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Key Points:

- Shallow, near-surface taliks in subarctic permafrost environments influence active layer thickness by limiting the depth of freeze
- Areas with taliks experience more rapid thaw of underlying permafrost than areas without taliks
- Proportion of areas with taliks can increase in years with high ground heat flux, potentially creating tipping point for permafrost thaw

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The Influence of Shallow Taliks on Permafrost Thaw and Active Layer Dynamics in Subarctic Canada

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Abstract Measurements of active layer thickness (ALT) are typically taken at the end of summer, a time synonymous with maximum thaw depth. By definition, the active layer is the layer above permafrost that freezes and thaws annually. This study, conducted in peatlands of subarctic Canada, in the zone of thawing discontinuous permafrost, demonstrates that the entire thickness of ground atop permafrost does not always refreeze over winter. In these instances, a talik exists between the permafrost and active layer, and ALT must therefore be measured by the depth of refreeze at the end of winter. As talik thickness increases at the expense of the underlying permafrost, ALT is shown to simultaneously decrease. This suggests that the active layer has a maximum thickness that is controlled by the amount of energy lost from the ground to the atmosphere during winter. The taliks documented in this study are relatively thin (<2 m) and exist on forested peat plateaus. The presence of taliks greatly affects the stability of the underlying permafrost. Vertical permafrost thaw was found to be significantly greater in areas with taliks (0.07 m year^{-1}) than without (0.01 m year^{-1}). Furthermore, the spatial distribution of areas with taliks increased between 2011 and 2015 from 20% to 48%, a phenomenon likely caused by an anomalously large ground heat flux input in 2012. Rapid talik development and accelerated permafrost thaw indicates that permafrost loss may exhibit a nonlinear response to warming temperatures. Documentation of refreeze depths and talik development is needed across the circumpolar north.

1. Introduction

The active layer is the top layer of ground subject to annual thawing and freezing in areas underlain by permafrost (Associate Committee on Geotechnical Research, 1988). In permafrost terrains, most ecological and hydrological processes of interest occur in the active layer, and consequently, there is a need to measure and document changes to active layer thickness (ALT) over long periods of time (Bonnaventure & Lamoureux, 2013; Brown et al., 2008; Tarnocai et al., 2004). The thickness of the active layer is dependent on the surface energy balance, which is affected by many factors, including air temperature (Åkerman & Johansson, 2008; Kane et al., 1991; Sannel et al., 2016), snow accumulation and soil moisture (Atchley et al., 2016; Guglielmin, 2006; Johansson et al., 2013), vegetation composition (Jean & Payette, 2014), slope aspect (Carey & Woo, 1999), and angle (Hannell, 1973). Natural or anthropogenic changes to these variables can lead to changes in ALT.

Continental permafrost exists at high latitudes and altitudes, and typically where the mean annual air temperature (MAAT) is below 0°C. MAAT has increased significantly in northern Canada over the last 65 years (Vincent et al., 2015), and Intergovernmental Panel on Climate Change Fifth Assessment Report climate models project rapid warming to continue (Intergovernmental Panel on Climate Change, 2014), threatening to degrade both the areal extent and thickness of permafrost. Many studies predict that ALT will increase in response to this warming (Frampton & Destouni, 2015; Ge et al., 2011; Lawrence et al., 2012). Thawing of permafrost may result in the formation of thermokarst landscapes (Jorgenson & Osterkamp, 2005; Kokelj & Jorgenson, 2013; Lara et al., 2016), change how water is cycled and stored (Connon et al., 2015; St. Jacques & Sauchyn, 2009; Woo, 1990), and alter carbon storage by either enhancing organic matter accumulation or increasing methane emissions (Helbig et al., 2016; Johnston et al., 2014; Turetsky et al., 2007).

In the zone of continuous permafrost, permafrost thaw occurs predominantly in the vertical direction (i.e., increase in ALT), but in warmer environments, where permafrost is discontinuous or sporadic, permafrost

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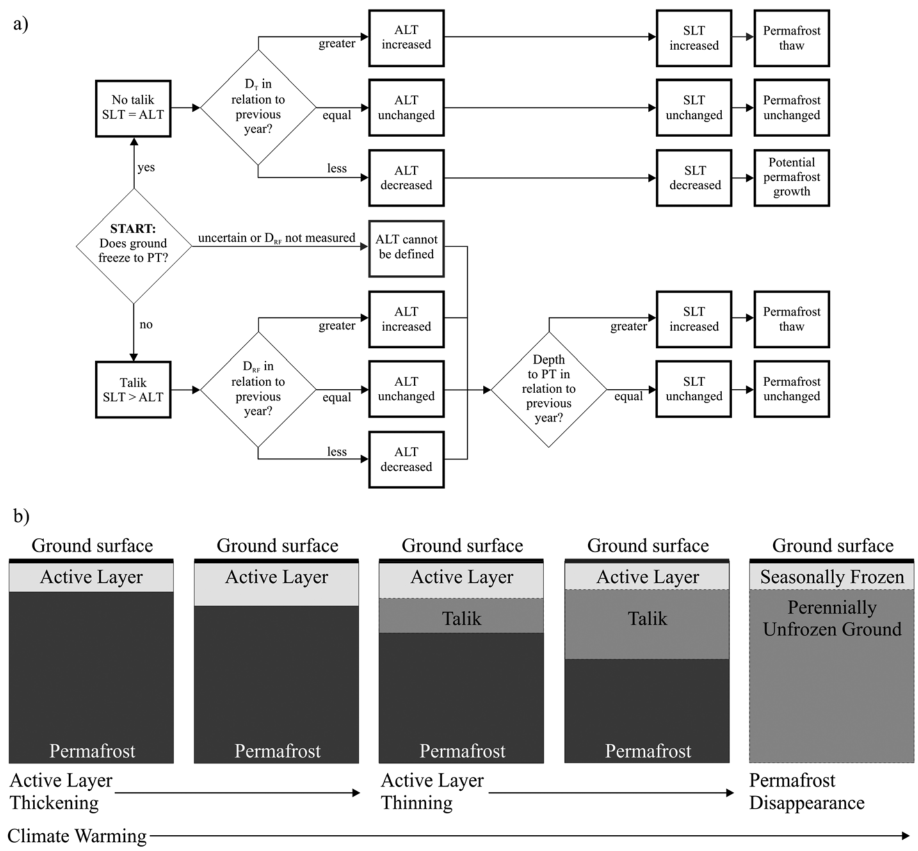

Figure 1. (a) Conceptual diagram of SLT and ALT changes based on field measurements and the associated impact on permafrost. D_{RF}: depth of re-freeze, D_T: depth of thaw; ALT: active layer thickness, SLT: suprapermafrost layer thickness, PT: permafrost table. (b) Changes in ALT in response to climate warming. ALT reaches a maximum prior to talik development. SLT is the combined thickness of the active layer and talik.

thaw can occur both laterally and vertically (Åkerman & Johansson, 2008; McClymont et al., 2013). In the southern fringe of discontinuous permafrost where MAAT is close to 0°C, permafrost is typically sporadic or discontinuous (<50% spatial coverage), thin (<10 m), relatively warm (> −2°C) and the ALT is relatively large and reported to be increasing (Brutsaert & Hiyama, 2012; Quinton & Baltzer, 2013). There has been a documented northward migration of the southern boundary of discontinuous permafrost (Beilman & Robinson, 2003; Kwong & Gan, 1994), and most climate and permafrost models predict that this trend will continue (Anisimov & Nelson, 1996).

ALT is typically measured in the field using a frost probe or simulated numerically using a thermal model. A common misconception is that ALT is equivalent to the depth to permafrost. As a result, ALT field measurements are almost always taken by measuring the distance from the ground surface to the permafrost table (PT) at the end of summer (i.e., Brown et al., 2008; Jean & Payette, 2014; Johansson et al., 2013; Sjöberg et al., 2012; Zenklusen Mutter & Phillips, 2012). Measurement of ALT using this method implicitly assumes that the entire thickness of ground above the PT refreezes during winter, though refreeze depths are rarely reported or measured. In areas of thawing discontinuous permafrost, this entire thickness may not refreeze, resulting in the formation of a shallow talik (layer of perennially unfrozen ground in permafrost areas) between the overlying active layer and the underlying permafrost. Complete refreeze can generally be assumed in areas of continuous permafrost where low temperatures and abundant ground ice limit thaw (Woo & Young, 2005); however, talik conditions may also exist locally in colder climates where the ground thermal regime and high snow cover can restrict energy loss over winter. For example, using a permafrost thermal hydrology model and simulating future ALTs, Atchley et al. (2016, Figure 4b) found that taliks may form at Barrow, Alaska, under inundated conditions with heavy snowfall.

As the subject of permafrost thaw is gaining interest across disciplines, there is a need to ensure consistency in how the active layer is defined and measured. Muller (1947) suggested that the term *suprapermafrost layer* be used to "describe the combined thickness of the active layer and talik", but this term is not currently used in the literature. In areas of discontinuous permafrost, or in areas where it is unknown whether the entire layer above the PT refreezes over winter, end-of-summer measurements of the depth to the PT are more accurately termed measurements of the suprapermafrost layer thickness (SLT). This term refers to the zone above the PT without implying the presence or absence of a talik. In areas where the suprapermafrost layer freezes entirely, ALT and SLT are synonymous. Changes to ALT and SLT in response to a warming climate are conceptualized in Figure 1, which also provides a basic framework that field practitioners can use to identify changes to ALT and SLT based on field measurements.

Most research on taliks has focused on those below aquatic bodies, such as lakes (Arp et al., 2016; Kokelj et al., 2009; You et al., 2017) and wetlands (O'Donnell et al., 2012; Sjöberg et al., 2016). Water flowing through taliks can introduce energy for permafrost thaw and can serve to limit downward progression of the freezing front in the winter. This process of energy advection through taliks has been evaluated through numerical simulations (e.g., see review by Kurylyk et al., 2014). Some studies have used numerical models to project the development of taliks in terrestrial environments (Atchley et al., 2016; Engelhardt et al., 2010; Lawrence et al., 2012); however, few have documented and studied them in the field (Jin et al., 2006; Zenklusen Mutter & Phillips, 2012). The presence of relatively shallow taliks in terrestrial systems is rarely reported.

In this study we present data from a field site in the southern Northwest Territories, Canada, where measurements indicate that thin taliks (thickness of <2 m) exist below terrestrial systems between the active layer and permafrost. We hypothesize that these shallow taliks facilitate rapid permafrost degradation and limit perpetual growth of the active layer. The objectives of this study are to (1) demonstrate that the active layer does not always extend to the PT, (2) examine the influence of taliks on thaw rates of the underlying permafrost, and (3) document changes to the ground thermal and moisture regime at a rapidly thawing permafrost cored peat plateau.

2. Study Site

Field work was conducted at the Scotty Creek Research Station (SCRS, 61°18′N, 121°18′W; Figure 2a), located about 50 km south of Fort Simpson, Northwest Territories, in the zone of sporadic-discontinuous permafrost (Heginbottom, 2000). MAAT (1981–2010) at Fort Simpson is −2.8°C, with a mean January temperature of −24.2°C and a mean July temperature of 17.4°C. MAAT has been rising rapidly in the region (2.5°C from 1950 to 2015) with the most pronounced increase in winter (4.5°C from 1950 to 2015) (Vincent et al., 2015). Mean annual precipitation (1981–2010) is 390 mm, with 149 mm (38%) falling in the form of snow. Annual precipitation has remained relatively stable over the past 50 years.

Scotty Creek drains a 152 km^2 subarctic boreal forest watershed in the Taiga Plains ecozone. Field studies were focused on the wetland-dominated headwaters, where the landscape is dominated by a mosaic of forested peat plateaus and wetlands mainly in the form of treeless collapse scar bogs and channel fens. Permafrost at the SCRS occurs below forested peat plateaus as described by Zoltai (1993), while the surrounding wetland terrain of bogs and channel fens is permafrost-free. Permafrost thaw has been rapid in this region (Robinson & Moore, 2000). Permafrost occupied approximately 70% of the Scotty Creek headwater area in 1947 but had decreased to approximately 43% by 2008 (Quinton et al., 2011). As the permafrost below plateaus thaws, the plateau ground surface subsides and becomes inundated by the adjacent wetlands, a process that results in the conversion of forest to wetland (Lara et al., 2016; Quinton et al., 2011; Zoltai, 1993). The predominant tree species of the forested plateaus is black spruce (*Picea mariana*), and ground vegetation takes the form of Labrador tea (*Rhododendron groenlandicum*), lichens (*Cladonia* spp.), and mosses (*Sphagnum* spp.).

Peat deposits in this region range from 2 to 8 m in thickness and overlie a silty-clay glacial till (Connon et al., 2015; McClymont et al., 2013). As the study site is blanketed by thermally insulating peat, the permafrost below the plateaus is protected by the large thermal offset between the ground surface and the permafrost (Robinson & Moore, 2000; Smith & Riseborough, 2002). Permafrost preserved by peat is a common feature of high boreal and subarctic regions throughout the circumpolar north, especially in the zones of discontinuous

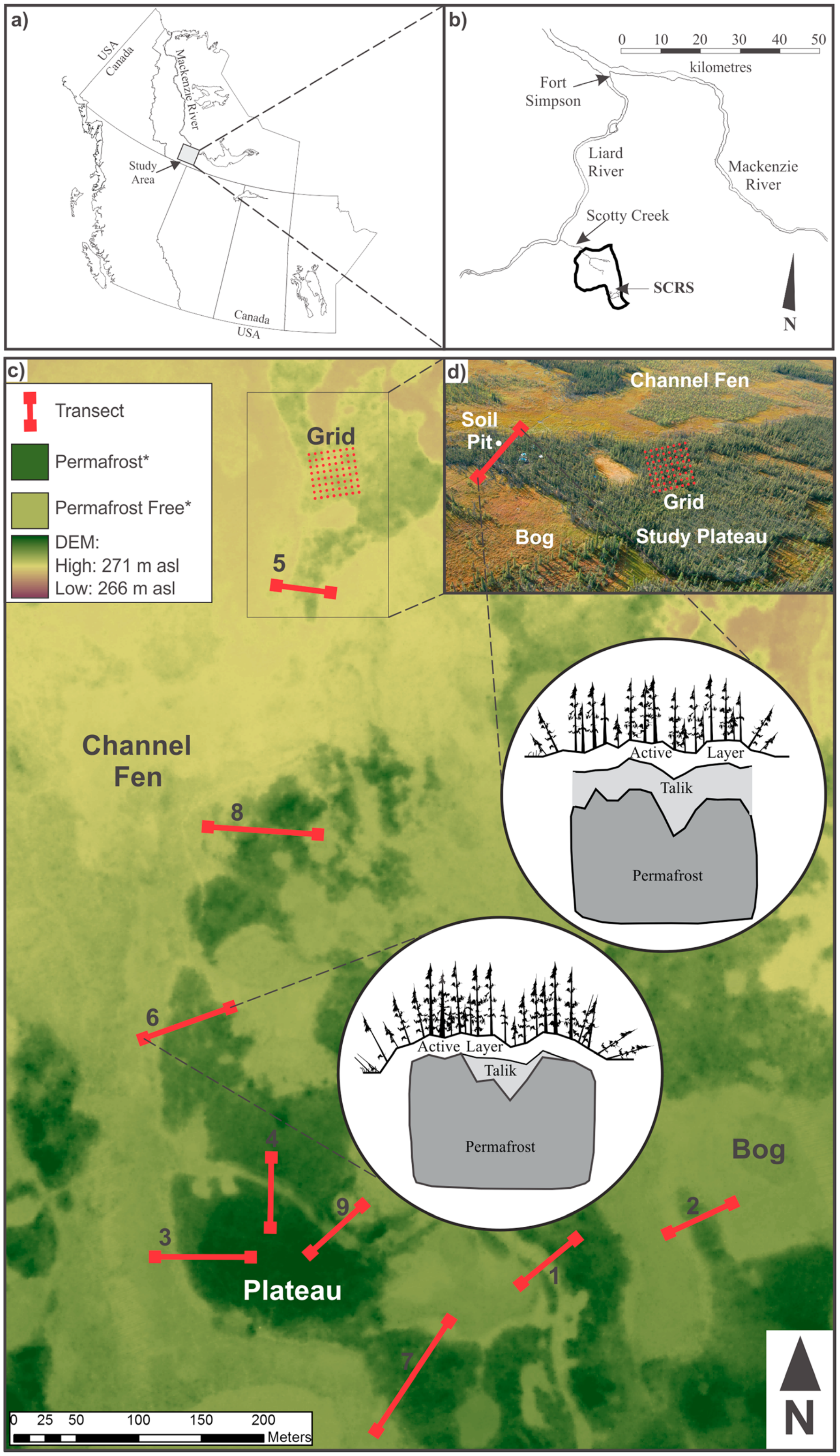

Figure 2. (a) Map of the study area within Canada. (b) Inset of the Scotty Creek region. Basin boundaries represent the area of the basin gauged by the Water Survey of Canada. (c) Study site, including nine transects and one grid overlain on a digital elevation model of the basin. *Colors for permafrost and permafrost-free terrains are approximate, as color is based on the digital elevation model and elevation decreases northward. Bubble insets show cross sections at two transects. Ground surface, active layer, talik, and permafrost boundaries are all to scale and were measured in the field. The base of the permafrost is for illustrative purposes only and is not to scale. Permafrost thicknesses at the Scotty Creek Research Station range from 5 to 13 m (McClymont et al., 2013). (d) Inset of Study Plateau from aerial photograph (2006).

and sporadic permafrost (Brown, 1970). A detailed description of Scotty Creek and the hydrological function of each land cover type can be found in Quinton et al. (2003).

Measurements of depth to permafrost and plateau width have been taken since 1999 at a "Study Plateau" (Figure 2d, Transect 5), along with standard meteorological data and subsurface temperature and soil moisture data. The Study Plateau is flanked by a flat bog on one side and a channel fen on the other. It is experiencing rapid lateral and vertical permafrost loss with the current width (<20 m) being less than half of what it was when measurements began in 1999 (~40 m). This Study Plateau allows for a unique investigation of a permafrost peat plateau that is actively transitioning into a wetland.

3. Methods

3.1. SLT and ALT Measurements and Talik Occurrence

SLT measurements have been taken at the end of summer since 1999 at 1 m intervals along a transect spanning the width of the Study Plateau (Transect 5). In 2011, eight additional transects (widths between 21 and 69 m) were created to determine if the changes occurring at the Study Plateau were representative of the rest of the basin. Measurements at the additional transects were made at 3 m intervals. Each additional transect intersected a wetland/plateau boundary and extended into the interior of a permafrost plateau. Each transect was positioned so it would include the permafrost conditions of both the stable plateau interior, and the 3 to 15 m wide plateau margin where the SLT is significantly greater (Baltzer et al., 2014). In 2011, a 40 m × 40 m grid with 5 m measurement intervals (64 points) was established on the interior of a large plateau to measure permafrost thaw without the influence of edge effects (Figure 2d).

Each measurement point on the transects and in the grids was marked with a flag and located using a differential Global Positioning System (SR530 RTK, Leica Geosystems Inc., Norcross, USA; system accuracy ±0.02 m). Ground surface elevation was also recorded at all points, apart from 15 points in the grid where the Global Positioning System signal was lost. SLT measurements were made at all points in late summer (26–29 August) in 2011, 2015, and 2016. Early spring (12–16 May) and late spring (4–6 June) measurements of seasonal thaw (i.e., depth to the frost table) at each transect were made in 2011 and 2015. Thaw depth measurements were made by inserting a 1 cm diameter, graduated steel rod (i.e., frost probe) into the ground until the depth of refusal (Nelson & Hinkel, 2004).

In view of the definition of the active layer, ALT measurements require a measurement of the depth of refreeze in addition to end of summer thaw depth measurements. Thermistor and soil moisture sensors can provide an approximate depth of refreeze, but logistical constraints typically prevent a large spatial distribution of these sensors. The depth of refreeze was measured along the nine transects using either a frost probe or an ice auger in early April 2016 (n = 135). Additional refreeze measurements (although a smaller sample size, n = 58) were taken in early April 2017 to include an additional year of data.

3.2. Frost Probe

After snow was removed from above each measurement point, a frost probe was inserted into the ground until the depth of refusal. The frost probe was then removed from the ground and reinserted forcefully and repeatedly in order to penetrate incrementally into the frozen active layer. Each time the frost probe was removed and reinserted into the ground, the new depth was read and recorded (average increase of <1 cm per increment). If the depth increased by at least 10 cm in a single increment, it was assumed that the active layer had been fully penetrated and a talik was reached. The last incremental depth value recorded prior to penetrating the talik was assumed to be the depth of refreeze. The depth to refusal on the next increment was assumed to be the PT. When a talik was not found (i.e., ALT = SLT), probing was terminated at the depth equal to SLT as recorded in the previous fall.

3.3. Ice Auger

Measurements taken using the frost probe were verified at 50 randomly selected points using an ice auger. A 15 cm diameter hand-held ice auger (*Rapala*, Oshawa, Canada) was used to drill through the frozen peat until the underlying talik (if present) was reached. The maximum depth of the freezing front was easily identifiable as the interface between frozen and unfrozen peat and can be accurately measured with a ruler. After the talik was reached, a frost probe was used to measure the remaining depth to the PT needed to define the

SLT. The water pressure in the talik was always greater than atmospheric, causing the water level in the borehole to rise above the base of the frozen layer. The ice auger method allows for an accurate measure of the depth of refreeze; however, it is destructive and can be labor-intensive and time-consuming. Measurement differences between the two methods were <5 cm, suggesting that the frost probe method was sufficiently accurate. Measuring the depth of refreeze using the frost probe is much more practical when many measurement points are required and when destructive sampling is not viable.

3.4. Ground Temperature and Soil Moisture

An array of 11 thermistors (soil temperature) and five water content reflectometers (soil moisture) were installed in a 0.7 m deep soil pit near the center of the Study Plateau in 2001 (see Hayashi et al., 2007, for instrumentation design). The data from these sensors are used in this study to monitor soil temperature and liquid water content. Soil moisture data were used to calculate the total number of days that the soil was frozen at each depth. A sharp decrease in volumetric liquid soil moisture is detected by the water content reflectometers during soil freezing. Typically, water content sensors at depth (0.3, 0.4, and 0.5 m below ground surface) are saturated and have a moisture content of about 0.8 (i.e., porosity). Liquid water content in frozen soils at the study site is typically in the range of 0.15 to 0.2. To allow for some variation in liquid water content in the frozen state, a frozen condition was assumed during winter when the liquid water content decreased below 0.3.

3.5. Ground Heat Flux

Ground heat flux (Q_G, W m^{-2}) at the Study Plateau was measured using a ground heat flux plate (Campbell Scientific, HFT3) at the soil pit referred to above. The heat flux plate was installed at 0.05 m depth and was calibrated as in Hayashi et al. (2007). Heat storage in the upper 0.05 m of the soil was added to the flux measured by the heat flux plates to obtain a measure of the heat flux at the soil surface (Mayocchi & Bristow, 1995). Hayashi et al. (2007) rigorously tested the quality of the ground heat flux plates by comparing these values to those derived from the calorimetric and gradient methods. The authors demonstrated that after applying the calibration, all three estimates yielded similar results.

3.6. Radiation and Temperature

Four component radiometers (Kipp & Zonen, CNR1) were installed 2 m above the ground surface and mounted on a tripod at a thawing peat plateau (Study Plateau), a stable plateau, and in an adjacent permafrost-free bog. Radiometers were not heated, but only measurements during the snow-free season are used in this study. Air temperature was recorded at the same locations with a thermistor housed in a passively ventilated Gill radiation shield. All sensors were connected to a data logger (Campbell Scientific, CR10X), which took measurements every minute, and averaged and recorded values either hourly or half-hourly.

3.7. Snow Measurements

Snow water equivalent (SWE) is measured annually at the end of winter along snow courses established in March 2006. Due to differences in canopy snow interception and snow accumulation in different land cover types, the end of winter snow surveys are conducted independently on plateaus, bogs, fens, and lakes. Measurements of snow depth were made at intervals of 1 to 5 m using a ruler, and SWE is measured at every fifth depth measurement point using an Eastern Snow Conference snow sampler (Wright et al., 2008) and calibrated scale. SWE values were then averaged for each transect and land cover type for each year.

4. Results and Discussion

4.1. Talik Occurrence

Our measurements indicate that points with greater SLT do not necessarily have greater ALT, demonstrating the need to take measurements of the depth of refreeze (Figure 3). These data also demonstrate that the likelihood of a talik at a given site can be evaluated from end of summer SLT measurements at this monitoring site. Specifically, when SLT is <60 cm, the ground completely refreezes during winter, preventing talik formation. In 2016, the maximum measured ALT among the 135 measurements was 74 cm. In 2017, the majority (78%) of refreeze depths ranged between 50 and 70 cm. Only 9% of the refreeze depths exceeded 70 cm that year; however, one depth also exceeded 80 cm (85 cm). Given that only one refreeze depth exceeded 80 cm over the two years, and considering the <5 cm error associated with the frost probe method, a talik can be reasonably assumed when the SLT is greater than approximately 80 cm. For the 60 to 80 cm depth range, a

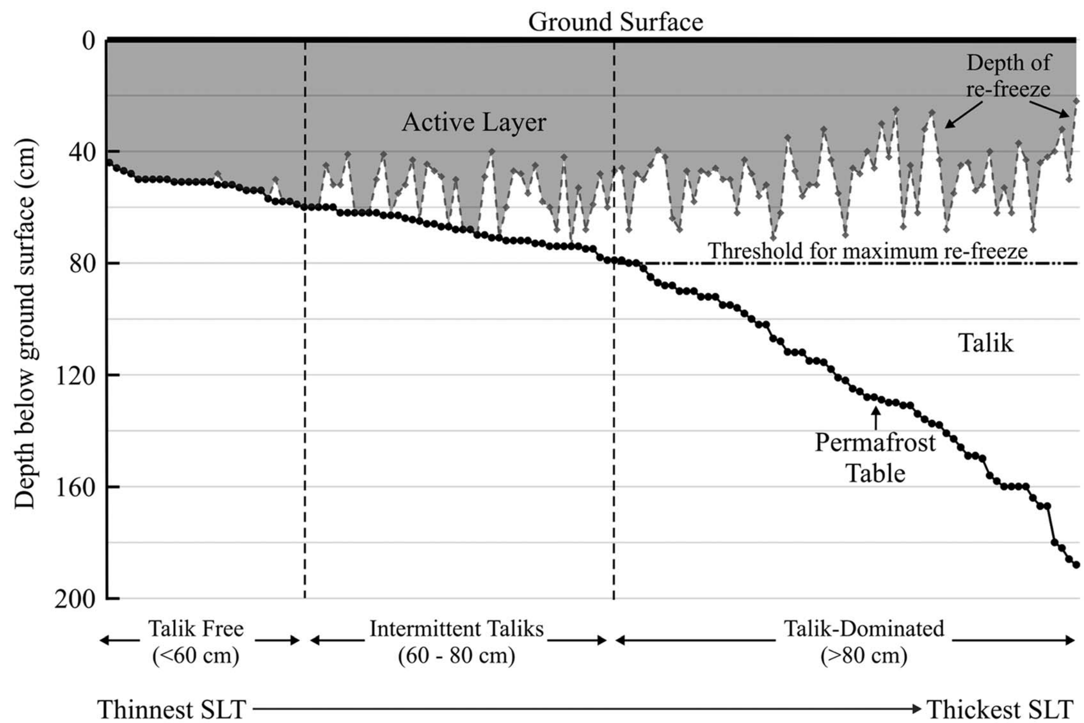

Figure 3. Suprapermafrost layer thickness measurements ranked from (left) thinnest to (right) thickest and associated thaw depth measurements. Active layer refreeze depth was measured in April 2016, following thaw depth measurements in August 2015.

talik may or may not be present. These findings indicate that there is a threshold for maximum ALT at this study site, preventing the perpetual growth of the active layer over time. To our knowledge, the concept of a threshold for maximum ALT has not yet been discussed in the literature. The data and locations of vertical boundaries plotted on Figure 3 represent the 2016 season at Scotty Creek and may vary year to year with variations in air temperatures, timing, and magnitude of snowfall and changes in soil moisture. Although the methods used here are applicable to other permafrost regions, site-specific measurements are required to evaluate local ALT values.

Similar to ecological space-for-time substitutions (Blois et al., 2012), Figure 3 suggests how SLT and ALT might change at a specific point or site over a period of decades while the underlying permafrost thaws. Space-for-time measurements involve using a spatial distribution of heterogeneous conditions to model and understand temporally changing conditions, which may not be possible to observe. Initially, active layer thickening is expected, as the ALT increases from 40 to 60 cm. As the SLT increases to between 60 and 80 cm, ALT may be highly variable interannually and may be governed by either maximum depth of thaw or freezing, depending on meteorological conditions. Eventually, when the ~80 cm ALT threshold is surpassed, ALT is controlled entirely by the maximum depth of freezing.

4.1.1. Active Layer Thinning

In response to higher winter air temperatures in northern Canada (Vincent et al., 2015) and/or increases in snowfall (Prowse & Furgal, 2009), freeze-thaw models predict a thinning of the layer which refreezes annually (Frauenfield et al., 2004; Lawrence et al., 2012). Assuming saturated conditions, the heat capacity of ground with a talik is greater than ground without a talik. The talik will retain more energy and experience a temperature increase (in the form of sensible heat). As this energy must be removed before refreeze can commence, refreeze in areas with taliks may lag those without taliks. This results in a delayed onset of the zero curtain period (period of time in which the ground remains isothermal at the freezing point due to phase change). This is compounded when early season snow accumulation insulates the ground from cold atmospheric temperatures and restricts energy loss. Furthermore, higher air temperatures in winter will also decrease the thermal gradient between the atmosphere and ground surface. This combination may limit the downward penetration of the freezing front, and in turn, decrease ALT. Therefore, in areas where ALT is governed by

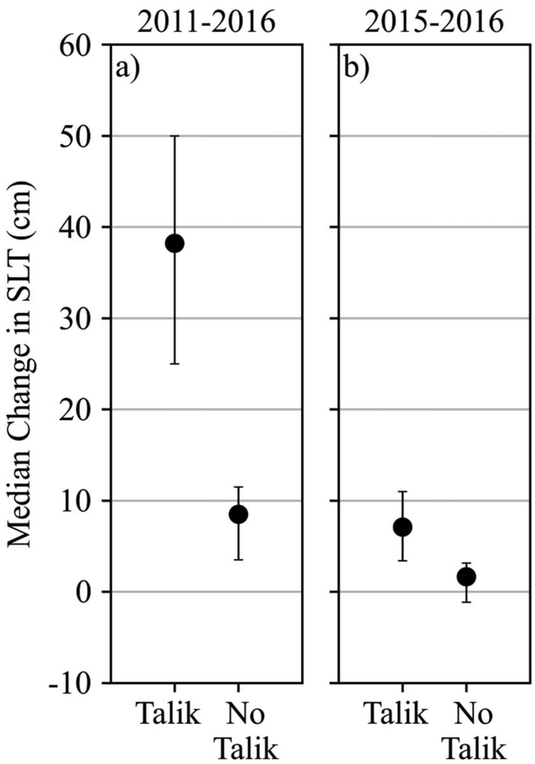

Figure 4. Change in median suprapermafrost layer thickness (SLT) over (a) 5 years (2011–2016) and (b) 1 year (2015–2016). The error bars indicate interquartile range.

the maximum annual depth of the freezing front, ALT should decrease in response to higher temperatures. This is supported by the data presented in Figure 3, which shows that ALT decreases slightly as the SLT increases. For example, ALT of <40 cm are observed only where SLT $>$ 1 m. To the knowledge of the authors, the concept of a thinning active layer in response to a warming climate has not yet been discussed in the literature.

4.1.2. Talik Classification

Shur et al. (2005) discussed the importance of classification when describing the vertical profile of a permafrost system and demonstrated the need to include the transition zone (top layer of permafrost that undergoes freeze-thaw on longer timescales) in conceptual models. Expanding on this idea, we recommend including the suprapermafrost layer in such models. Although the presence of taliks are widely recognized by permafrost researchers (i.e., Engelhardt et al., 2010; Marchenko et al., 2008), we feel that it is important to distinguish between SLT and ALT measurements for the thermodynamic implications. In the absence of a talik, permafrost aggrades, degrades, or remains stable by the balance between energy gained during summer when the thermal gradient is directed downward, and energy lost during winter when the thermal gradient is directed upward. However, once a talik has formed, the permafrost body continually gains energy from the downward directed thermal gradient of the relatively warmer talik during winter and throughout the year. The presence of a talik also introduces an upward directed flow of energy to the active layer. If active layer measurements are used to validate numerical models (see Brown et al., 2008, pp. 168), it is necessary to differentiate between the active layer and suprapermafrost layer (when applicable) to accurately represent subsurface thermodynamics.

4.2. Effects of Taliks on Permafrost Thaw

These observations indicate that once a talik is formed, thawing of the underlying permafrost accelerates. Increases in SLT are significantly greater ($p > 0.01$) at points that have a talik than at those without (Figure 4). The median SLT increase over five years (2011 to 2016) was 37 cm at points with a talik, but only 8 cm at points without a talik. Measured increases in SLT over the one year (2015 to 2016) period indicate a median SLT increase of 7 cm at points with a talik, but only a 1 cm increase at points without a talik.

A frequency distribution (Figure 5) compares thaw depths at all transects for early spring, late spring, and late summer between 2011 and 2015. Late summer thaw depth measurements for the grid are also included for the same two years. Q_G during the summer period (1 May to 31 August) of 2011 and 2015 was similar (183.4 and 179.3 MJ m^{-2}, respectively), as was the location of the frost table relative to the ground surface in early spring (Figure 5). If it is assumed that the frost table defines the top of the saturated, frozen layer, then ground ice content is similar between the two years as well. This would suggest that average end of season thaw depth should also be similar between the two years in a stable system. The distributions of early and late spring thaw depths are similar; however, the distributions of late summer thaw depths vary significantly. In 2011, only 20% of points on the transects had an SLT $>$ 80 cm, compared to almost half of the points (48%) in 2015. Assuming that points with an SLT $>$ 80 cm have a talik (Figure 3), there is a drastic increase in the number of points with a talik over the course of four years. This trend is also observed when considering data from the grid. In 2011, 8% of the grid had an SLT $>$ 80 cm, whereas by 2015 this value increased to 33%. The proportion of points in the grid with taliks is likely smaller than the proportion of points on the transects with taliks because the transects traverse the edges of plateaus (see Figure 2c), which are more likely to have increased thaw depths (Baltzer et al., 2014). The grid is located entirely on the interior of a plateau and is devoid of these edge effects.

4.2.1. A "Tipping Point" Type Change

We hypothesize that the dramatic changes occurred to ground thermal regimes at the study site between 2011 and 2015 and that these constituted a type of tipping point that generated large increases in the

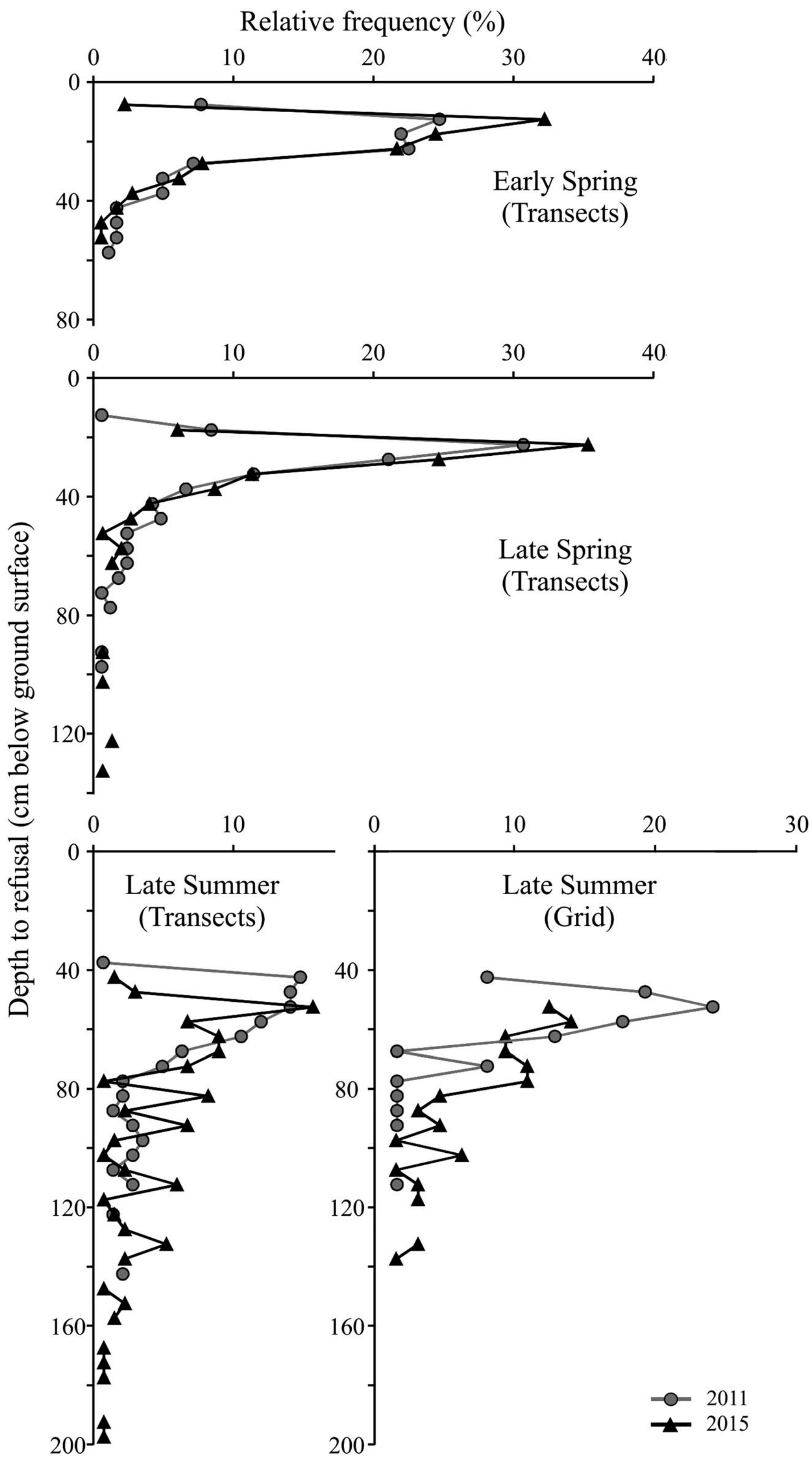

Figure 5. Frequency distribution of thaw depths at all transects for early spring (12–16 May), late spring (04–06 June), and late summer (26–29 August) of 2011 and 2015. Late summer thaw depths for the grid are also shown. Of note is the increase in late summer thaw depths of greater than 80 cm for 2015, suggesting increased talik development.

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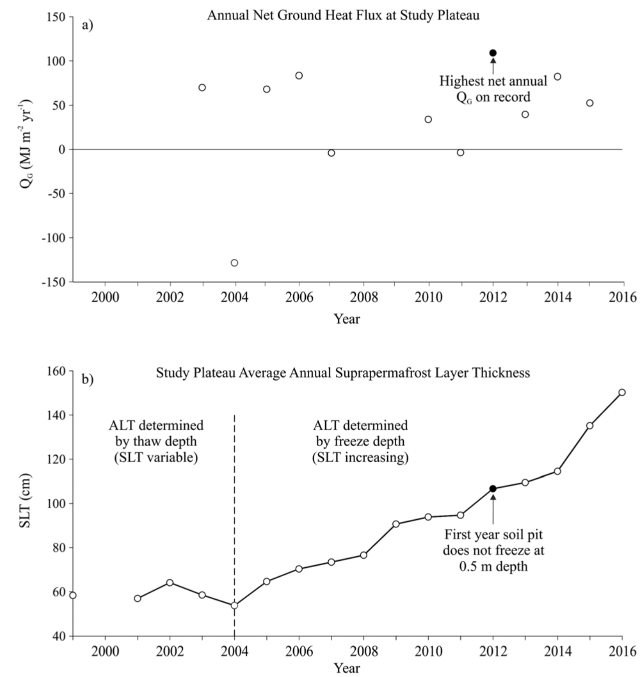

Figure 6. (a) Net annual ground heat flux measured by a ground heat flux plate at the Study Plateau since 2003. Instrument malfunction prevented data collection in 2009. (b) Suprapermafrost layer thickness (SLT) measured at the end of summer at the Study Plateau.

rate of talik development and expansion. The net annual ground heat flux (Figure 6) in 2012 (108.9 MJ m^{-2}) was the largest since measurements began in 2003, and the summer contribution (192.4 MJ m^{-2}) was among the highest as well (average: 170.6 MJ m^{-2}; SD: 18.6 MJ m^{-2}). The following winter, end of season SWE on the plateaus was 151 mm, much higher than the average (127 mm) of the 13 year record at Scotty Creek. Together, the abnormally high summer energy input combined with the insulating effects of increased snow cover inhibited penetration of the freezing front during the winter of 2012/2013. This is likely to have initiated the talik development documented in this study. The soil moisture data (Figure 7) also show that 2012 was the first year of incomplete refreeze at the 40 and 50 cm depths. In three of the four years following 2012, refreeze does not occur at 50 cm depth. This suggests that one abnormally warm thaw season, followed by a winter with shallow refreeze depths, can cause widespread talik development leading to rapid permafrost thaw. The recurring net annual positive Q_G contributions indicate that permafrost in this region is in disequilibrium with the current climate and is especially susceptible to degradation during warm years. This observation is consistent with a numerical modeling study by Christensen (2014, Figure 2.12), who used the physically based Northern Ecosystem Soil Temperature model (Zhang et al., 2003) forced by the data from our study sites to show that the ALT starts to increase rapidly after it reaches a threshold depth of ~1.0 m and a talk develops between the active layer and the PT.

Chasmer and Hopkinson (2016) postulate that the strong El Niño/Southern Oscillation (ENSO) event of 1997/1998 may also have been a tipping point for accelerated permafrost thaw in areas of discontinuous permafrost. They show that permafrost coverage and runoff ratios change significantly after this event; however, they do not identify a mechanism for this expedited thaw. We propose that similarly to the warm summer of 2012, the ENSO event may have initiated talik development at some locations within the basin. Unfortunately, field monitoring at the SCRS did not begin until 1999, so field-based analysis of the impact of the ENSO event on thaw depth is not available. It has been well documented that permafrost exerts control on water cycling and storage (Carey & Woo, 1999; Wright et al., 2009) and that permafrost thaw may change these patterns (Connon et al., 2014, 2015; St. Jacques & Sauchyn, 2009; Walvoord & Kurylyk, 2016). As shown in this study, talik formation results in more rapid permafrost thaw and may in turn make the basin more effective at conveying runoff and thereby increase runoff ratios.

4.3. Case Study of a Rapidly Thawing Permafrost Plateau

Ongoing field measurements since 1999 have documented vertical and lateral retreat of permafrost at a long-term Study Plateau in the SCRS (Figure 8). Thaw rates at eight additional transects indicate that this rapid permafrost loss is not consistent across the sampled portion of the basin (Table 1). The Study Plateau transect is underlain by a talik that provides a subsurface connection between the bog and the channel fen (as shown in cross sections Figure 2c). The additional eight transects do not cross any other taliks connecting wetlands; however, additional probing in August 2016 found other locations in the basin with a fully connected talik between two wetlands. All features were found in areas where the plateau width between two wetlands is $<$30 m. The data presented in this study show that the study transect has undergone nearly full conversion from a raised peat plateau to a wetland. Initial SLT measurements at the Study Plateau (1999–2004) suggest that taliks were not present on the plateau when it was first instrumented (Figure 6), and subsequent measurements illustrate the growth and expansion of taliks. This plateau offers a unique opportunity to document changes to subsurface soil properties as the permafrost thaws over time.

4.3.1. Ground Heat Flux Changes

Net annual Q_G was positive for 8 of the 11 years in the study (Figure 6), providing unstable conditions for the underlying permafrost. Year 2004 had the lowest net ground heat flux ($-$128.6 MJ m^{-2}) and was the year with the lowest recorded average SLT. Other years with a small negative annual ground heat flux (2007 and 2011)

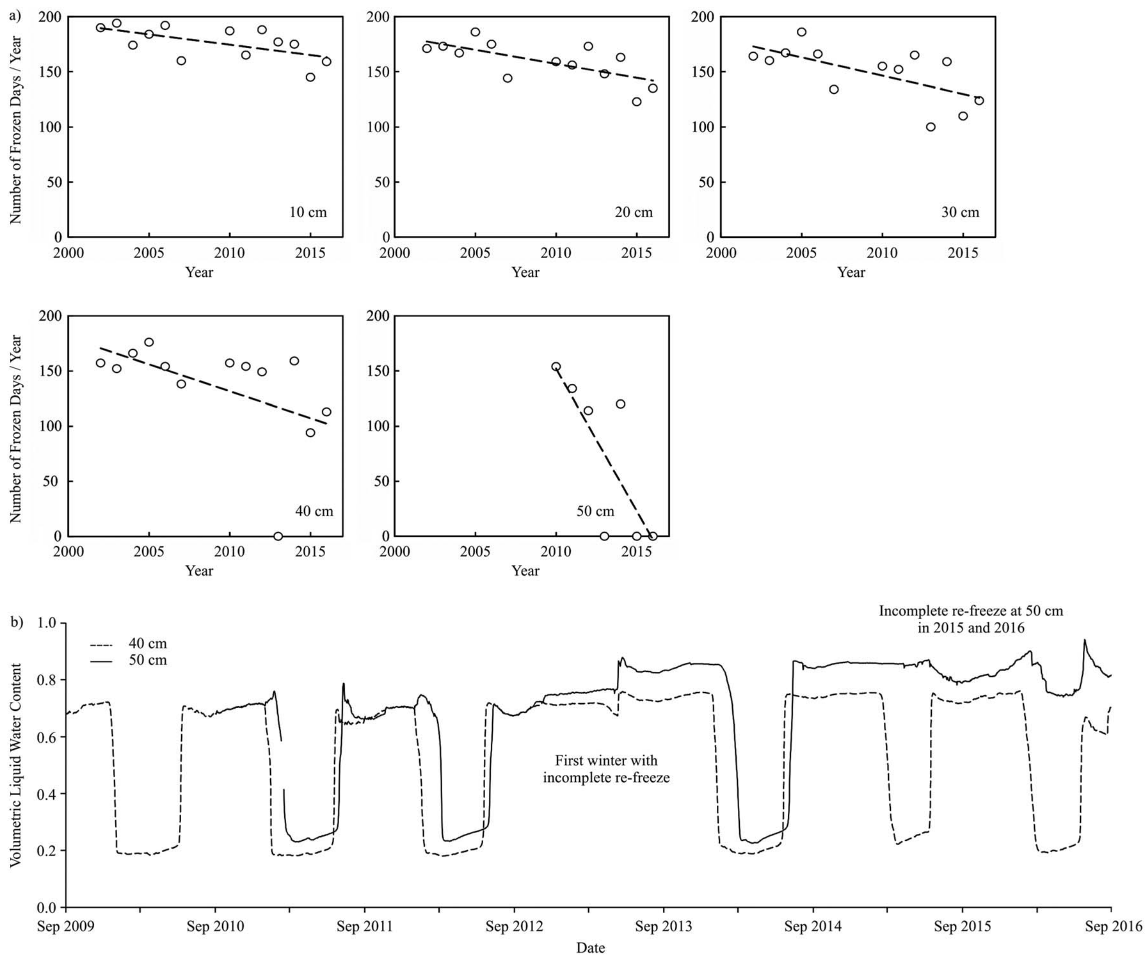

Figure 7. (a) The annual number of frozen days at 10, 20, 30, 40, and 50 cm depths at the Study Plateau as indicated by the water content reflectometers. A frozen day is assumed when volumetric liquid water content (VWC) dropped below 0.3. (b) VWC at 40 and 50 cm depths at the Study Plateau from September 2009 to 2016. Soil freezing can be observed as periods when VWC drops to values at ~0.2. During years when VWC does not drop, the soil remains saturated with liquid water year round and a talik is assumed.

did not respond with decreases in SLT, nor did they experience the appreciable increases in SLT observed in other years. During these years, there was enough energy to thaw the active layer, but not enough to thaw the underlying permafrost. The year with the largest Q_G (2012) was the first year that the water content reflectometers indicated incomplete freezing of the soil. In 2015, a relatively small annual Q_G resulted in the second largest increase in SLT. This suggests that downward conduction of energy may not be the only mechanism contributing to soil thaw. Quinton and Baltzer (2013, Figure 6c) plotted thaw curves for each year from 2002 to 2010 at each of the 11 thermistor depths. These curves were relatively linear (i.e., unattenuated) throughout the soil profile, despite a decreasing thermal gradient as the thaw front extended further below the ground surface. The reason for the lack of attenuation is unclear; however, advection of energy through the connecting talik may provide an additional energy source to expedite permafrost thaw. Further investigation is required to quantify the contribution of advection to permafrost degradation.

There is a demonstrated link between moisture levels and thaw depth (Hayashi et al., 2007; Wright et al., 2009, Figures 6 and 7). In 2006 the point with the highest elevation on the plateau along the Study Plateau transect was 0.9 m higher than the adjacent wetlands (Wright et al., 2009). In 2015, the highest point was only 0.42 m higher than the wetland surface, indicating subsidence of the plateau in response to vertical permafrost thaw. As the ground surface subsides, it becomes closer to the elevation of the water table in the wetlands, and the thermally insulating unsaturated zone thins. This gradual subsidence is consistent with increases in near-surface soil moisture conditions, which increases seasonal thaw through an increase in thermal conductivity. When the elevation of the PT at all points along the transect drops below the elevation of

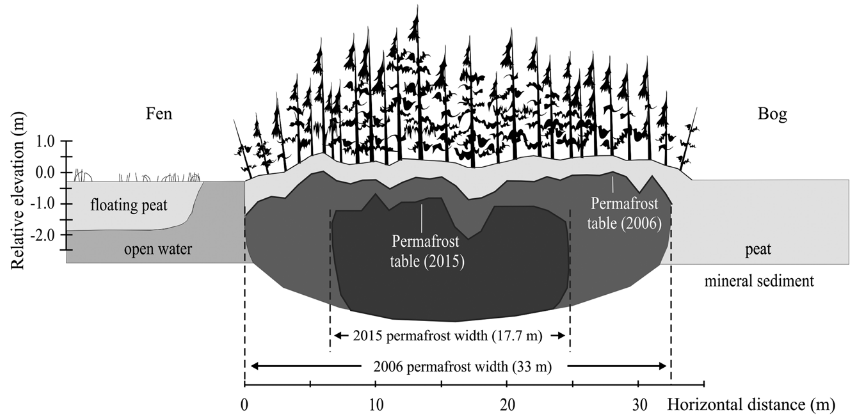

Figure 8. A cross section of the Study Plateau depicting lateral and vertical loss of permafrost between 2006 and 2015.

the water table in both wetlands, water movement through the plateau is initiated in the direction of the hydraulic gradient. The combination of subsidence, increased moisture levels, talik development, and cross-plateau flow enhances permafrost thaw on the plateau and will result in the eventual conversion to a wetland.

4.3.2. Radiation and Soil Moisture Changes

Ongoing permafrost thaw and talik development at the Study Plateau has resulted in marked changes to subsurface thermal and moisture conditions. Annual maximum subsurface temperatures have been increasing since 2001, with the most significant changes occurring at the three deepest thermistor depths (50, 60, and 70 cm below the ground surface; Figure 9). For example, the maximum temperature at 70 cm depth has increased by 6.7°C over the last 15 years. Soil temperatures at the three depths shown in Figure 9 do not drop below the zero curtain for three of the last four years, indicating the presence of a talik in which the soil does not completely freeze. Analysis of soil moisture data shows a decline in the number of days the soil is frozen each year at all depths (10, 20, 30, 40, and 50 cm below the ground surface; Figure 7). The changes documented here may be caused by greater energy input through increased net radiation, less energy loss through increased snowpack, or greater thermal storage in a thickening talik. It has been suggested that in discontinuous permafrost terrains, shading provided by the tree canopy reduces incoming shortwave radiation (K↓) enough to maintain permafrost, where otherwise it would degrade (Shur & Jorgenson, 2007). As the permafrost core of a plateau thaws and retreats laterally, biomass at the plateau edges is reduced (Chasmer et al., 2011), thereby increasing K↓, and the amount of energy incident at the ground surface. This effect is pronounced at high latitudes, where the low sun angle increases the shading influence of trees at plateau edges.

To investigate this, total K↓ on the plateau was compared to K↓ in an adjacent treeless bog on cloud-free days in 2005, 2007, and 2015. It was found that K↓ on the plateau relative to the bog had increased significantly

Table 1
Average SLT at Each Transect and Grid in 2011, 2015, and 2016 and the % Cover With a Talik

	Average SLT (cm)				% With talik		
Location	2011	2015	2016	Change	2011	2015	2016
Transect 1	53.1	71.4	73.2	20.1	8%	25%	25%
Transect 2	77.5	85.1	90.6	13.0	25%	43%	43%
Transect 3	57.1	66.5	70.7	13.6	0%	24%	25%
Transect 4	65.5	84.1	83.8	18.3	13%	36%	36%
Transect 5	90.0	135.2	149.7	59.7	73%	100%	100%
Transect 6	58.2	69.6	72.0	13.8	13%	33%	33%
Transect 7	48.5	67.3	70.8	22.2	0%	13%	22%
Transect 8	57.3	82.4	87.2	29.9	10%	45%	58%
Transect 9	63.7	84.6	95.3	31.6	14%	68%	76%
Grid	57.4	76.7	74.7	17.4	6%	33%	38%

Note. Taliks were assumed when suprapermafrost layer thickness (SLT) $>$ 80 cm.

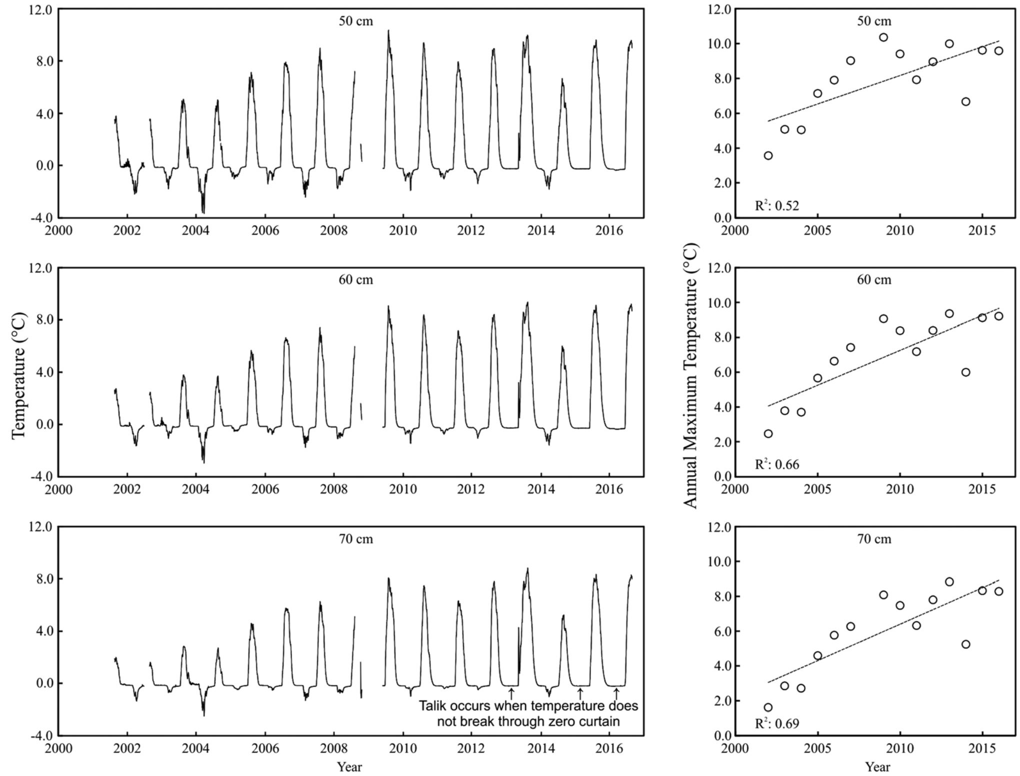

Figure 9. Soil temperatures at 50, 60, and 70 cm below the ground surface at the Study Plateau. Annual maximum temperatures have been increasing steadily since 2002.

between the two periods (Figure 10), aiding in the thaw of the plateau. In 2005, the Study Plateau received, on average, 80% of the total K↓ that the bog received, as opposed to 87% in 2015. Decreases in late summer plateau to bog K↓ ratios are reflective of lower sun angles at this time of year. K↓ was also compared between a stable plateau and the bog between 2007 (the first year measurements were made) and 2015, and no significant differences in K↓ were found, providing evidence that the changes in K↓ ratios at the Study Plateau are a response to thawing permafrost. Increased K↓ ratios at the Study Plateau suggest a reduction in LAI, allowing for more shortwave radiation to penetrate through the canopy to the ground surface (see half hour resolution in Figure 10). It can be reasoned that this canopy thinning may also reduce the interception of snow in the tree canopy, allowing for more snow accumulation on the ground. Increasing snow cover (during early winter) will reduce the amount of over-winter energy loss from the ground and may explain the warmer soil temperatures and talik development.

4.3.3. Talik Distribution

Baltzer et al. (2014) demonstrate that thaw rates around the periphery of plateaus are much higher than on the interior and conclude that the fragmentation of plateaus will cause faster thaw at the landscape scale. We hypothesize that similar processes occur along the periphery of taliks in the plateau interior and that plateaus may begin to fragment internally, which is consistent with the results of geophysical imaging indicating the presence of deep (~2 m) PT along the edge of the Study Plateau (McClymont et al., 2013, Figure 4b). Within a plateau, taliks can appear as either isolated or connected features (see insets in Figure 2c). We suggest that taliks initially occur on plateaus in areas with a sparse tree canopy, increasing the net radiation incident to the forest floor and enhancing summer thaw depth. If the ground loses insufficient energy over winter to completely refreeze to the PT, then an isolated talik is formed. This process is analogous to the formation of collapse scar bogs as described by Robinson and Moore (2000). Once multiple isolated taliks form on a plateau, their growth and coalescence enables subsurface connections among them and may facilitate perennial groundwater flow. Such a talik will eventually form a subsurface hydrological connection with adjacent wetlands where vertical thaw rates may be enhanced by the lateral transfer of energy via advection (i.e., Rowland et al., 2011; Sjöberg et al., 2016). The cross section of the study

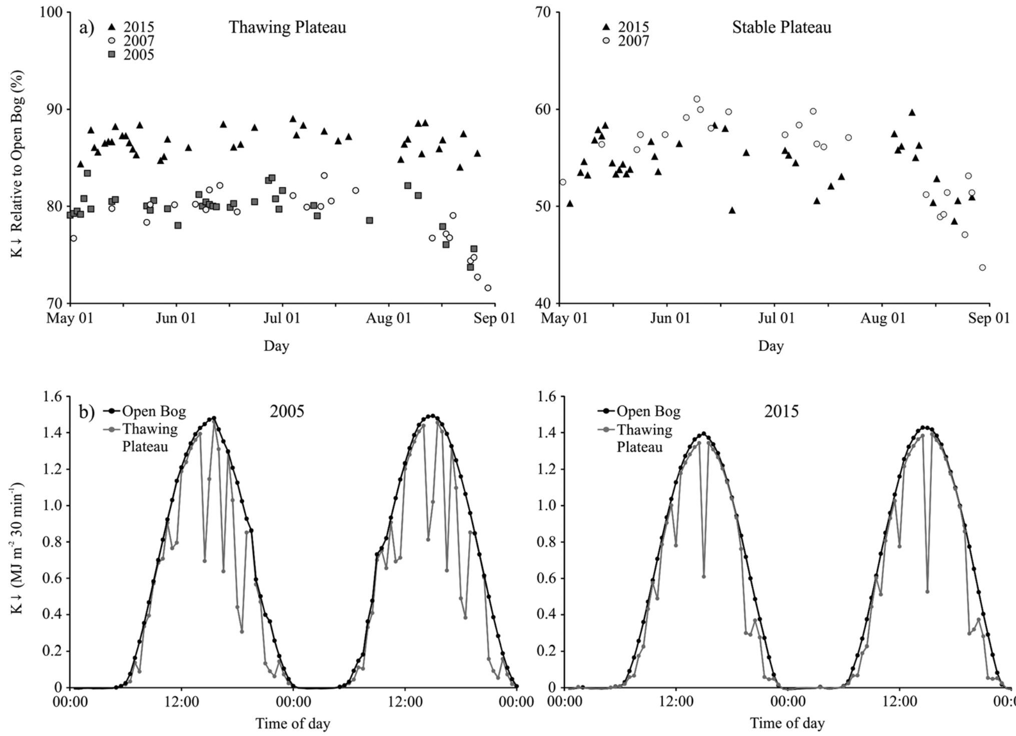

Figure 10. (a) Comparison of incoming shortwave radiation (K↓) between a thawing plateau (Study Plateau) and a treeless bog and a stable plateau and a treeless bog. Data shown are for cloud-free days in 2005, 2007, and 2015. Note that the stable plateau radiometer was installed in 2007. (b) Half hourly K↓ for back-to-back cloud-free days in 2005 (8–9 June) and 2015 (18–19 May) for a thawing plateau and a treeless bog. Periods when K↓ on the plateau decrease relative to the bog are likely periods when the sensor is shaded.

transect in 2006 (Figure 8) shows a depression in the center, possibly a remnant of an isolated talik as demonstrated by geophysical imaging (McClymont et al., 2013). We predict that the processes observed and documented on the Study Plateau are indicative of what may happen in other areas of the basin given further warming and thawing of permafrost in this region. At the landscape scale, large interconnected talik networks may change how much water is delivered to the stream network over winter, a period typically assumed to be quiescent in most permafrost environments.

The freeze-thaw processes documented at this site are greatly influenced by the high water content of the saturated peat soil, and the associated latent heat requirements. The maximum refreeze thresholds documented here apply to Scotty Creek, but similar thresholds likely occur in other environments characterized by poorly drained peat soils. We hypothesize that incomplete refreeze in peatlands will become increasingly prevalent in response to future climate warming, especially where conditions allow for a positive net ground heat flux. Such conditions include high summer air temperatures, wet soil conditions, early onset of, and high snow accumulation (Christensen, 2014). Talik formation under these conditions will be most probable in peatlands in the discontinuous/sporadic permafrost zones but may also occur locally in peatlands in the continuous permafrost zone. Tarnocai et al. (2009) estimate that peatlands cover approximately 23% of all permafrost soils in the discontinuous/sporadic zones in North America and approximately 19% of all permafrost soils in the circumpolar north (Table 2).

5. Conclusion

Active layer measurements have traditionally been made at the end of summer and are assumed to be analogous with the depth to the PT. However, this assumption is falsified by the present study, which demonstrates the presence of a talik in the suprapermafrost layer. In the peatland regions of discontinuous and sporadic permafrost environments, the vertical profile of a permafrost system should be recognized as

Table 2
Distribution of Peatlands Across Permafrost (PF) Soils in North America and the Circumpolar North

	North America			Circumpolar North		
	All PF soil	Peatlands		All PF soil	Peatlands	
Permafrost zones	(10^3 km^2)	(10^3 km^2)	(%)	(10^3 km^2)	(10^3 km^2)	(%)
Continuous	2,868	228	7.9	10,123	2,123	21.0
Discontinuous/sporadic	2,592	593	22.9	5,685	992	17.4
Isolated	1,186	227	19.1	2,974	441	14.8
Total	6,646	1,048	15.8	18,782	3,556	18.9

Note. Modified from Tarnocai et al. (2009).

potentially containing three layers: an active layer, in which soil pore water changes phase at least twice annually; a talik, in which pore water is perennially unfrozen; and the permafrost, where temperatures are ≤0°C for two or more years. This study defines a maximum threshold for ALT at our study sites in the Scotty Creek watershed, beyond which the ground is incapable of losing enough energy to completely refreeze the following winter. It is reasonable to conclude that the thaw and eventual disappearance of permafrost from Scotty Creek will be accompanied by a thinning and eventual disappearance of the overlying active layer (Figure 1b). This thinning will be the result of shallower frost penetration during warmer winters, combined with greater heat storage in taliks as they thicken. This study demonstrates that wide-spread talik development can be induced by a summer with greater than average thaw depth followed by a winter with high snowfall. Once developed, the permafrost underneath taliks thaws much faster than in areas without taliks. This suggests that warm years may generate an abrupt and nonlinear response (i.e., tipping point) facilitating the simultaneous rapid development of taliks and thaw of permafrost.

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