Using remote sensing-based spatial modelling to assess the changes of permafrost in Wapusk National Park

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ABSTRACT
Each Canadian national park is required to monitor and report on the state of the park. Permafrost is an integral part of the northern landscapes and ecosystems. Observations show that permafrost is thawing in response to climate change. Northern national parks are large and expensive to access and monitor in the field. This study reports on the application of remote sensing-based spatial modelling to assess the changes of permafrost in Wapusk National Park located in the northwest of the Hudson Bay Lowlands. Permafrost was mapped at an unprecedented high resolution of 30 m by 30 m using a process-based model. Spatial input datasets were developed based on remote sensing data and site observations. The results show that the active-layer had a deepening trend throughout most of the park and that permafrost was degrading in areas in recent decades, especially in treed areas in southern regions.

RÉSUMÉ
Chaque parc national du Canada doit surveiller et faire rapport sur l'état de ses parcs. Le pergélisol fait partie intégrante des écosystèmes et des paysages nordiques. Des observations montrent que le pergélisol fond sous l'effet des changements climatiques. Les parcs nationaux nordiques sont vastes; leur accès sur le terrain et leur surveillance est dispendieux. Cette étude rend compte de l'utilisation de la modélisation spatiale à partir de la télédétection pour évaluer les changements quant au pergélisol du parc national Wapusk situé dans le nord-ouest des basses terres de la Baie d'Hudson. Le pergélisol a été cartographié à une résolution jamais vue de 30 m par 30 m d'après un modèle de processus continu. La saisie de l'ensemble des données spatiales a été effectuée à partir de mesures de télédétection et d'observations sur le terrain. Les résultats révèlent que la couche active a tendance à s'accroître dans la majeure partie du parc et que le pergélisol se détériore dans certains secteurs au cours des dernières décennies, en particulier dans les secteurs boisés des régions du sud.

1 INTRODUCTION

Parks Canada Agency manages 42 national parks, covering about 0.3 million km^2. The *Canada National Parks Act* requires that the maintenance or restoration of ecological integrity "shall be the first priority of the Minister when considering all aspects of the management of parks". For that purpose, each national park is required to produce a state-of-the-park report every five years. Northern national parks are large and expensive to access and monitor in the field. However, increasingly detailed spatial information is available from satellite remote sensing. Therefore Parks Canada Agency is working with Canada Centre for Remote Sensing to develop a satellite-based system for monitoring the ecological integrity of the northern national parks.

Permafrost is an integral part of the northern landscapes and ecosystems. Observations and modelling studies have shown that permafrost is warming and thawing in most northern regions in recent decades (e.g., Brown et al. 2000; Smith et al. 2005; Zhang et al. 2005; 2006), and permafrost degradation will be accelerated during the 21st century (e.g., Lawrence and Slater 2005; Zhang et al. 2008a; 2008b). Permafrost degradation affects landscapes, infrastructure, terrestrial ecosystems, animal habitats, and could have positive feedbacks on climate warming.

Thus, it is essential to monitor and assess changes in permafrost.

Since satellite remote sensing cannot directly detect permafrost, several studies have correlated permafrost conditions with land surface features such as vegetation, frost mounds, hummocks, ice wedges, polygons, thermokarst, which can be detected using satellite remote sensing (Duguay et al. 2005). However, this approach is indirect and has several limitations. For example, the relationships between land surface features and permafrost could change over time and space, and there are time lags between changes in climate, permafrost and the related land surface features (Duguay et al. 2005). In this study, therefore, we used a modelling approach to map permafrost using a combination of remote sensing data and field observations as the inputs for the model.

Several studies have used modelling approaches to quantify the spatial distributions and changes of permafrost conditions with climate warming (e.g., Lawrence and Slater 2005; Zhang et al. 2006; 2008a; 2008b). Most of these spatial modelling studies, however, used very coarse resolutions, usually 0.5º latitude/ longitude (equivalent to about 28 km by 55 km for a grid at 60 °N). At such a coarse resolution, the models cannot reflect the effects of different landscape features, which are essential for assessing the state of the parks. Therefore we need to model permafrost at a higher spatial resolution. To capture permafrost conditions at the landscape scale, we modelled permafrost at a spatial resolution of 30 m by 30 m.

We selected Wapusk National Park (WNP) as the first case study area. WNP covers 11,475 km^2, and is located in a low-lying, peatland dominated plain in the northwest part of the Hudson Bay Lowlands (ranging from 57.1 °N to 58.8 °N and from 94.0 °W to 92.3 °W). WNP was selected in this study for several reasons. First, permafrost plays an important role in the unique landscape, ecology and animal habitats in this region. Secondly, this area is a transitional zone between continuous and discontinuous permafrost and between boreal forest and Arctic tundra, and therefore permafrost and the ecosystems could be sensitive to climate change. Thirdly, the spatial climate data and remote sensing products are more reliable for flat areas than mountainous areas. And lastly, considerable field observations are available in this region.

2 METHODOLOGY

Figure 1 shows the overall scheme for monitoring and assessing the changes in permafrost using remote sensing-based spatial modelling. The key component is the Northern Ecosystem Soil Temperature model (NEST), a process-based model that simulates ground temperature regimes, from which permafrost conditions can be determined. Remote sensing data and field observations were used to develop input data layers for the model, as well as to test the model results. The assessment of permafrost conditions and changes are based on the model outputs.

The NEST is a one-dimensional process-based model developed to simulate the transient response of the ground thermal regime to climate change (Zhang et al. 2003). NEST considers the effects of different ground conditions, including vegetation, snow, organic soils, mineral soils, and bedrock (Figure 2). Ground thermal dynamics are simulated by solving the one-dimensional heat conduction equation. The upper boundary condition (the ground surface or snow surface when snow is present) is determined by the surface energy balance and the lower boundary condition (at a depth of 120 m) was defined based on the geothermal heat flux. The dynamics of snowpack and soil water are also incorporated. Soil thawing/freezing and the associated changes in ice and liquid water fractions are determined based on energy conservation. Lateral water flow is parameterized based on Zhang et al. (2002). The model has been validated against measurements of energy fluxes, snow depth, soil temperature, thaw depth, and spatial distributions of permafrost and ground thermal conditions (Chen et al., 2003; Zhang et al. 2003; 2005; 2006; 2008c).

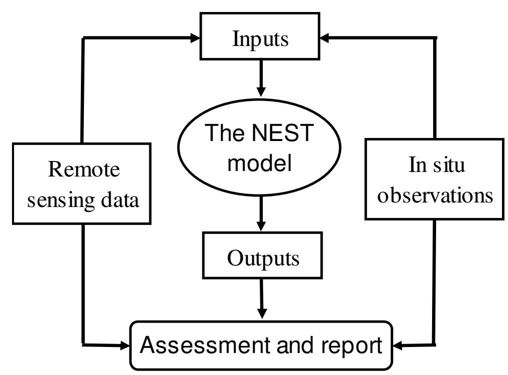

Figure 1. The information flow for monitoring and assessing the changes of permafrost in national parks based on spatial modelling.

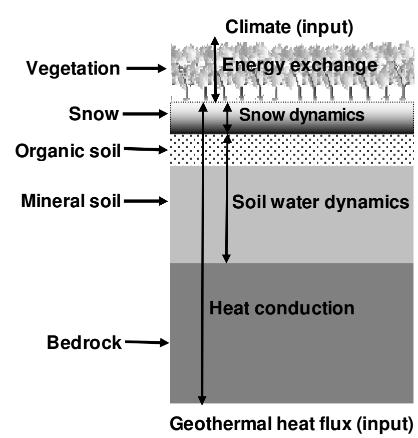

Figure 2. The structure and major processes considered in the NEST model.

The input data needed for the model include climate, land cover types, leaf area index, peat thickness, the texture and thickness of mineral soils, the thermal conductivity of bedrock and the geothermal heat flux. Land cover type and leaf area index were derived from Landsat imagery. The resolution of the Landsat data (30 m by 30 m) was used as the resolution for the spatial modelling and mapping. Climate data were interpolated from climate observation stations (McKenney et al. 2006). Site observations in WNP showed that peat thickness was correlated with elevation because elevation was directly related to the length of time available for peat to accumulate (the terrain has been progressively emerging from Hudson Bay over the last 8000 years due to the postglacial rebound (Dredge and Mott 2003)). Therefore we estimated peat thickness based on elevation. Mineral soil conditions were based on Dredge and Nixon (1986; 1992). The snow drifting parameter was estimated based on observations of snow depth (Kershaw and McCulloch 2007). The current climate warming in Canada began largely from the end of the Little Ice Age (circa 1850) (e.g., Overpeck et al. 1997). Therefore we began the simulation from 1850 and initialized the model based on the equilibrium assumption during that time. Climate data during 1850-1900 were extrapolated linearly backward from the data available for 1901-1990.

There are about 10 million 30 m by 30 m non-water pixels in WNP. Directly simulating each pixel was not feasible since that requires about 20 years computing time for a typical personal computer. However, input data, especially the climate and peat thickness, generally did not change significantly from pixel to pixel. Therefore, we divided the input data into types and ran the model for each unique combination of input data type (WNP was divided into 200 grids of 10 km by 10 km for climate data, 20 types for leaf area index, and 15 types for elevation; land cover and mineral soil conditions were already in discrete categories). This approach significantly reduced computation time. Detailed description of the input data, as well as results validation and analysis, will be reported in another paper. Here we focus on how to use the spatial modelling results to assess changes in permafrost, especially for producing the state-of-the-park reports.

Since each national park needs to report the state-of-the-park every five years on the changes in ecological integrity as well as the long-term patterns, we structured our analysis accordingly to show how to monitor, assess and report on the changes of permafrost in WNP. We selected a recent 5-year period (2001-2005) to reflect the state-of-the-park reporting interval and used the period 1961-1990 for long-term trend analysis since this 30-year period is usually used by Environment Canada to calculate climate normals.

3 RESULTS AND ANALYSES

3.1 Defining near-surface permafrost

On the time scale of years to decades, the ecological integrity of the park is mainly related to the near-surface processes. The sub-surface biological and ecological processes occur mainly within the top metre of the soil. Therefore we focussed on near-surface permafrost conditions for the state-of-the-park report. Modelled maximum summer thaw depth was <13 m for all pixels in WNP during the simulation period, and most commonly <2 m (the percentages of pixels and years with maximum summer thaw depths >2 m, >3 m and > 4m were 2.25%, 0.17% and 0.04%, respectively). Summer thaw greater than 4 m was usually associated with formation of supra-permafrost taliks (Figure 3). Supra-permafrost taliks form when the summer thaw exceeds the depth which can be frozen back during the following winter, while permafrost persists deeper in the ground (Zhang et al. 2006; 2008a). That means, although permafrost exists at depth, its effect on near-surface processes is limited by the intervening year-round unfrozen layer. Therefore, for this study we defined near-surface permafrost to be within 4 m of the ground surface.

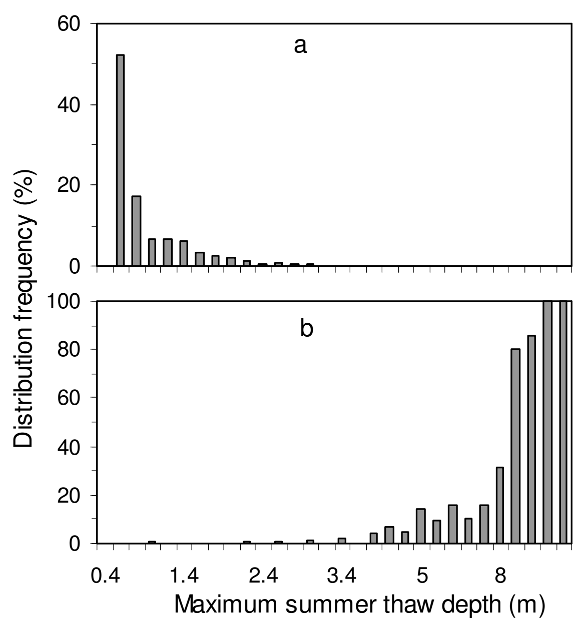

Figure 3. a) The frequency distribution of maximum summer thaw depth for all the pixels and years (1901-2008) in WNP, and b) the frequency distribution of the supra-permafrost taliks with maximum summer thaw depth in WNP.

3.2 Extent of near-surface permafrost

Model results show that most of land area in WNP is underlain by permafrost (Figure 4). The pixels with near-surface permafrost account for about 99.95% of the total non-water pixels in WNP for 1961-1990. Most of the non-permafrost pixels were located in the southeast and southwest regions of the park (Figure 4). This pattern is comparable with the maps of Dredge (1979; 1992) who delineated the discontinuous permafrost zone in the southern portion of WNP.

Our results show a reduction in permafrost extent over the last two decades. While the non-permafrost pixels comprised just 8% of the total land pixels in WNP for 2001-2005, this is about a 90% increase of the average non-permafrost pixels calculated for 1961-1990. Near-surface permafrost degradation occurred mainly in areas with trees (spruce and larch) and in some shrub fens, which were located mainly in southern areas of the park and along rivers and streams (Figure 4).

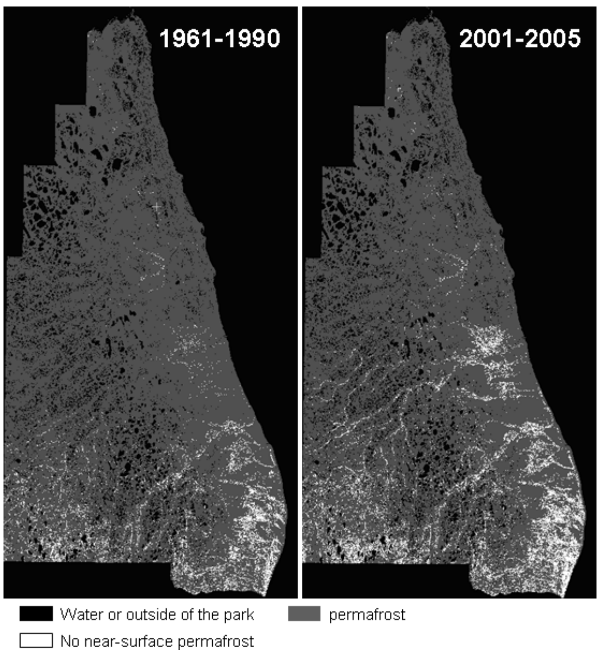

Figure 4. Modelled distributions of near-surface permafrost for the periods 1961-1990 and 2001-2005.

3.3 Active-layer thickness

Figure 5 shows the modelled distribution of active-layer thickness during 2001-2005 in WNP. Active-layer thickness ranged from 0.5 m to more than 3 m across the park. Active-layer thickness was >2.5 m in non-vegetated lands and tidal zones, 1 m to 1.5 m in marshes and fens, and <1 m in bogs. Spatially, active-layer was deep near the coastal areas, thinning inland, corresponding to changes in land cover types and peat thickness.

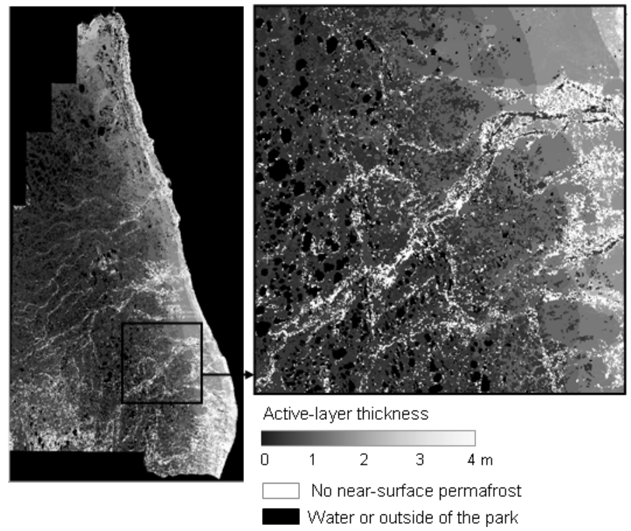

Figure 5. Modelled distribution of active-layer thickness averaged during 2001-2005 in Wapusk National Park.

Figure 6 shows a typical temporal variation pattern of active-layer thickness in WNP. Active-layer thickness fluctuated from year to year but shows a general increasing trend since 1900. For the site shown in Figure 6, the average and the maximum active-layer thicknesses during 2001-2005 increased by 0.15 m (13.9%) and 0.23 m (19.9%), respectively, compared to their 30-year normal (the normal maximum active-layer thickness was calculated by averaging the maximum active-layer thickness for each 5-year period between 1961 and 1990). Although the results show that the 2001-2005 average and maximum active-layer thicknesses increased significantly compared to their 30-year normals, they were slightly less than that calculated for the previous 5-year period (1995-2000), during which the average and maximum active-layer thicknesses increased by 0.16m (15.1%) and 0.24m (20.1%), respectively, relative to the 30-year normals.

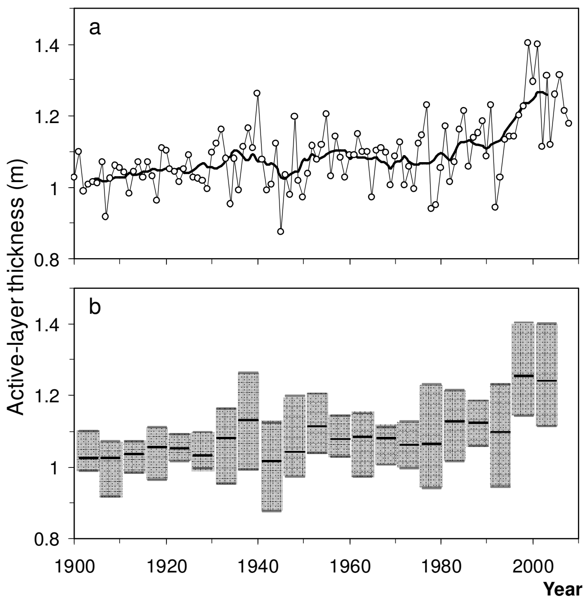

Figure 6. Changes of active-layer thickness at a sedge fen site. a) Annual values and the 10-year running average, b) the average and range for each 5-year period.

Figure 7 shows the modelled spatial distribution of changes in active-layer thickness during 2001-2005 compared to the averages for 1961-1990. We used relative change in the map for clarity; it was calculated as the difference relative to the 30-year average for each pixel. Active-layer thickness increased almost everywhere, the largest changes occurred mainly in the southeast and southwest regions in the park. The average change in active-layer thickness for the entire non-water pixels with near-surface permafrost was 19.2% or 0.15 m. The changes in active-layer thickness were larger in treed areas (e.g., sedge larch fens, lichen spruce bogs, and sphagnum spruce bogs). The changes in active-layer thickness were also large in shrub fens and in non-vegetated areas (beach ridges and tidal zones). The smallest change occurred in melting lichen bogs (lichen bogs that are melting, usually with some shallow ponds) and lichen bogs (Figure 8).

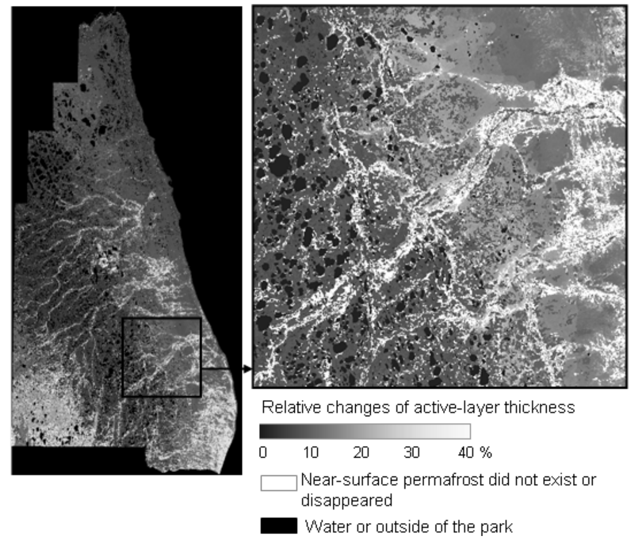

Figure 7. Changes of active-layer thickness during 2001-2005 comparing to the average during 1961-1990.

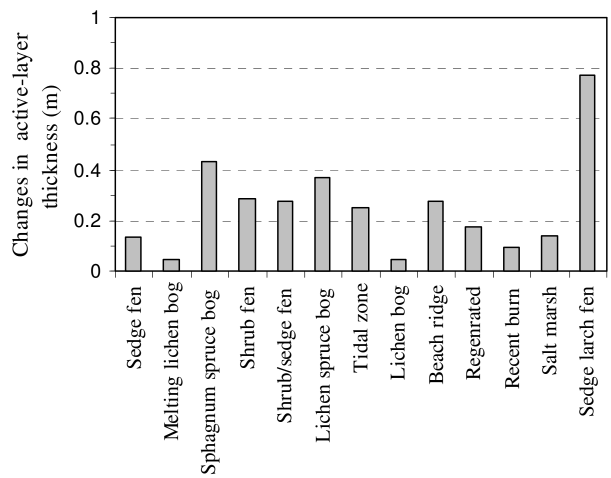

Figure 8. Changes in active-layer thickness of different land cover types from 1961 -1990 to 2001-2005.

4 DISCUSSION AND CONCLUSION

Permafrost has been monitored in recent two decades by measuring ground temperatures and probing summer thaw depth. However, these methods are costly, only suitable for limited sites, and usually for a limited period of time. In this study, we used a spatial modelling approach to monitor the changes in permafrost conditions at a 30 m by 30 m spatial resolution. At such a spatial resolution, small units of land types, vegetation patches, soil, and other landscape processes can be considered, satellite remote sensing data can be used effectively, and the results are useful for ecosystem monitoring, land management and planning. More importantly, at such detailed spatial resolution, the pixel size is comparable with the land areas represented by field observations, thus allowing precise ground-truthing for model testing and improvement.

Compared to the methods of correlating permafrost with land surface features detectable from satellite remote sensing, our modelling approach directly traces the thermal dynamics of the ground. This approach is more direct for monitoring permafrost conditions, and it can provide information for understanding the processes and interactions regarding changes in permafrost and the related surface features.

The changes of permafrost include both long-term patterns and short term fluctuations. Our results showed a long-term trend of deepening of active-layer thickness and disappearing of near-surface permafrost in WNP. However, active-layer thickness in one reporting period may not necessarily be deeper than in the immediately previous reporting period. Therefore it is necessary to report both on the current status and the long-term trend for permafrost monitoring and assessment.

In our study, we used 4 m to define near-surface permafrost for WNP since active-layer thickness is usually much less than 4 m, and a year-round unfrozen layer (talik) often exists above the permafrost table when summer thaw depth is greater than 4 m. In addition, the permafrost conditions in 4 m near the ground surface are more meaningful physically and ecologically for WNP. A deeper depth may be needed for warmer areas, or in areas with shallow or no organic layers. However to model the transient response of near-surface permafrost to climate change, it is necessary to use a much deeper ground profile (120 m was used in this study) to model the ground thermal dynamics (Delisle, 2007).

A related issue is how far back in time do we need to consider for modelling the current and the near future changes in permafrost conditions. The cost of computation and availability and quality of input data limit our capacity to model permafrost from the early 20th century. However, the response of ground thermal regime to changes in atmospheric conditions could take years to millennia. Most of the permafrost thermal regime is currently in disequilibrium, and the disequilibrium will increase with time due to the accelerated climate warming (Zhang et al. 2008a). We initialized the model and began the simulation from 1850 since the current climate warming largely began from that time (e.g., Overpeck et al. 1997), and our analysis focused on the patterns after 1900, especially after the 1960s.

This study produced a permafrost distribution for WNP at an unprecedented high resolution. The results show the effects of land cover types and vegetation conditions on permafrost. Although permafrost is widespread in WNP, our results show that permafrost degraded and active-layer became deeper in recent decades, especially in treed areas, which were located mainly in southern areas in the park. The results not only provide a detailed baseline map of permafrost conditions for WNP, they can also be used to monitor and assess the changes in permafrost for the entire land area of the park at the landscape scale. Since climate and satellite remote sensing data are readily available, this spatial modelling approach can be used operationally to monitor permafrost in WNP and for reporting on the state-of-the-park. At the same time, the input data, the model, and the results can be improved as more field data becomes available in the park. Thus, this spatial modelling approach serves as a framework to integrate different data sources to improve our understanding of the permafrost dynamics in WNP.

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