Ground temperature variation with snow, Kendall Island Bird Sanctuary, outer Mackenzie Delta, Northwest Territories

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ABSTRACT
Near-surface ground temperatures in the Kendall Island Bird Sanctuary (KIBS), investigated from 2005 to 2009, were principally influenced by snow depth. The snow pack evolves primarily by wind redistribution and follows the same spatial pattern annually. Snow depth was dominantly influenced by topography in uplands and vegetation height in the alluvial plain. Ground temperatures and active-layer thicknesses, and their ranges, were greater at the alluvial plain than at the upland. Considerable snow during active-layer freezing significantly prolonged the zero curtain.

RÉSUMÉ
Les températures du sol au Kendall Island Bird Sanctuary (KIBS), étudiées entre 2005 et 2009, étaient principalement influencées par la profondeur de la neige. L'épaisseur de la couche nivale résulte principalement de la redistribution aéolienne et celle-ci suit le même modèle annuellement. Dans les hautes terres la profondeur de la neige était influencée par la topographie tandis que dans la plaine alluviale elle était controllée par la hauteur de la vegetation. La température moyenne du sol était plus élevées dans la plaine alluviale que dans les hautes terres du à l'épaisseur accrue du couvert nival et de la couche active. Le développement d'un couvert nival considérable au moment du regel a nettement prolongé la durée de la période zero.

1 INTRODUCTION

The Kendall Island Bird Sanctuary (KIBS) (Figure 1) was established in 1960 to protect 623 km^2 of migratory bird habitat (Bromely and Fehr 2002). An alluvial plain, generally less than 1.5 m above mean sea level, covers nearly 78% of the area. The remaining terrain consists of rolling tundra uplands that are a western extension of Richards Island (Mackay 1963). KIBS is within the continuous permafrost zone (Nguyen et al. 2009), permafrost is ice rich (Morse et al. 2009), and the ground thermal regime is dominated by the eight-month long freezing season. Snow-cover and active-layer conditions are strong influences on the ground thermal regime (Goodrich 1982). At KIBS the influence of each controlling factor varies significantly at the local scale, but their interannual variation is unknown and near-surface ground temperature variation is poorly defined.

This paper has 3 objectives: (1) to characterize the spatial and interannual variation of snow-pack conditions at KIBS; (2) to demonstrate the distinct snow-cover and active-layer characteristics at an alluvial site versus a nearby remnant upland; and (3) to determine their influence on near-surface ground temperatures.

2 BACKGROUND

2.1 Ground Temperatures and the Influence of Snow

Ground temperatures and active-layer thickness are a function of air temperature but vary locally with site-specific surface and subsurface conditions. The surface organic-layer, soil moisture, mineral soil conditions, and topographic setting influence the local thermal regime, but vegetation type and snow pack are the most important factors (Smith 1975; Goodrich 1982; Liston et al. 2002; Stieglitz et al. 2003). Ground temperature variation is most sensitive to changes in snow cover when it is thin and dense (Mackay and MacKay 1974). Early snowfall or early snow melt can increase ground temperature, while late snowfall or late snowmelt has the opposite effect, so the timing of the arrival and departure of snow can be significant (Ling and Zhang 2003).

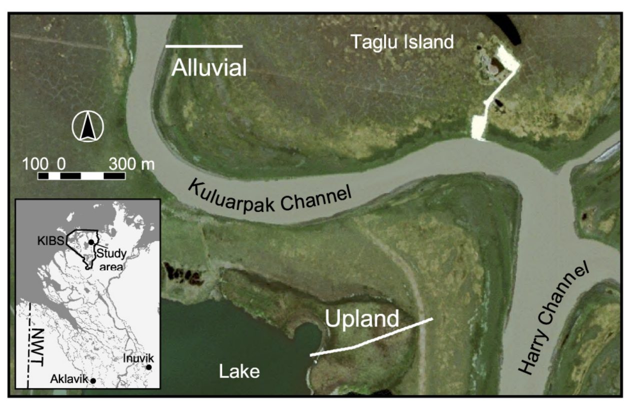

Figure 1. Study sites near Taglu (69°22'N, 134°58'W), Kendall Island Bird Sanctuary (KIBS), NWT. Locations of alluvial and upland transects are indicated.

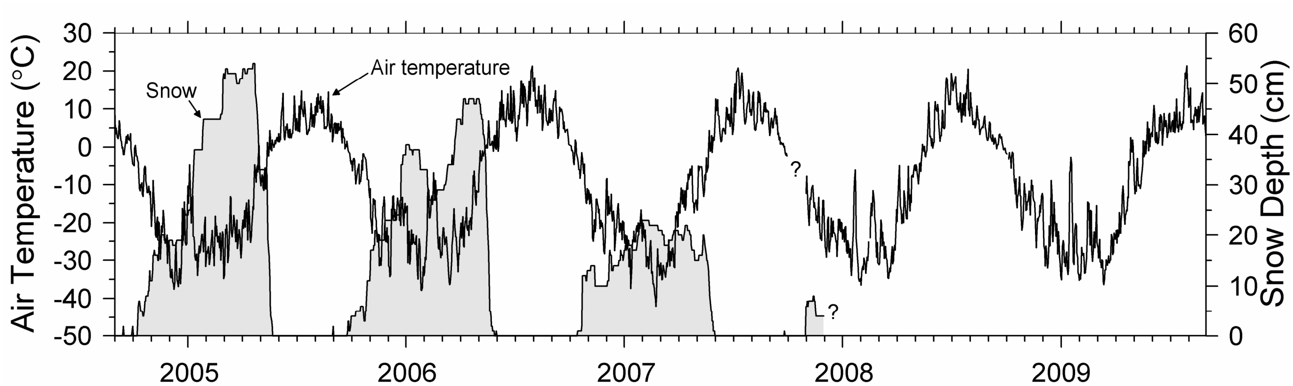

Figure 2. Daily mean air temperature (missing October 2007) and snow depth (not reported after November 2007) at Tuktoyaktuk, NWT, the closest meteorological station (Environment Canada 2010).

2.2 Kendall Island Bird Sanctuary

KIBS (Figure 1) is characterized by two physiographic subdivisions of the outer Mackenzie Delta (Mackay 1963; Rampton 1988): (1) Tununuk Low Hills, a rolling upland tundra usually less than 50 m above mean sea level, and (2) the flat Big Lake Delta Plain which is covered by numerous water bodies and may flood in spring or with storm surges. Low shrub tundra with willow (*Salix* spp.), alder (*Alnus crispa*) and ground birch (*Betula nana*) characterizes the uplands, while the vegetation in poorly drained alluvial plain consists of extensive sedge wetlands with successional willows on aggrading point-bars (Mackay 1963).

Permafrost temperatures are locally influenced by snow depth, vegetation, proximity to shifting channels, and topographic setting (Mackay and MacKay 1974; Mackay and Burn 2002). Permafrost thickness ranges from about 400 to 600 m near Taglu (Figure 1) (Taylor et al. 1996). Taliks exist immediately below water bodies that do not freeze to the bottom and beneath tall shoreline willows that hold deep snow (Dyke 2000b; Nguyen et al. 2009). In general, mean annual ground temperatures in KIBS range from -3 to -5°C (Burn and Kokelj 2009, Figure 11). Near-surface permafrost at KIBS is ice-rich (>20% mean excess-ice content in the upper meter of permafrost) and the greatest mean excess-ice content (34%) is in the alluvial plains due to high moisture availability (Morse et al. 2009).

Active-layer thickness varies with ground cover and thermal properties of soil materials which are governed mainly by organic-layer thickness and soil moisture. Active-layer thickness reported at KIBS ranges between 30 and 124 cm at upland tundra sites and between 38 and 130 cm at alluvial sites (Morse et al. 2009).

Winters in the region are long and cold, and summers are short and cool (Figure 2). Winds, dominantly north-westerly or easterly (Dyke 2000a), may blow from the offshore ice pack in summer and depress air temperatures near the Beaufort Sea coast (Burn 1997). Annual mean air temperature is increasing in the region, and has risen nearly 3°C since 1970 at Inuvik (Figure 1), driven mainly by rising winter air temperatures (Burn and Kokelj 2009).

2.3 Snow

Normal annual precipitation 75 km to the east at Tuktoyaktuk A, the closest weather station, is 75 mm (Environment Canada 2010). Snowfall deposition begins in September, increases to its maximum amount in October, and then tapers through the rest of the winter. On an annual basis snow cover is the dominant surface condition (Figure 2). Snow depth varies mainly by wind redistribution, with accumulation related to topographic setting or vegetation snow-holding capacity (Mackay and MacKay 1974; Smith 1975). The snow-holding capacity of vegetation critically influences ground temperatures and is controlled by vegetation structure (Smith 1975; Kokelj et al. 2007). Snow cover is thin at upland tundra surfaces where the snow-holding capacity of low shrubs is minimal. The wind redistributes snow to drifts that accumulate where there are taller shrubs, or to lee slopes, valley bottoms, and topographic concavities (Mackay and MacKay 1974; Lantz et al. 2009). Snow densities range between 0.35 and 0.4 g cm^{-3}.

Flooding at spring break-up eliminates snow from the alluvial plain (Mackay 1963), while upland snow may persist for some weeks afterwards, especially in deep drifts (Morse et al. 2009, Figure 3).

3 METHODS

Two nearby transects were established in upland tundra and alluvial terrain in March 2005 and monitored for four years, to determine the influence of snow-pack variation on near-surface ground temperature (Figure 1). The upland tundra site has considerable topographic variation, but relatively little variation in vegetation, with low shrubs (5–40 cm high) dominant, and green alder and willows at the foot of slopes (60–140 cm high). About 750 m north, the alluvial site is largely flat and poorly drained, and the vegetation structure, which varies along a topographic/successional sequence, ranges from bare ground near the channel at the point bar slip-off slope, to tall willows (150–300 cm high), to medium willows (60 – 100 cm high), to low willows (40 – 50 cm high), to wet sedge meadow (20 – 40 cm high) that grades into a lake. Ground temperatures in the active layer and at the top of permafrost were continuously logged at 4 monitoring sites along each transect where there was a distinct difference in topography and/or vegetation height. Onset Hobo data loggers recorded temperatures at 2, 20, 50, 100, and 150-cm depths every 2 hours, from which daily characteristics were obtained. To supplement the ground temperature data, end-of-winter subnivean temperatures (2005 – 2008) and late-summer 20-cm active-layer temperatures (2005 and 2007) were measured at regular intervals along each transect with calibrated YSI thermistors (± 0.01°C tolerance) attached to wooden dowels which were pushed down to depth and allowed to equilibrate for 20 minutes or until stable. Finally, end-of-winter snow depth and late-summer thaw depth were measured yearly at 5 m intervals along each transect with a graduated steel probe.

4 RESULTS

Air temperatures at Tuktoyaktuk ranged from 21.4°C to -42.1°C over the study period, during which the mean annual air temperature was -9.4°C (Figure 2, Table 1). Mean seasonal temperatures varied by up to about 3°C (Table 1). First-of-April snow depths at Tuktoyaktuk were 51 cm (2005), 43 cm (2006), and 21 cm (2007).

Table 1. Air temperature summaries (September 1st anniversary date), Tuktoyaktuk, NWT (Environment Canada 2010).

Characteristics	04/05	05/06	06/07	07/08	08/09
Annual mean	-10.4	-8.7	-8.8	-9.1	-10.1
Dec. – Feb. mean	-25.5	-22.1	-24.3	-24.6	-24.9
Jun. – Aug. mean	7.1	10.3	9.6	7.5	7.6

4.1 Variation of Snow Pack Conditions at KIBS

The distribution of snow depth and subnivean temperatures followed a similar pattern each year so only data from 2005 and 2006 are shown in Figure 3. Four-year median snow depth at upland sites (38 cm) was less than alluvial sites (53 cm). Over the uplands, observed snow depths ranged between 10 and 220 cm. Median snow depths along the entire transect from 2005 to 2008 were, respectively, 39, 43, 36, and 35 cm. Mean late-winter snow depths over the four years were 84 cm at the west slope (0 – 70 m), 29 cm at the tundra plateau (100 – 240 m), 30 cm at the peatland (300 – 400 m), and 123 cm at the east slope (425 – 435 m). The greatest interannual variation of mean snow depths occurred at the short and steep east slope (123-cm range), while depths at the west slope, tundra plateau, and peatland were relatively consistent with ranges of 16, 9, and 2 cm, respectively. In the 4 years, late March/early April subnivean temperature measurements made on one day each year ranged from -4.2 to -25.7°C, were lowest at the tundra plateau and the peatland and over 6°C higher at the east slope drift in a given year (Figure 3a).

At the alluvial site, snow cover ranged from 9 cm (unvegetated slip-off slope) to 197 cm (tall willows) (Figure 3b). Mean late-winter snow depths were 57 cm at the unvegetated slip off slope (0 – 15 m), 126 cm at the tall willows (15 – 75 m), 66 cm at the medium willows (75 – 150 m), 50 cm at the low willows (150 – 255 m), and 30 cm at the sedges (255 – 300 m). Median snow depths along the entire transect were 67, 52, 52, and 58 cm from 2005 to 2008, respectively. The greatest interannual variation of mean snow depths occurred at the slip-off slope (83 cm range), followed by tall willows (74 cm range). Snow depths in medium willows, low willows and sedges varied respectively by 29, 11, and 13 cm. Over the study period, subnivean temperatures measured in late winter at the alluvial site ranged between -1.7 (tall willows) and -19.3°C (unvegetated slip-off slope) (Figure 3b). Subnivean temperatures along the transect were lowest at the unvegetated slip-off slope, warmest at tall willows and then steadily lowered again as willows gave way to sedge (Figure 3b).

4.2 Snow-cover and Active-layer Characteristics

Like the snow pack, active-layer conditions follow the same general pattern from year-to-year so only summer 2007 data are shown in Figure 4. Active-layer thickness at uplands typically ranged between 24 and 71 cm (Figure 4a). Median active-layer depth from 2006 to 2008 was 49 cm annually at the upland site. Average three-year active-layer thickness was 43 cm at the west slope (5 – 70 m), 57 cm at the level plateau (100 – 240 m), 45 cm at the peatland (300 – 400 m), and 39 cm at the east slope (425 – 435 m). The most interannual variation of mean active-layer thickness occurred at the short and steep east slope (4-cm range), but the interannual ranges at west slope, tundra plateau, and peatland were also small, respectively, 2, 3, and 1 cm. Twenty-cm active-layer temperatures (20 August 2007) were lowest at the east slope, warmer at the west slope, and highest at the tundra plateau and peatland (Figure 4a).

Active-layer thickness at the alluvial site ranged from 36 cm (sedge) to greater than 255 cm beneath tall willows where a talik likely exists (Figure 4b). Median active-layer depth for the transect from 2006 to 2008 was 72 cm in 2006, and 79 cm in 2007, and 78 cm in 2008. Three-year average active-layer thickness was 130 cm at the unvegetated slip-off slope, 186 cm at the tall willow (likely an underestimate since a 175-cm probe was used in 2007 and 2008, versus the 255-cm probe used in 2006), 102 cm at medium willows, 57 cm at low willows, and 47 cm at the sedges. Interannual variation in active-layer thickness was greatest at the tall willows (42-cm range; likely an underestimate due to probe lengths). The range in active-layer thickness was much less at the unvegetated slip-off slope (12 cm), medium willows (18 cm), at the low willows (9 cm), and at the sedges (4 cm).

Active-layer temperatures (20-cm depth; 20 August 2007) gradually decreased with distance away from the river channel (Figure 4b).

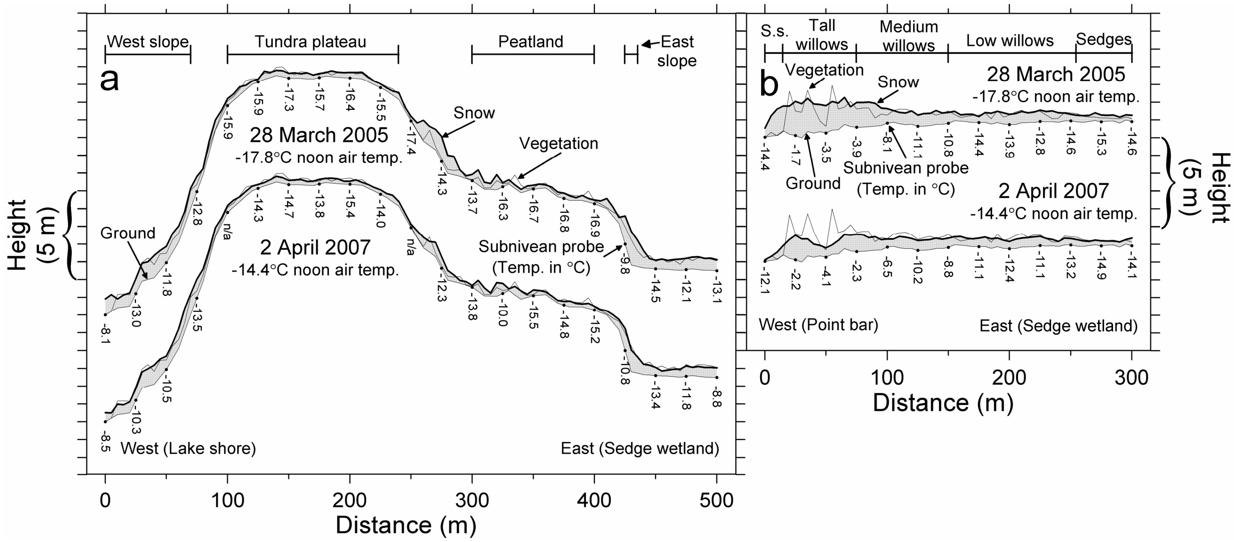

Figure 3. Late-winter snow-pack depth and one-day subnivean temperatures at (a) upland and (b) alluvial transects. Notice the deep snow at the foot of slopes in the upland transect and with the tall vegetation in the alluvial.

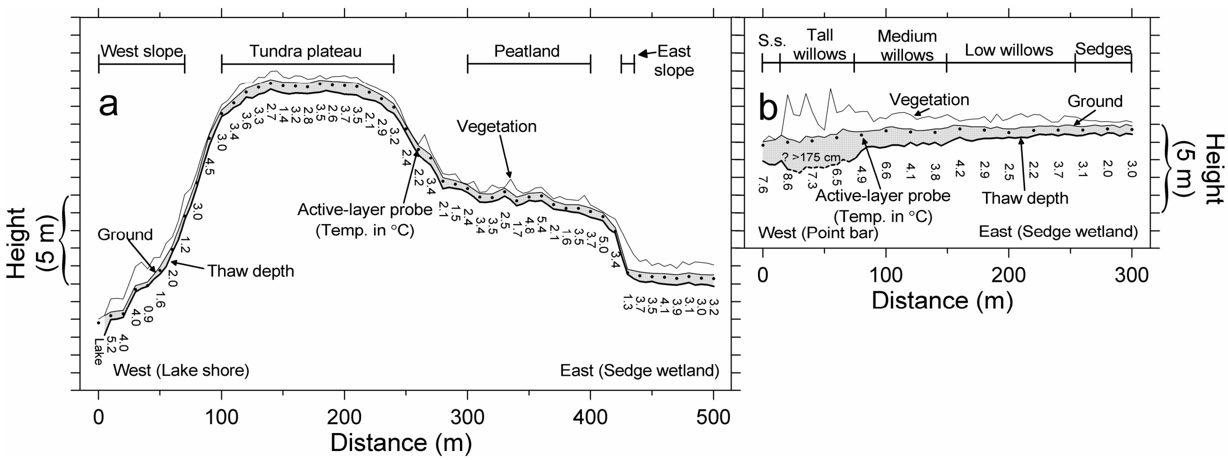

Figure 4. Active-layer thaw depths and one-day 20-cm ground temperatures, 20 August 2007 at (a) upland and (b) alluvial transects. Noon air temperature was 8.2℃.

4.3 Near-surface Ground Temperature Variation

Ground temperatures were recorded at upland tundra plateau and alluvial low willows for three years and the remaining sites for 2 years, but damage by foxes at the peatland, and flooding at medium willows and sedges, limited data acquisition (Table 2, 3; Figure 5). Ground temperatures at the uplands were highest at the east slope (425 m), slightly lower at the west slope (50 m), lower at the tundra plateau site (170 m), and lowest at the peatland site (390 m) throughout the temperature profile and in all years (Table 2; Figure 5a). For example, in 08/09, mean annual top of permafrost temperatures (100-cm depth) were -3.7℃ at the east slope, -4.4℃ at the west slope, -6.5 at the tundra plateau site, and -7.2℃ at the peatland. Ground surface temperatures followed a similar spatial pattern, with mean temperatures generally between -3 to -4℃ at the east slope, -4 to -5℃ at the east slope, -5 to -6℃ at the tundra plateau, and -6 to -7℃ at the peatland. The minimum and maximum temperatures also maintained this thermal-spatial pattern relative to each other, but, there was a seasonal difference. The range of maximum 20-cm ground temperatures across upland sites in a given year was less than 4℃ while minimum winter temperatures varied by nearly 12℃ (Table 2; Figure 5a).

Mean annual temperatures at alluvial sites in all years and at all depths were highest at tall willows (40 m), lower with increasing proximity to the sedges (300 m), and generally warmer than upland terrain (Table 3; Figure 5b). For instance, 07/08 mean annual 20-cm ground temperatures were 0.3°C at tall willows, -0.8°C at medium willows, -3.8°C at low willows, and -5.2°C at sedges. This spatial temperature gradient was marked by increasingly lower minimum temperatures along the vegetation gradient (9.6°C range).

However, maximum temperatures did not directly relate to this gradient as they rose about 4°C from tall

Table 2. Upland monitoring station characteristics and ground temperatures for three years of investigation.

	Upland sites											
	West slope at 50m			Tundra plateau at 170m			Peatland at 390m			East slope at 425m		
Characteristics†	06/07	07/08	08/09	06/07	07/08	08/09	06/07	07/08	08/09	06/07	07/08	08/09
Snow depth (cm)	74	79	-	24	25	-	17	12	-	124	48	-
Active layer												
Depth (cm)	42	42	43*	65	50	66*	44	43	-	37	42	43*
Freeze back (days)	-	37	44	50	48	57	-	-	-	-	30	65
End of freeze back		24 Oct.	8 Nov.	22 Nov.	6 Nov.	11 Nov.					23 Oct.	29 Nov.
2-cm temp. (°C)												
Mean	-	-4.7	-4.3	-4.6	-5.1	-6.0	-	-5.7	-7.0	-	-3.9	-3.4
Min	-	-17.4	-13.5	-19.9	-23.8	-24.1	-	-25.4	-27.7	-	-12.3	-11.7
Max	-	12.3	13.0	13.1	12.9	13.1	-	13.2	13.9	-	10. 6	10.9
20-cm temp. (°C)												
Mean	-	-5.0	-4.4	-5.1	-5.7	-6.2	-	-	-	-	-4.4	-3.4
Min	-	-14.1	-11.7	-18.1	-19.8	-21.8	-	-	-	-	-11.7	-10.0
Max	-	5.7	4.6	7.7	7.9	7.5	-	-	-	-	4.8	4.0
50-cm temp. (°C)												
Mean	-	-5.0	-4.3	-5.3	-5.8	-6.3	-	-	-	-	-4.7	-3.6
Min	-	-12.3	-10.4	-16.0	-16.0	-18.1	-	-	-	-	-9.5	-8.9
Max	-	0.7	-0.2	1.9	2.3	1.2	-	-	-	-	-0.6	-0.6
100-cm temp. (°C)												
Mean	-	-4.9	-4.3	-5.5	-6.0	-6.5	-	-	-7.2	-	-4.6	-3.7
Min	-	-10. 6	-8.9	-14.1	-14.0	-16.0	-	-	-17.4	-	-8.8	-7.9
Max	-	-0.7	-0.2	-0.5	-0.6	-1.1	-	-	-1.1	-	-1.1	-1.1
150-cm temp. (°C)												
Mean	-	-4.9	-4.4	-5.4	-5.9	-6.3	-	-	-	-	-4.7	-3.8
Min	-	-9.5	-8.4	-12.9	-12.9	-14.7	-	-	-15.7**	-	-8.4	-7.9
Max	-	-1.5	-1.2	-1.1	-1.5	-1.5	-	-	-	-	-1.5	-1.5

†Snow depth and active-layer thickness were measured at the station.

*Active-layer estimated from ground temperature data.

**Only the fall and winter seasons were recorded.

Table 3. Alluvial monitoring site characteristics and ground temperatures for three years of investigation.

	Alluvial sites											
	Tall willows at 40m			Medium willows at 100m			Low willows at 155m			Sedges at 300m		
Characteristics†	06/07	07/08	08/09	06/07	07/08	08/09	06/07	07/08	08/09	06/07	07/08	08/09
Snow depth (cm)	74	112	-	45	45	-	47	41	-	42	33	-
Active layer												
Depth (cm)	Talik	Talik	Talik	111	112	105*	63	66	70*	36	48	-
Freeze back (days)	Talik	Talik	Talik	-	126	150	71	53	72	-	47	-
End of freeze back	Talik	Talik	Talik	-	27 Jan.	14 Feb.	11 Dec.	16 Nov.	7 Dec.		4 Nov.	
2-cm temp. (°C)												
Mean	-	1.0	1.3	-	-	-	-2.4	-3.7	-4.5	-	-	-
Min	-	-4.7	-1.5	-	-	-	-14.5	-16.6	-20.7	-	-	-
Max	-	14.9	16.4	-	-	-	13.7	14.0	15.2	-	-	-
20-cm temp. (°C)												
Mean	-	0.3	1.0	-	-0.8	-1.1	-2.9	-	-	-	-5.2	-
Min	-	-5.5	-1.5	-	-7.9	-10.0	-14.1	-	-	-	-17.4	-
Max	-	12.5	13.1	-	12.8	15.0	12.3	-	-	-	7.0	-
50-cm temp. (°C)												
Mean	-	0.2	0.7	-	-1.2	-1.5	-3.6	-4.2	-4.8	-	-	-
Min	-	-2.9	-0.7	-	-6.8	-8.4	-12.9	-13.9	-18.1	-	-	-
Max	-	7.1	9.4	-	6.6	7.9	3.2	5.0	5.6	-	-	-
100-cm temp. (°C)												
Mean	-	-0.1	0.3	-	-1.5	-1.6	-4.9	-5.8	-6.6	-	-5.8	-
Min	-	-2.0	-0.6	-	-5.3	-6.3	-12.3	-12.9	-16.7	-	-13.5	-
Max	-	4.6	6.0	-	0.7	0.3	-1.4	-1.5	-2.0	-	-1.1	-
150-cm temp. (°C)												
Mean	-	-0.2	-0.0	-	-1.5	-1.6	-3.9	-4.4	-5.0	-	-	-
Min	-	-1.4	-0.6	-	-4.3	-5.3	-9.5	-10.6	-12.9	-	-	-
Max	-	3.3	3.7	-	-0.6	-0.6	-1.1	-1.1	-1.0	-	-	-

†Snow depth and active-layer thickness were measured at the station.

*Active-layer estimated from ground temperature data.

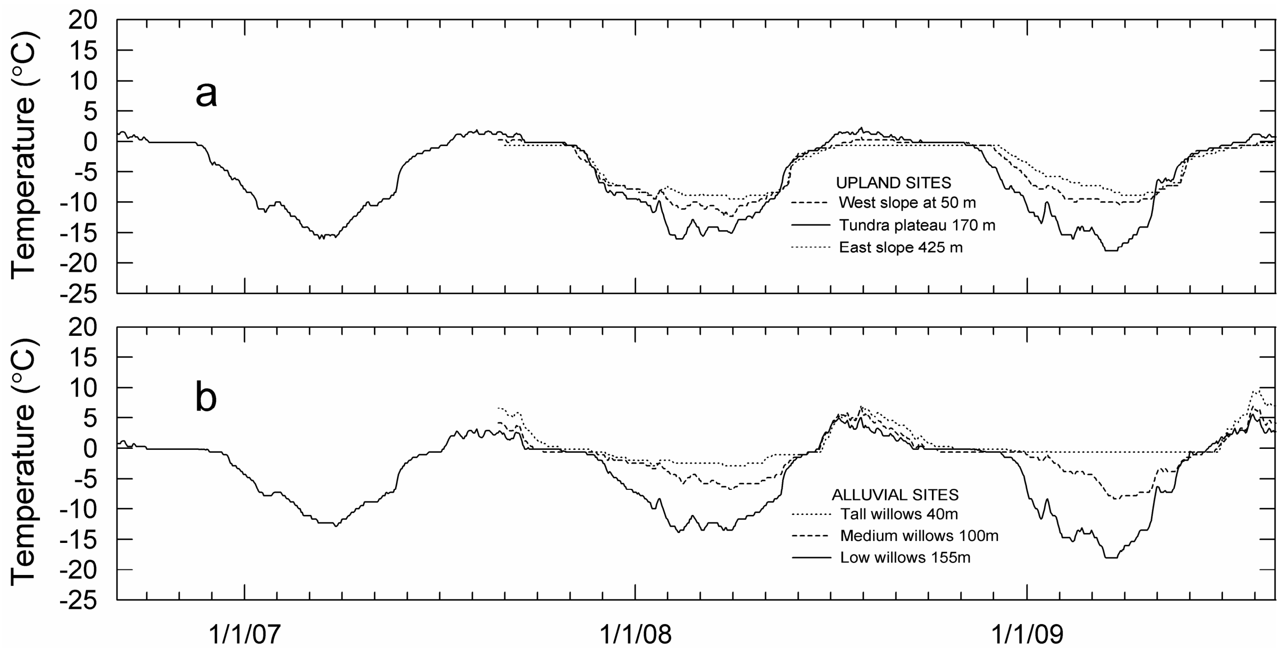

Figure 5. Active-layer temperatures (50-cm depth) at (a) upland and (b) alluvial sites.

willows to low willows followed by a nearly 10°C step decrease to cold ground at sedges (Table 3; Figure 5b). Snow depth and active-layer thickness at upland ground temperature sites (Table 2) reflects those measured along the adjacent transect (Figure 4a). The duration of active-layer freeze back across all years ranged between 30 and 65 days, and was completed between 23 October and 29 November. The duration was generally greater at tundra plateau than at other sites, with the exception of the east slope (450 m) in fall of 2008, though all sites experienced a longer freeze back that year than in 2007 (Table 2).

Like at upland sites, active-layer thickness and snow depths at alluvial sites (Table 3) were within ranges measured along the transect (Figure 4b). The active layer took up to 47 days to freeze back at sedge, 72 days at low willows, up to 150 days at medium willows, and was above a talik at the tall willow site. The date of freeze-back completion at the alluvial site during the study period ranged from 4 November to 14 February, and as at upland sites, freeze back took longer in the fall of 2008.

5 DISCUSSION

5.1 Characteristics of Snow-cover Variation

At the upland and alluvial sites the spatial distribution of snow follows the same pattern from year-to-year. Considerable variation in snow depth occurs interannually at large drifts, especially at the alluvial site, but less at other sites where the vegetative snow-holding capacity is filled each winter. Upland snow thicknesses closely mirror vegetation height, with taller vegetation growing where topography causes protective deep snow to accumulate. Active-layer thickness and freeze-back duration are inversely proportional to vegetation height, which suggests that upland vegetation height is limited by winter snow conditions, rather than summer soil conditions. At the alluvial site, snow thickness varies directly with vegetation height, and the deepest drifts are in the tall willows, which were not completely covered by snow. Vegetation height, active-layer thickness, and freeze-back duration are directly proportional to each other, suggesting that the depth of snow trapped by vegetation in the winter influences soil conditions in summer. Snow at deep drift sites may remain into the early summer and was observed, for example, at alluvial and upland sites on 17 June 2006.

5.2 Snow-cover and Active-layer Characteristics

The upland and alluvial terrains exhibited considerable late-winter subnivean temperature variation along each transect in relation to snow depth, and upland temperatures were generally lower. The coldest conditions were beneath the thinnest snow at the upland peatland and the unvegetated point-bar slip-off slope. The warmest were beneath upland topographic drifts and drifts in the alluvial tall willows. Summer 20-cm active-layer temperatures, measured on one day, followed a pattern related directly to active-layer thickness. One-day active-layer temperature was lower and inversely related to vegetation height at uplands, and was higher and directly related at the alluvial site.

Active-layer thickness was generally deep in alluvial deposits and shallow at uplands (Tables 2 and 3). Interannual variation of active-layer thickness was less than 6% about the mean at the upland but could be up to 9% at the alluvial site. Active-layer thickness, and freeze-back duration are directly proportional to vegetation height at the alluvial site, but are inversely proportional to vegetation height at the upland site. This suggests that upland and alluvial terrain must be treated differently when modelling relations between snow, vegetation and the ground thermal regime.

5.3 Influence of Snow-cover Variation on Near-surface Ground Temperatures

Ground temperature data reflected the spatial patterns demonstrated by the one-day subnivean and active-layer temperature data. Annual mean and winter temperatures increased directly with snow depth, and upland sites were commonly cooler than alluvial sites due to generally less snow (Figures 3-5; Tables 2, 3). Alluvial willows sites had a much greater thermal offset than upland sites due to thick, wet active layers (Tables 2, 3). Summer temperatures at upland sites were lower than alluvial willow sites with little to no surface organic layer, but not the sedge site in standing water and with a thick surface organic layer.

The effect of deep snow on winter and thus annual ground temperatures is modified by antecedent active-layer conditions. Upland slopes, compared to tall and medium alluvial willow sites, are not as warm in summer and have a thin active layer due to summer shading by dense alders and a thick surface organic layer. The thin active layer completely freezes back at these slopes before any other site which allows the ground to begin to cool earlier than at alluvial willows (Tables 2, 3; Figure 5).

The influence of high spatial variation of snow depth on ground temperature is considerable at upland and alluvial terrain, and can be highlighted by comparing the peatland with the east slope. Both sites have thick organic layers, but greater shade at the east slope yields a lower summer temperature at all depths. However, the comparatively thick snow at the slope results in higher winter temperatures at all depths to the point that at the 100-cm depth, the annual mean temperature at the slope was 3.5°C warmer than the peatland site in 08/09 only 35 m away. The west slope and tundra plateau demonstrated an analogous pattern each year of study.

From 06/07 to 08/09, summer ground temperatures at the upland and alluvial terrain were relatively uniform within each terrain type, from site to site and year-to-year (Tables 2, 3). Winter temperatures exhibited a significant range within each terrain type, but interannual site variation was relatively uniform (Figures 3-5; Tables 2, 3). This is in contrast to air temperature data, which varied most in the summer and least in the winter (Table 1). Locations, other than where deep drifts occur, have relatively little interannual snow depth variation as the vegetation is filled to its snow-holding capacity each year. Only snow depths at deep drift sites have significant interannual variation, and in low snow years the drift sites generally have enough snow to significantly ameliorate winter cooling from frigid air. Therefore, variation of ground temperature is dominantly controlled by winter snow depth, and as such varying significantly in space, but less so with time.

Winter ground temperatures at locations with relatively thin snow tracked winter air temperatures which cooled slightly from 06/07 to 08/09 (Table 1). Conversely, at the upland slopes and at alluvial tall willows where blowing snow develops deep drifts, there was warming in 08/09 (Tables 2, 3). This may be a result of the 29 September 2008 snow storm when nearly 20 cm of snow fell in Inuvik (no snow fall records exist from Tuktoyaktuk for this time), a depth usually attained in late November, and blowing snow with winds up to 44 km h^{-1} were reported at Tuktoyaktuk (Environment Canada 2010). The early deep snow would have enhanced latent heat effects at freeze back, the deep snow would have been in place at an early stage to ameliorate winter cooling, and the combined effect was an increase in winter maximum and annual mean ground temperatures.

Where snow was thin, the overall effect may not have been enough to cause an increase in mean annual ground temperature, but there were significant effects on the ground thermal regime. The early 2008 snowfall occurred just as the active layer was beginning to freeze and latent heat effects were enhanced, especially in alluvial willows where the active layer is thick. Compared to 2007, freeze back took over twice as long to complete at the east upland slope (65 days) and more than three weeks longer at tall willows (150 days) where freeze back was not complete until 14 February 2009 (Tables 2, 3; Figure 5).

6 CONCLUSIONS

In summary, snow-cover is the dominant influence on the ground thermal regime at KIBS. Coincidence of significant snow fall accumulation with active-layer freeze back enhanced latent-heat effects, reinforcing snow-pack variation as the primary control on near-surface ground temperatures. Differences observed at upland versus alluvial terrain suggest that they must be treated differently when modelling relations between air temperature, snow, vegetation and the ground thermal regime.

The following details can be drawn from the investigation of snow-pack, active-layer, and near-surface ground temperature conditions at KIBS:

1. Snow-depth variation is dominantly influenced by topography in the upland transect and vegetation height at the alluvial plain. The wind-redistributed snow pack evolves to the same general spatial distribution from year-to-year, with low interannual snow depth variation at most locations as the vegetation is filled to its snow-holding capacity.

2. Active-layer thickness and variation were greater at alluvial than at upland terrain, but interannual variation was less than 10% at all locations. Active-layer

thickness was inversely proportional to vegetation height at the upland, but mirrored vegetation height at alluvial terrain

3. Near-surface ground temperature variation in both space and time was primarily influenced by snow depth variation, as winter temperatures varied with snow depth, while summer temperatures were relatively invariant.

4. The greatest range in mean annual ground temperature at 150 cm depth (0.0 to -5.0°C) occurred at the alluvial transect where mean temperatures varied positively with late-winter snow depth. In general, ground temperatures were lower (from -3.8 to -6.3°C at 150 cm) than at the alluvial transect, as median snow depths were less.

5. Freeze back of the active layer was typically completed by mid-November at uplands, but the zero-curtain duration was generally twice as long at alluvial sites and could last until mid-February. The duration of the zero curtain was greatest when significant snow accumulated at the beginning of the freezing season.

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