Snowpack–Vegetation–Terrain Relationships
Across the Arctic Treeline, Churchill MB

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ABSTRACT

The arctic treeline at churchill is a 10-km-wide ecotone from open tundra to upland white spruce and lowland black spruce forest. Characteristics of the snowpack include depth, density, snow water equivalent, and heat transfer coefficient measured over two years during mid-winter. These studies reveal differences induced by vegetation variations and associated microclimates. As expected, mid-winter snowpack varies considerably between open tundra and forest sites. Despite the dramatic differences in canopy, the post-fire forest snowpack differed little from that of the unburned forests. In the peatlands, depressions associated with degrading ice wedges had snowpack characteristics more similar to forested sites than adjacent polygon centers. Interannual variations were much less than intersite variations in most snowpack characteristics. These studies are intended to be repeated annually in order to establish a longitudinal study of snowpack variation across the arctic treeline during a period of predicted dramatic change in climate.

Keywords: snowpack SWE, snowpack density, Arctic, Taiga, forest, tundra

INTRODUCTION

The study area spans the transition between tundra and subarctic forest. This ecotone is narrow with less than 12 km separating the inland open forests from the treeless coastal tundra. These vegetation zones are representative of biomes with a much broader circumpolar distribution. Thus the area presents an excellent opportunity to investigate the influence of plant cover on snowpack characteristics that are representative of a much larger geographical area.

Snowpack characteristics in the Churchill area vary due to differences in vegetation architecture, which affects wind characteristics (Rouse, 1982, Scott *et al*, 1993). Wind causes redistribution and its characteristics are directly related to surface roughness as dictated by vegetation architecture (Kind, 1981, Timoney *et al*, 1992) at the treeline.

The study area contained upland and lowland forests, burned forest stands, polygonal peat plateaus and upland tundra (Figure 1). The forests in the area are open (<15% canopy closure) with trunks in upland stands approximately twice the height of the 5-m-tall trees in the lowland areas. Raised areas in the lowland forests have bog characteristics such as soil water pH in the 4.7 range while the adjacent wetlands have pH commonly in the 7.7 range and could be termed fens (Zoltai, 1988). Peatlands in the study area were frequently marked by ice wedge polygon networks with diameters of 7 to 10 m.

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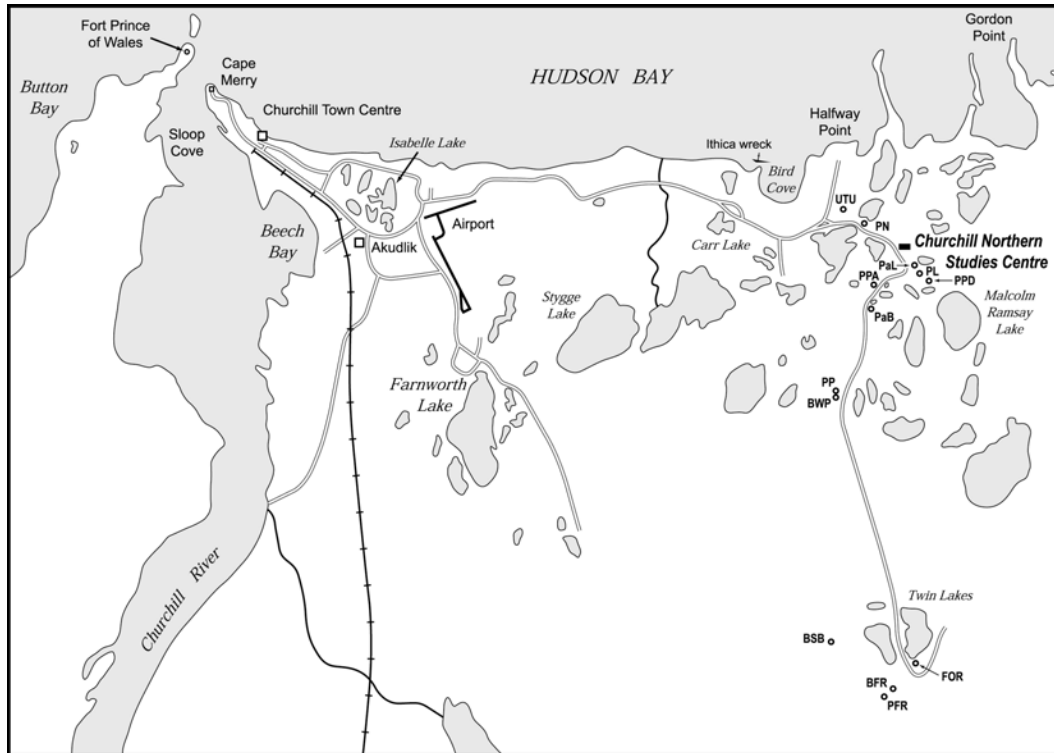
Figure 1: The sampling sites extended from forested and burned sites 15 km inland from the coast. Coastal locations were dominated by Tundra. Sites sampled include: White Spruce Forest (FOR), Burned Forest (BFR), Black Spruce "Bog" (BSB), Degrading Polygonal Peat Plateau (PPDw & c), Aggrading Polygonal Peat Plateau (PPAw & c), and Tundra (UTU). The w and c modifiers were for ice wedge troughs and polygon centers, respectively. Other sites are not discussed here.

Purpose:

The study was set up to assess the influence of vegetation architecture and terrain characteristics on snowpack characteristics. It is a component of a larger study that has been established to evaluate the impacts of climate change in the region.

METHODS

Sampling was conducted over an eight-day period in mid-February of both 2002 and 2003. Three to five field groups selected sites within pre-determined tundra, peatland, forest (upland and lowland), and burn sites (Figure 1). In each site, random sampling was conducted within a 50- to 75-m-radius of the center of the stand. Sampling was based on snow pits, snow cores and RAM penetrometer measurements (McclungandSchaerer, 1993). Only the snow core data collected with an Adirondack snow corer were analyzed for this paper. No correction was applied to the core data (Goodison, 1978). Sample sizes varied among sites and between years. In the second year in the Tundra and Polygonal Peat Plateau centers the very shallow snowpack was not always cored, rather, a known volume was taken by using a snow spatula to remove the sample for weighing. This procedure was not systematically applied by all the groups conducting the sampling and consequently the resulting data can differ from those collected using the Adirondack corers.

Using the depth (d), density (ρ) and snow thermal conductivity properties (k) (Abel's, 1893) an index of the potential heat conductance was calculated which was called the heat transfer coefficient (HTC) (Kershaw, 1991, Kershaw, 2001).

HTC = k/d

where k is the thermal conductivity (Abel's, 1893) of the snowpack and d is the snowpack depth

$$k = (2.94 \cdot 10^{-6}\ \mathrm{W\ m^{-1}\,^{\circ}K^{-1}})(\rho)^2$$

where k is in Watts per meter per degree Kelvin

where ρ is snowpack density (kg m^{-3})

The HTC was derived to provide an integrated value to reflect the influence of depth and density on the thermal properties of the snowpack since both characteristics must be considered when evaluating snowpack heat conductance. For example, it is possible that a thick, high-density snowpack has similar heat conductance characteristics to a thin, low density snowpack and the HTC was developed to provide a means for comparing the thermal properties of different snowpacks. Since the publication of the HTC, Sturm *et al.* (1997) have produced a more accurate method, using quadratic or logarithmic equations, to estimate thermal conductivity with changes in snow density, the latter, best suited to low-density snow. Since several sites had high-density snow, the HTC was used as the basis for comparison among the sites.

Statistical analysis was conducted using the SigmaStat 3.0 program (Spss, 2003). Initially a Kruskal-Wallis one way analysis of variance on ranks was conducted (P <0.001) and then to isolate the group or groups that differ from the others, Dunn's pairwise multiple comparison procedure was used to assess significant differences (P <0.05).

Table 1. Dunn's pairwise multiple comparison procedure was used to assess significant differences (P <0.05) between sites. A blank indicates no significant difference while text indicates whether density, depth, snow water equivalent (SWE) or heat transfer coefficient (HTC) values differed significantly. The two-digit code for year is followed by the site code. UTU: Undisturbed Tundra, PPA: Polygonal Peat Plateau Aggrading, (c: polygon center, w: ice wedge trough), PPD: Polygonal Peat Plateau Degrading, FOR: white spruce forest, BSB: Black Spruce "Bog", BFR: Burned spruce forest.

	02FOR	02BFR	02BSB	02PPDw	02PPDc	02PPAw	02PPAc	02UTU	03FOR	03BFR	03BSB	03PPDw	03PPDc	03PPAw	03PPAc	03UTU
02FOR					Depth	Depth	Depth	Depth					Depth	Depth	Depth	Depth
02BFR					Depth	Depth	Depth	Depth					Depth	Depth	Depth	Depth
02BSB					Depth	Depth	Depth	Depth					Depth	Depth	Depth	Depth
02PPDw	Density	Density	Density		Depth	Depth	Depth	Depth					Depth	Depth	Depth	Depth
02PPDc				Density		Depth			Depth	Depth	Depth	Depth	Depth			
02PPAw				Density				Depth	Depth	Depth	Depth	Depth	Depth		Depth	
02PPAc				Density					Depth	Depth	Depth	Depth		Depth		
02UTU	Density	Density	Density			Density	Density		Depth	Depth	Depth	Depth	Depth			
03FOR				Density				Density					Depth	Depth	Depth	Depth
03BFR				Density				Density					Depth	Depth	Depth	Depth
03BSB				Density				Density					Depth	Depth	Depth	Depth
03PPDw				Density									Depth	Depth	Depth	Depth
03PPDc				Density				Density					Depth			
03PPAw				Density				Density							Depth	Depth
03PPAc				Density				Density								
03UTU				Density				Density								

	02FOR	02BFR	02BSB	02PPDw	02PPDc	02PPAw	02PPAc	02UTU	03FOR	03BFR	03BSB	03PPDw	03PPDc	03PPAw	03PPAc	03UTU
02FOR					HTC			HTC		HTC			HTC	HTC		
02BFR					HTC			HTC		HTC			HTC	HTC		
02BSB					HTC			HTC		HTC			HTC	HTC		
02PPDw					HTC			HTC		HTC				HTC		
02PPDc	SWE	SWE	SWE	SWE					HTC		HTC	HTC		HTC		
02PPAw	SWE	SWE	SWE	SWE						HTC						
02PPAc	SWE	SWE	SWE	SWE												
02UTU	SWE	SWE	SWE	SWE					HTC		HTC	HTC		HTC		
03FOR				SWE	SWE	SWE	SWE			HTC			HTC		HTC	
03BFR				SWE	SWE	SWE	SWE				HTC	HTC		HTC		HTC
03BSB				SWE	SWE	SWE	SWE						HTC		HTC	
03PPDw				SWE	SWE	SWE	SWE						HTC		HTC	
03PPDc	SWE	SWE	SWE	SWE					SWE	SWE	SWE	SWE		HTC		
03PPAw	SWE	SWE	SWE	SWE					SWE	SWE	SWE	SWE			HTC	
03PPAc	SWE	SWE	SWE	SWE					SWE	SWE	SWE	SWE				
03UTU	SWE	SWE	SWE	SWE					SWE	SWE	SWE	SWE				

RESULTS

Sample sizes varied at the six sites between years (sample sizes in 2002 and 2003 respectively): Tundra (n=90, 110), Aggrading Polygonal Peat Plateau Ice Wedge Trough (n=60, 99) and Raised Center (n=30, 110), Degrading Polygonal Peat Plateau Ice Wedge Trough (n=80, 121) and Raised

Center (n=30, 110), White Spruce Forest (n=90, 110), Black Spruce "Bog" (n=90, 110), Burned Forest (White Spruce) (n=80, 110).

Snowpack depth:

Mean snowpack depth varied from just over 60 cm in the forested sites to <5cm on the centers of Polygonal Peat Plateaus and approximately 10 cm on the tundra (Table 1, Figure 2). Depressions associated with the polygons had 5 to 10 times the snow depths on adjacent polygon centers.

There were no significant differences in snowpack depths between years at a site (Figure 2). All the forest sites had similar depths, including the burned forest. Forest snowpacks were significantly deeper than the treeless tundra and peat plateau sites except in the ice wedge troughs on the Degrading Polygonal Peat Plateau where they were the same as in the forest.

Figure 2: Snowpack depth was significantly deeper in forested areas than in non-forested. The topographically-depressed ice wedge troughs collected deeper snowpack than adjacent polygon centers. Histogram of mean with error bar for one standard deviation. **UTU**: Undisturbed Tundra, **PPA**: Polygonal Peat Plateau Aggrading, (**c**: polygon center, **w**: ice wedge trough), **PPD**: Polygonal Peat Plateau Degrading, **FOR**: white spruce forest, **BSB**: Black Spruce "Bog", **BFR**: Burned spruce forest.
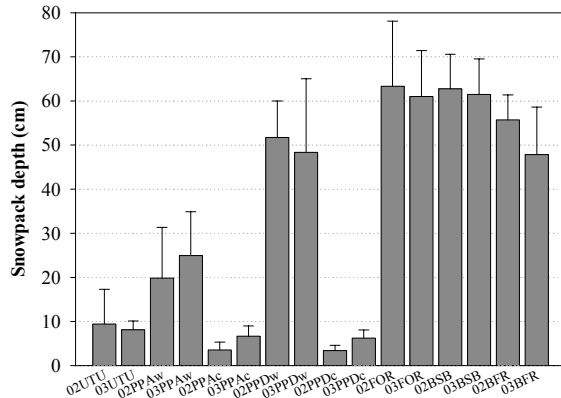

Figure 3: Snowpack density varied between the open tundra and the forest sites. There was little difference in the forest sites with the exception of the burned stand where wind enhanced crystal packing to produce higher densities. Histogram of mean with error bar for one standard deviation. **UTU**: Undisturbed Tundra, **PPA**: Polygonal Peat Plateau Aggrading, (**c**: polygon center, **w**: ice wedge trough), **PPD**: Polygonal Peat Plateau Degrading, **FOR**: white spruce forest, **BSB**: Black Spruce "Bog", **BFR**: Burned spruce forest.
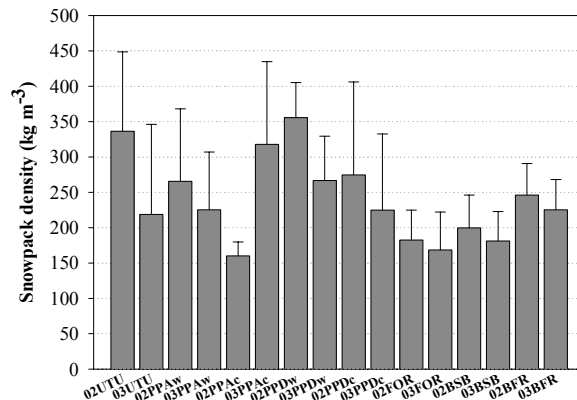
Snowpack density:

The snowpack density was lowest in forested sites, ranging from approximately 160 kg m^{-3} to 246 kg m^{-3} (Table 1, Figure 3). The Tundra had significantly lower density and the Degrading Polygonal Peat Plateau wedge had higher values in the second sampling year. All other sites were similar between years. The forested sites, including the burn had similar density values each year and among sites. In the first sampling year the Tundra densities differed significantly from the forested sites. The first year on the Tundra differed significantly from both Polygonal Peat Plateau centers and wedges.

Snowpack SWE:

Figure 2: SWE was similar between years at a site. Treeless sites had significantly less SWE than treed sites, including the burned forest. Where depressions occurred in association with ice wedges on the Polygonal Peat Plateaus, higher SWE values were found than on the adjacent polygon centers. Histogram of mean with error bar for one standard deviation. **UTU**: Undisturbed Tundra, **PPA**: Polygonal Peat Plateau Aggrading, (**c**: polygon center, **w**: ice wedge trough), **PPD**: Polygonal Peat Plateau Degrading, **FOR**: white spruce forest, **BSB**: Black Spruce "Bog", **BFR**: Burned spruce forest.
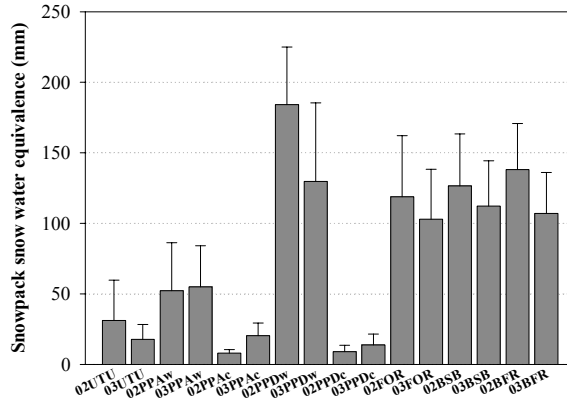
Snow water equivalent values were similar between the two sampling years at all sites (Table 1, Figure 4). On open sites the values were <10 mm but in ice wedge troughs on the Degrading Polygonal Peat Plateau they were the highest at approximately 180 mm. The forest areas, including the burned stand had significantly higher SWE than all but the Degrading Polygonal Peat Plateau ice wedge troughs.

Snowpack HTC:

The potential ability to conduct heat as assessed by the HTC indicates that the snowpacks on the wind-swept tundra and Polygonal Peat Plateau centers would offer little resistance to heat loss (Table 1, Figure 5). In contrast, the forest stand snowpacks would have at least a factor greater resistance to heat loss.

The HTC was significantly different between the snowpack over the ice wedge troughs and the polygon centers on both the Degrading and Aggrading Peat Plateau sites. However, the greatest difference was found on the Degrading Polygonal Peat Plateau where the differences varied by more than a factor.

Figure 3: Heat Transfer Coefficient values were plotted on a log scale since the range was great. Forest HTC values were similar, although the burned forest values were significantly different at times. Tundra snowpack heat conduction characteristics were similar to Polygonal Peat Plateau centers. Histogram of mean with error bar for one standard deviation. **UTU**: Undisturbed Tundra, **PPA**: Polygonal Peat Plateau Aggrading, (**c**: polygon center, **w**: ice wedge trough), **PPD**: Polygonal Peat Plateau Degrading, **FOR**: white spruce forest, **BSB**: Black Spruce "Bog", **BFR**: Burned spruce forest.
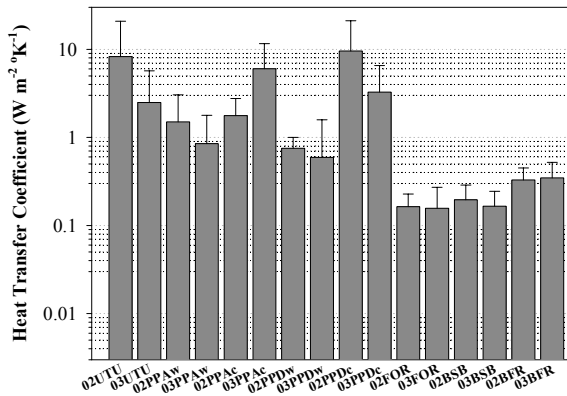
DISCUSSION

Snowpack depth:
    With no differences in snowpack depth between years it is reasonable to conclude that the prevailing climate conditions were similar between years – snowfall, wind speed and wind direction. The similarity among the forested sites, including the burned site suggests that an overriding influence on snowpack is wind and the standing tree snags were sufficient to maintain this effect. The depressed troughs associated with the degrading ice wedges accumulated snow depths similar to those of the forest stands. This was despite the lack of tree cover on these features.

    On elevated polygon centers snowpack depths were similar to the open tundra. This was the case whether the features were aggrading or degrading. It appears that the low height of the plant cover dominating the polygon centers and the tundra has the same effect on snow depth.

Snowpack density:
    The differences between years at sites with thin snowpack were probably an artifact of the variation in sampling procedures used by some of the groups. However, this difference cannot be quantified since deviation from the prescribed method was not recorded at the time of sampling. The density data for the thin snow of the Tundra and the Polygonal Peat Plateau centers could be incorrectly estimated but the amounts should be close to what they would have been if derived solely from the corers.

Snowpack SWE:
    The areas sheltered from wind, either due to tree trunks/burned snags or because of topographic depression, retained snow due to the inability of wind to effect drift. Where wind scour occurred, the snowpack was reduced and the SWE values were low in these areas – Tundra and Polygonal Peat Plateau centers.

Snowpack HTC:
    Characteristics of depth and density are the core of the calculation of the snowpack's potential to conduct heat. The wind-swept Tundra and Polygonal Peat Plateau centers with thin, high-density snow would offer little resistance to winter heat loss. However, the thicker, lower-density snow of the forests and the burn would offer better insulation and retention of heat gained during the thaw season. At sites where wind could scour the surface and entrain snow grains, topographic depressions trap snow that is in transit. The topographically-depressed ice wedge troughs consequently had deeper, higher-density snow with considerably higher insulative capacity when compared to the polygon centers.

CONCLUSIONS

    The snowpack depth on the depressed ice wedge troughs at the Degrading Polygonal Peat Plateau permitted the accumulation of snowpacks similar in depth to the sheltered interior of forest stands. However, because the snow was redistributed by wind, the density and SWE values in the ice wedge troughs were higher than in the forest areas. Wind-entrained snow grains accumulate best where the depressions are deepest and these were formed by surface subsidence as the ice wedges melted on the Degrading Polygonal Peat Plateau. The forest snowpacks were similar in most respects and the burned forest retained enough burned snags that wind had little effect on the snowpack. Considering the differences in stand characteristics between the upland and lowland forests and the burn it is noteworthy that there are few differences in snowpack characteristics.

    The characteristics of vegetation architecture in forest stands produce relatively uniform and similar showpacks over a broad range of tree heights and densities. Terrain characteristics such as surface depressions of as little as a few decimeters can dramatically alter the snowpack characteristics over short distances and often support snowpacks more similar to forest areas.

Snowpack characteristics affect their ability to insulate the ground against heat loss and this will affect the temperature characteristics of the soil, permafrost, and subnivean environment.

These studies are part of a long-term study to assess the impacts of climate change on snowpack characteristics in the future. Sampling protocols will be refined to insure consistency with future sampling at the permanent sites. Continuous monitoring of microclimate will provide details of snowpack depth, wind and temperature characteristics at these same sites.

ACKNOWLEDGMENTS

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