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Thawing of permafrost peatlands: Effects of water-energy feedback on landscape evolution

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ABSTRACT

The Hay River Lowland in the Northwest Territories is a 140,000-km^2 region of peatlands underlain by discontinuous and sporadic permafrost. The dominant landscape units in this region are permafrost-cored peat plateaus that support forest and seasonally frozen flat bogs and channel fens. The region has experienced rapid warming over the past several decades, and large-scale (e.g. 50-km grids) vertical energy transfer models suggest a pole-ward shift of the discontinuous permafrost zone in the future. At a smaller scale, however, lateral thawing of frozen peat appear to have strong influence on the transition of peat plateaus to bogs and fens. At the Scotty Creek research basin in the Hay River Lowland, recent observations indicate a rapid lateral thawing of permafrost and deepening of the active layer. Detailed hydrological and soil physical monitoring shows that the deepening of the active layer is controlled by the water-energy feedback processes, whereby a small amount of differential deepening of the active layer causes wetter condition in localized areas, which enhances soil heat transfer during thawing seasons and further deepens the active layer. Geophysical data obtained with the electrical resistivity imaging technique have shown that localized deepening of the active layer may eventually lead to complete thawing of permafrost and generation of new bogs. The effects of these processes on watershed-scale hydrology are largely unknown. Linking field-based observations to large-scale models of permafrost energetics and hydrological fluxes is a necessary prerequisite for developing process-based explanations for recently observed shifts in arctic river-flow regimes.

RÉSUMÉ

1 INTRODUCTION

The western Arctic of Canada is one of the most rapidly warming regions on the planet (Johannessen et al., 2004; Serreze et al., 2000). There is mounting evidence that the water resources of this region are affected by this warming. For example, the frequency of mid-winter melt events has increased, end-of-winter melt occurs earlier, and there is mounting evidence that key hydrological and climatic variables such as snowpack depth, river discharge, and seasonal precipitation have deviated from long-term means. As a result, there is growing uncertainty regarding the future availability of the northern freshwater resource.

Recent model simulation studies have predicted the disappearance of permafrost in southern margins and development of supra-permafrost taliks (Delisle, 2007; Zhang et al. 2008). However, these models are one dimensional and run on a large grid (e.g. 0.5° × 0.5°), and do not consider the co-existence of permafrost and non-permafrost that defines discontinuous permafrost. As such, they do not explicitly account for sub-grid processes, such as the lateral heat transfer between permafrost and non-permafrost terrain involving the flow of water. Sub-grid scale prediction is needed for informed water resource management practises, but the development of this predictive capacity requires a physically-based understanding of permafrost thaw in sporadic and discontinuous permafrost settings where the role of subsurface lateral energy flow is poorly understood.

Much of the discontinuous permafrost region in northern Canada consists of peatlands, where the complex interaction among soil, vegetation, water, and atmosphere may result in positive or negative feedback processes that enhance the aggradation and degradation of permafrost (Jorgenson et al., 2010). The objective of this paper is to present an overview of field-based studies of permafrost thaw conducted over the past decade at the Scotty Creek research basin located near Fort Simpson, Northwest Territories and demonstrate how the positive feedback between water and energy fluxes contribute to the thawing of discontinuous permafrost and changes in the distribution of different types of peatlands.

2 STUDY SITE AND METHODS

The Hay River Lowland (Fig. 1a) is a ~140,000 km^2 region of discontinuous and sporadic permafrost with a high density of peatlands. As such it is typical of the southern extent of permafrost because of the large thermal offset created by dry, insulating peat (Robinson and Moore, 2000; Smith and Riseborough, 2002). We have conducted hydrological field studies since 1999 in the Hay River Lowland at Scotty Creek (Fig. 1a), a 152 km^2 drainage basin blanketed by >3 m of peat overlying a silt-clay deposit of very low permeability (Aylesworth and Kettles, 2000). The landcover consists of permafrost plateaus, channel fens and ombrotrophic flat bogs (Quinton et al. 2003), occurring as a complex “mosaic” of different size patches (Fig. 1b). The permafrost at Scotty Creek is contained within peat-covered permafrost plateaus that rise 1 to 2 m above the surrounding channel fens and ombrotrophic flat bogs (Fig. 2), and support black spruce with a ground cover dominated by lichen and moss species. Permafrost plateau surfaces are relatively dry as seasonal soil thaw extends to a depth of ~1 m, enabling the water table to descend to ~0.5 m or more by late summer.

Most of our research has been conducted in the instrumented sites on a permafrost plateau and adjacent wetlands (Fig. 1b). Instrumentation includes automatic weather stations located on plateau, bog, and fen; instrumented “soil pits” on plateau where the peat was excavated to install soil temperature and moisture sensors to a maximum depth of 0.7 m and carefully refilled to minimize the effects of disturbance; water level sensors for surface water and groundwater; and a transect through plateau where the depth to frost table (i.e. top of the frozen peat) is measured every summer (in late August or early September) to monitor the thickness of the active layer. In some years, ground-surface elevation of the frost-table transect is measured at one meter interval using a total station to monitor the subsidence of ground surface associated with permafrost thaw. Details of site instrumentation can be found in Hayashi et al (2007) and Wright et al. (2008, 2009).

To image the extent of permafrost on two-dimensional vertical profiles, electrical resistivity tomography (ERT) data were acquired using an Iris Syscal Pro 10-channel system. We used electrode spacings of 3 m and dipole-dipole array geometries. Along some profiles, higher-resolution images of shallower regions were produced by reducing the electrode spacing to 1 m. Resistivity tomograms of each profile data set were computed using the RES2DINV inversion program; an iterative Gauss-Newton smoothness-constrained least-squares algorithm constrained by L1-norm (Loke and Dahlin, 2002).

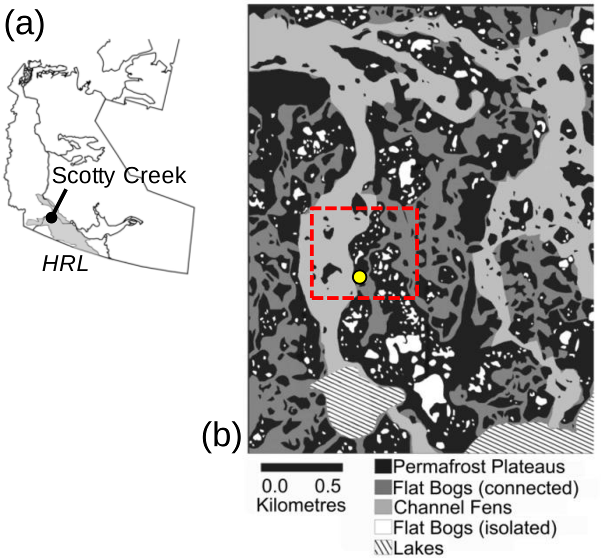

Figure 1. (a) Map showing the boundary of the Northwest Territories, Hay River Lowland (*HRL*), and Scotty Creek. (b) Distribution of landcover types in the study area within the Scotty Creek watershed. The red square indicates the area shown in Fig. 5, and the yellow circle indicates locations of the frost-table transect and instrumented soil pits.

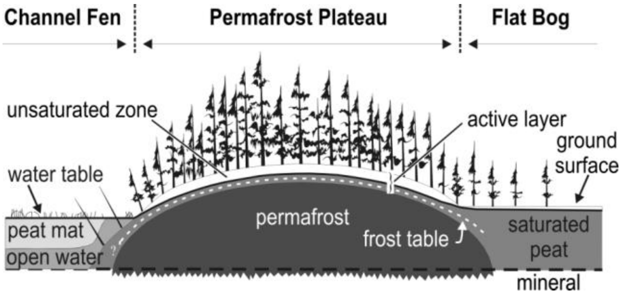

Figure 2. Schematic cross-section of permafrost plateau flanked by channel fen and flat bog.

3 RESULTS AND DISCUSSION

3.1 Overview

Our field studies have lead to the following conceptual model of the hydrological functions of the different landcover types (Quinton et al., 2003; Hayashi et al., 2004). Permafrost plateaus function as runoff generators, owing to their relatively large end-of-winter snow water equivalent moisture supply, limited active layer water storage capacity, and relatively large hydraulic gradient directed toward the surrounding bogs and fens (Fig. 2). Channel fens convey water along their broad, hydraulically rough channels, thus plateau runoff entering these features flows toward the basin outlet. Analysis of water samples collected along fens indicates that fens receive groundwater discharge, whereas the water chemistry of bogs indicates they recharge groundwater, consistent with the general conceptual model of bog-fen complexes (Siegel and Glazer, 1987). The bogs that are completely surrounded by permafrost plateaus are hydrologically isolated from other bogs and fens in terms of surface flow and active-layer flow, so water entering such bogs is stored until removed by evaporation or groundwater recharge. Water entering bogs with connections to channel fens will enter the latter during periods of high water supply (e.g. spring snowmelt period and in response to large rain events), but otherwise is stored as in the case of isolated bogs. Overland flow from plateaus is rare owing to the very high permeability of their surfaces. Lateral drainage is therefore conveyed through a subsurface flow zone with a lower boundary defined by the impermeable frost table (Fig. 2). The spatial pattern of soil thaw over a permafrost plateau is largely controlled by spatial pattern of soil moisture, as wet peat is a better conductor of energy to the thawing frost table than dry peat.

3.2 Differential Thawing of the Active Layer

The topography of the frost table was similar to that of the ground surface in a broad sense (Fig. 3). However, depths to the frost table varied substantially (0.5 to >1.3 m) with the deepest frost table generally occurring under topographic depressions (Fig. 3). The depth pattern was consistent every year, indicating that the depth variability is controlled by deterministic processes, not by random chances. The thawing of peat in the active layer is primarily driven by conductive heat transfer from the ground surface to the frost table. Owing to high porosity (up to 0.9) of peat and low thermal conductivity of peat skeletons consisting of organic material, bulk thermal conductivity of unfrozen peat above the frost table is strongly dependent of the water content (Hayashi et al., 2007). Soil temperature and water content were monitored at two instrumented sites located on the frost table transect in 2004 (see Fig. 3). West Pit is located in a topographically high area, where the active layer is shallow and Centre Pit is located in a depression, where the active layer is deep. The rate of lowering of the frost table indicated by the location of 0 °C isotherm was much faster in Centre Pit than in West Pit (Fig. 4a). Liquid water content measured at 0.2-m depth in Centre Pit was much higher than in West Pit (Fig. 4b) indicating the wetter condition of Centre Pit. This example clearly demonstrates the effects of higher water content, thus higher thermal conductivity on the faster thawing at Centre Pit.

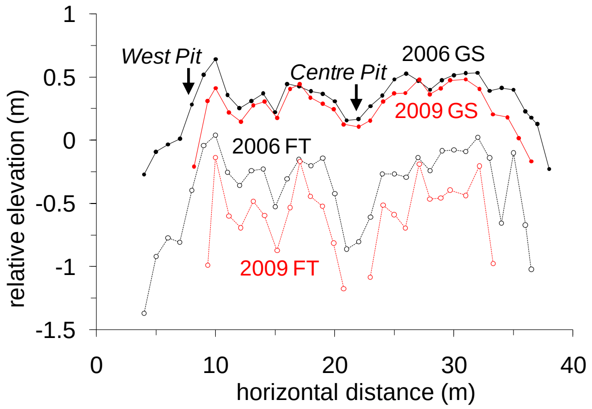

Figure 3. Elevation of ground surface (GS) and frost table (FT) measured in September 3, 2006 and August 27, 2009, referenced to a local benchmark. Location of instrumented soil pits (West and Centre) are shown by arrows.

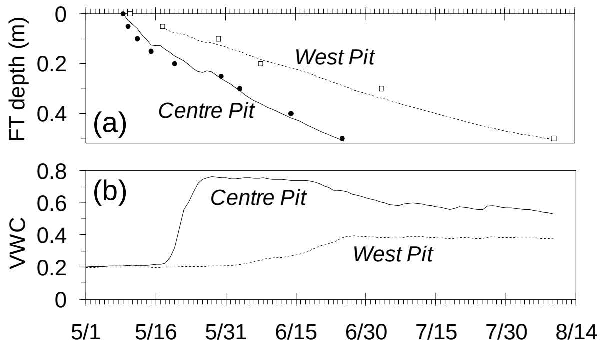

Figure 4. Comparison of Centre Pit and West Pit in 2004. (a) Measured (symbols) and simulated frost-table (FT) depth. (c) Liquid water content at 0.2-m depth (modifed after Hayashi et al., 2007).

Depressions such as Centre Pit are kept wet throughout the thawing season because the topography of impermeable frost table causes groundwater flow to converge to depressions. Wright et al. (2009) surveyed detailed three-dimensional frost-table geometry in a 5 by 6-m study plot located near the instrumented site and demonstrated the positive feedback between water flow and energy flow. Differential thawing of the frost table caused groundwater flow to converge to depressions, which maintained the wet condition necessary for further thawing and deepening of the frost-table depressions.

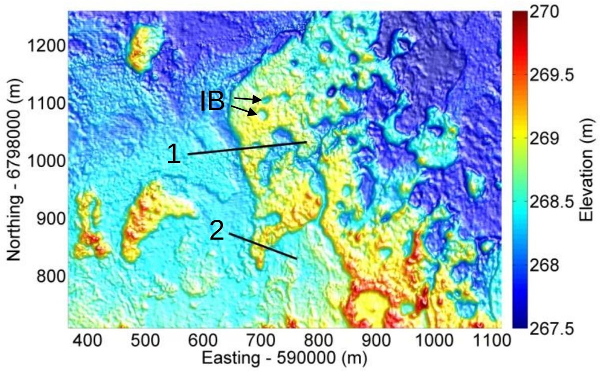

Figure 5. Detailed elevation map of the square region shown in Fig. 1. Solid lines indicate electrical resistivity tomography (ERT) profiles 1 and 2, and IB indicates examples of isolated bogs. Easting and northing are given in the Universal Transverse Mercator (UTM) coordinates referenced to North American Datum 1983.

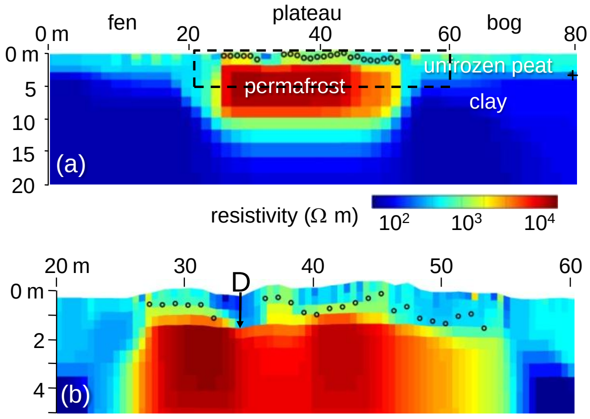

Figure 6. Central portion of the electrical resistivity tomography (ERT) profile 1, conducted with electrode spacing of 3 m (location shown in Fig. 5). (b) High-resolution (1 m electrode spacing) ERT profile of the region indicated by the rectangle in (a). Symbol D indicates a depression in the frost table. Circles indicate the frost table detected by a frost probe, and a cross symbol indicates the peat/clay boundary determined from a hand-auger borehole.

3.3 Geophysical Imaging

While there are clear evidences demonstrating the water-energy feedback processes at a point (1 m) to plot (10 m) scales, it is not clear if these small scale features evolve into larger features affecting hydrological pathways. Geophysical imaging provides a useful tool for investigating the thickness and geometry of permafrost bodies at a larger scale (Fortier et al., 2008). The ERT profile 1 (see Fig. 5 for location) reveals a lens-shaped body of permafrost underneath the peat plateau. The thickness of the permafrost lens is estimated to be 10-12 m (Fig. 6a). The profile 1 also shows the contact between peat and the underlying clay at approximately 3 m, which is consistent with the contact determined in a hand-augered borehole. High resolution ERT image of the profile 1 (Fig. 6b) shows a depression in the frost table (D). Low electrical resistivity in the unfrozen peat in the frost-table depression indicates very wet condition. A surface topographic depression with nearly saturated peat was visually observed at the same location. We interpret this depression to have evolved from a very small scale differential thawing feature similar to the deep thaw at Centre Pit (Fig. 4).

The high-resolution digital elevation map of the area shows that the peat plateaus are pockmarked by circular bogs that are isolated from other bogs or fens (examples marked as IB in Fig. 5). The ERT profile 2 reveals resistivity structure under and around the location of an approximately 15-m-wide circular bog confined within a peat plateau of slightly higher elevation (Fig. 7; location shown in Fig. 5). Permafrost that surrounds the isolated bog has thicknesses of 5 to 8 m. Resistivities of < 500 Ωm are equivalent to those found within the shallow active layer and indicate that the permafrost beneath the bog has completely thawed. At depths below 11 m, a zone of higher resistivities of approximately 1000 Ωm may indicate a lens of higher resistivity sand within the clay. We interpret these isolated bogs to have evolved from small depressions similar to the depression identified in Fig. 6b. Once a depression grow to a sufficient size, the wet condition causes the trees to die, which subsequently opens up the canopy cover and increases radiation inputs, thereby causing further deepening of the active layer and an eventual break through.

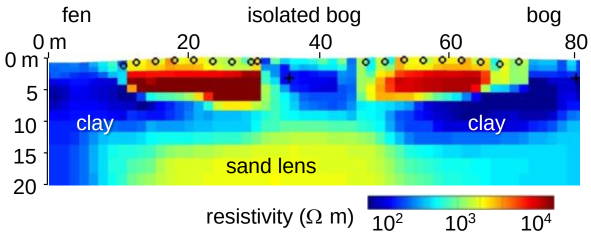

Figure 7. Central portion of the electrical resistivity tomography (ERT) profile 2, conducted with electrode spacing of 3 m (location shown in Fig. 5). Circles indicate the frost table detected by a frost probe, and a cross symbols indicate the peat/clay boundary determined from a hand-auger borehole.

3.4 Implication on Landscape Evolution and Basin Runoff

In recent years, stark changes have been noted on the permafrost plateaus at Scotty Creek, including subsidence, active layer thickening and flooding and paludification of their margins, all of which appears to be due to permafrost thaw. A comparison of 1947 and 2000 aerial images of Scotty Creek indicated widespread permafrost loss as evidenced by the creation of isolated bogs, expansion and merger of bogs, and the disappearance of plateaus (Quinton et al., 2011).

Permafrost thawing results in a transformation of permafrost plateaus into bogs or fens (Robinson and Moore, 2000). Since the three major cover types are known to have specific hydrological functions, this landscape transformation is expected to affect the basin hydrograph. The total annual runoff of Scotty Creek and three other rivers in the Hay River Lowland appears to be increasing since 1995 (Fig. 8a), which is consistent with the trends observed in other northern river basins in Canada (St. Jacques and Sauchyn, 2009). Annual precipitation over the past 15 years has not increased systematically (data not shown), and the increase in runoff appears to be caused by the increase in runoff ratio (= runoff/precipitation) (Fig. 8b). Despite these evidences of changes in basin runoff, the linkage between permafrost thaw and the volume and timing of basin runoff production is poorly understood. Future research is needed to understand the mechanistic linkage between the shrinking permafrost and changes in river flow regime.

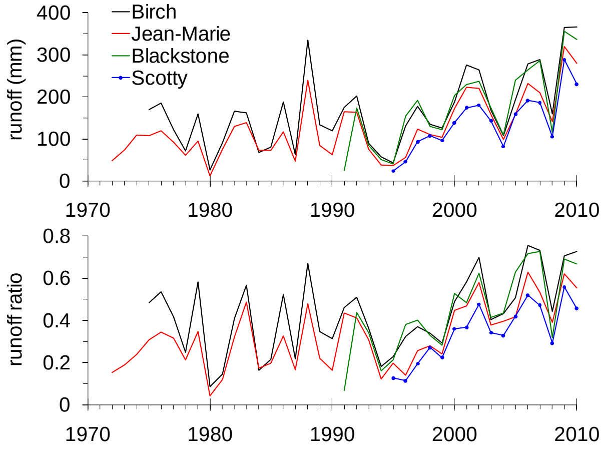

Figure 8. (a) Total annual discharge of four river basins located within the Hay River Lowland eco-region, expressed as basin runoff. (b) Approximate runoff ratio defined as total discharge divided by total precipitation recorded at the Fort Simpson airport.

4 CONCLUSIONS

Rapid thawing of discontinuous permafrost is occurring in the Scotty Creek research basin in the Northwest Territories. Transition of permafrost plateaus to channel fens and flat bogs occurs at the edges of permafrost plateaus and also by the creation, growth, and merger of isolated bogs within permafrost plateaus. Detailed plot scale monitoring combined with geophysical imaging demonstrated the effects of positive feedback between water and energy fluxes, whereby small-scale (< 1 m) differential thawing features evolves to depressions in the frost table, and which may eventually evolves to isolated bogs. The increase in basin runoff and runoff ratio over the past two decades suggest that the rapid changes in the distribution and connectivity of fens and bogs may be affecting the basin-scale hydrological storage and pathways, but our understanding of mechanistic linkage between permafrost thaw and basin runoff is still lacking. In addition, we have relatively little understanding of the reverse process, whereby non-permafrost wetlands evolve into permafrost plateaus in the region. Future research is needed in these areas to improve our understanding of the biophysical processes and strengthen our capability to predict the potential impacts of climatic variability and anthropogenic disturbances on peatlands in the discontinuous permafrost regions.

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