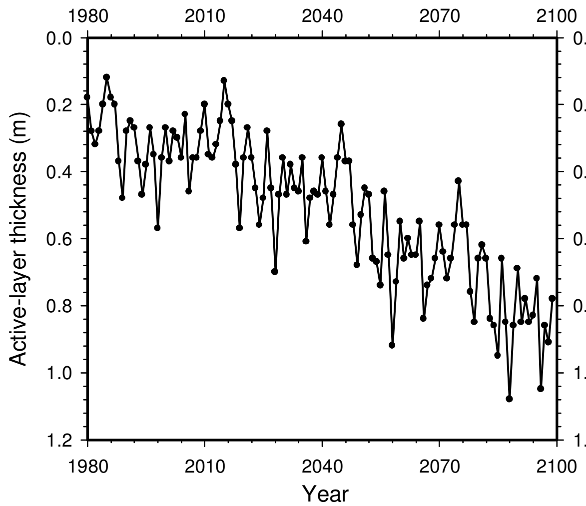

Figure 9: Active-layer thickness over the 21st century for Illisarvik simulated by a numerical model.

Table 2. Mean observed and calculated active-layer thickness (cm) and standard deviation (STD, cm) for 1983-2009 and three 30-year periods in the 21st century.

Period	Method	Mean	STD
1983-2009	Observation[1]	46	3
	Stefan	104	11
	Numerical	32	10
2011-2040	Stefan	109	11
	Numerical	40	13
2041-2070	Stefan	120	10
	Numerical	58	15
2071-2100	Stefan	130	10
	Numerical	76	15

[1]mean of 12 sites along a monitoring course at Illisarvik.

Table 3. Changes of mean active-layer thickness (cm) for three 30-year periods compared to the mean of 1980-2009 as simulated by the numerical model under several climate change (CC) scenarios.

CC scenarios	2011-2040	2041-2070	2071-2100
Same as in Table 1	8	26	44
Annual mean changes applied to all seasons	11	32	54
Summer mean changes applied to all seasons	6	16	30
Changes as in Table 1 except none in summer	5	17	26
Changes only in summer	4	9	17

The sensitivity of active-layer depth to climate warming in various seasons is summarized in Table 3. For this analysis, the ramped warming driving the simulation was adjusted seasonally, as described, in order to investigate the importance of changes to summer conditions in comparison with the other seasons. Table 3 suggests that under this climate simulation, more than half of the increase in active-layer depth is due to changes in the freezing season, and that these combine with summer warming to compound active-layer deepening.

5.3 Energy Partitioning

In order to determine the energetic basis for the results in Table 3, a budget of sensible and latent heat has been computed for each year of the simulation presented in Fig. 6. The sink of sensible heat has been estimated from the change in ground temperature between the date of the mean minimum temperature profile and the point at which warming of the active layer ceases in summer. The sensible heat arrives from the atmosphere and warms the ground to the depth of zero annual amplitude. A correction was made for the contribution of geothermal heat. The latent heat was calculated from the maximum depth of the active layer and the water content specified in the simulation.

Figure 10 shows the changing use of heat entering the active layer over the period of simulation. Total energy entering the ground increases due to climate warming, but the consumption of sensible heat falls as rising autumn and winter temperatures delay freeze-back and restrict ground cooling in winter. As a result, the energy available for thawing increases and the latent heat component rises. In 1980-2009, the ratio of latent to sensible heat was calculated at about 30%, but by 2071-2100 the scenario forecasts a ratio close to unity (Table 4).

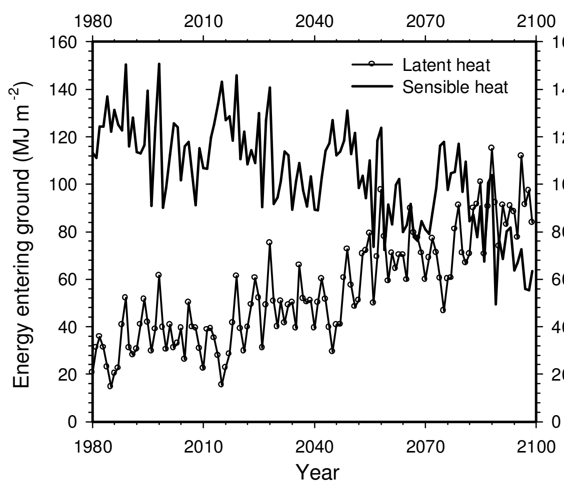

Figure 10. Partitioning of energy annually entering the ground as sensible or latent heat over the period of simulation, 1980-2100.

Table 4. Ratio of latent to sensible energy consumption during four 30-year periods as simulated by the numerical model under climate changes as in Table 1.

Period	1980-2009	2011-2040	2041-2070	2071-2100
Ratio	0.30	0.38	0.62	0.95

6 CONCLUSION

The simulations presented in this paper demonstrate that active-layer development is sensitive to changes in climate outside the thawing season. At present, the sensible heat required to raise ground temperatures to 0°C to enable thawing of the active layer, to warm the ground below the active layer, and to raise the active layer above 0°C once thawed, dominates the energy budget of the ground temperature envelope. As climate warms and there is less cooling in winter, less sensible heat is required to warm the ground annually, and, as a result, more energy is available for deepening the active layer.

ACKNOWLEDGEMENTS

The research has been supported by the Natural Sciences and Engineering Research Council, the Government of Canada's Program for the International Polar Year, the Polar Continental Shelf Project (PCSP), Natural Resources Canada, and the Aurora Research Institute, Aurora College. We thank Julian Kanigan, Genviève Hétu, Andrew Fehr, John Kearns, and Logan Roots for field assistance with drilling. Long-term assistance in the western Arctic has been given by Peter Morse and Douglas Esagok. We thank J.Ross Mackay and Steve Kokelj for many helpful comments and discussions at Illisarvik and elsewhere. A conversation with Don Hayley in December 2009 stimulated this paper, which is PCSP contribution 01110.

REFERENCES

Andersland, O.B., and Ladanyi, B. 1994. An introduction to frozen ground engineering. Chapman and Hall, New York.

Brown, J., Hinkel, K.M., and Nelson, F.E. 2000. The circumpolar active layer monitoring (CALM) program: Research designs and initial results. Polar Geography, 24: 165-258.

Burn, C.R. 1997. Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western Arctic coast, Canada. Canadian Journal of Earth Sciences, 34: 912-925.

Burn, C.R. 1998. The active layer: two contrasting definitions. Permafrost and Periglacial Processes, 9: 411-416.

Burn, C.R., and Kokelj, S.V. 2009. The environment and permafrost of the Mackenzie Delta area. Permafrost and Periglacial Processes, 20: 83-105.

Burn, C.R., and Zhang, Y. 2009. Permafrost and climate change at Herschel Island (Qikiqtaruk), Yukon Territory, Canada. Journal of Geophysical Research, 114: F02001. doi: 10.1029/2008JF001087.

Burn, C.R., and Zhang, Y. 2010. Permafrost response to climate change at Illisarvik, western Arctic coast, Canada. *In* Thermal state of frozen ground in a changing climate during the IPY, Abstracts from the Third European Conference on Permafrost, Longyearbyen, Svalbard, 13-17 June 2010. p. 91.

CSA (Canadian Standards Association). 2010. Technical guide: Overview of Key Considerations Relating to Community Infrastructure, Permafrost & Climate Change. Canadian Standards Association, Mississauga, Ont.

Farouki, O.T. 1986. Thermal properties of soils. Trans Tech, Clausthal-Zellerfeld, Germany.

Hayley, D.W., and Horne, B. 2008. Rationalizing climate change for design of structures on permafrost: a Canadian perspective. *In* Proceedings, Ninth International Conference on Permafrost, Fairbanks, Alaska. Edited by D.L. Kane and K.M. Hinkel. Institute of Northern Engineering, University of Alaska Fairbanks, Vol.1, pp. 681-686.

Mackay, J.R. 1970. Disturbances to the tundra and forest tundra environment of the western Arctic. Canadian Geotechnical Journal, 7: 420-432.

Mackay, J.R. 1974. Seismic shot holes and ground temperatures, Mackenzie Delta area, Northwest Territories. *In* Report of Activities, Part A. Geological Survey of Canada, Paper 74-1A, pp. 389-390.

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

Mackay, J.R. 1995. Active layer changes (1968 to 1993) following the forest-tundra fire near Inuvik, N.W.T., Canada. Arctic and Alpine Research, 27: 323-336.

Mackay, J.R. 1997. A full-scale field experiment (1979-1995) on the growth of permafrost by means of lake drainage, western Arctic coast: a discussion of the method and some results. Canadian Journal of Earth Sciences, 34: 17-33.

Mackay, J.R., and Burn, C.R. 2002. The first 20 years (1978-1979 to 1998-1999) of active-layer development, Illisarvik experimental drained lake site, western Arctic coast, Canada. Canadian Journal of Earth Sciences, 39: 1657-1674.

Majorowicz, J.A., Jones, F.W., and Judge, A.S. 1990. Deep subpermafrost thermal regime in the Mackenzie Delta basin, northern Canada – Analysis from petroleum bottom-hole temperature data. Geophysics, 55: 362-371.

Osterkamp, T.E. 2007. Characteristics of the recent warming of permafrost in Alaska. Journal of Geophysical Research, 112: F02S02. doi:10.1029/2006JF000578.

Pullman, E.R., Jorgenson, M.T., and Shur, Y. 2007. Thaw settlement in soils of the Arctic Coastal Plain, Alaska. Arctic, Antarctic, and Alpine Research, 39: 468-476.

Smith, S.L., Burgess, M.M., Riseborough, D., and Nixon, M. 2005. Recent trends from Canadian permafrost thermal monitoring network sites. Permafrost and Periglacial Processes, 16: 19-30.

Smith, S.L., Burgess, M.M., and Riseborough, D.W. 2008. Ground temperature and thaw settlement in frozen peatlands along the Norman Wells pipeline corridor, NWT Canada: 22 years of monitoring. *In* Proceedings, Ninth International Conference on Permafrost, Fairbanks, Alaska. Edited by D.L. Kane and K.M. Hinkel. Institute of Northern Engineering, University of Alaska Fairbanks, Vol.2, pp. 1665-1670.

Smith, S.L., Wolfe, S.A., Riseborough, D.W., and Nixon, F.M. 2009. Active-layer characteristics and summer climatic indices, Mackenzie Valley, Northwest Territories, Canada. Permafrost and Periglacial Processes, 20: 201-220.

Smith, S.L., Romanovsky, V.E., Lewkowicz, A.G., Burn, C.R., Allard, M., Clow, G.D., Yoshikawa, K., and Throop, J. 2010. Thermal state of permafrost in North America - A contribution to the International Polar Year. Permafrost and Periglacial Processes, 21: in press.

Taylor, A.E., Burgess, M., Judge, A.S., and Allen, V.S. 1982. Canadian geothermal data collection – Northern wells 1981. Earth Physics Branch, Energy Mines and Resources Canada.

Zhang, Y., Carey, S., and Quinton, W. 2008. Evaluation of the algorithms and parameterizations for ground thawing and freezing simulation in permafrost regions. Journal of Geophysical Research, 113: D17116, doi:10.1029/2007JD009343.