# Evaluating the major controls on permafrost distribution in Ivvavik National Park based on process-based modelling

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ABSTRACT
The permafrost status at some representative sites in three typical land types (as mountain tops, coastal plains, and river valleys) in Ivvavik National Park was evaluated using a process-based model. The results showed that ground conditions were the most important factor controlling the Active Layer Thickness (ALT). ALT in rocky or gravel ground was deeper (80 - 220 cm), whereas peaty or clay soil made ALT shallower (25 - 50 cm deep) in the park. Active-layer is usually deeper in mountain sites due to the rocky ground conditions. Air temperature is another significant factor affecting both ALT and permafrost thickness. ALT has become significantly deeper since the mid 1980s corresponding to the climate warming.

RÉSUMÉ
L'état du pergélisol de trois sites typiques de type de terrain (comme les sommets, les plaines côtières, et les vallées des rivières) dans le parc national Ivvavik a été évalué sur différents paramètres du sol par un modèle fondé sur les processus. Les résultats ont montrés que la composante sol est le facteur le plus important dans le contrôle de l'épaisseur de La Couche Active (L'ECA). L'ECA dans le sol rocheux ou de gravier a été plus profonde, environs de 80 - 220 cm, que les sols argileux ou tourbeux où l'ECA plus mince est d'environs de 25 - 50 cm dans le parc. La couche active est généralement plus profonde dans les sites montagneux en raison des conditions du sol rocheux. La température est un autre facteur important affectant à la fois l'ECA et l'épaisseur du pergélisol. L'ECA est de plus en plus profonde depuis le milieu des années 1980, ce qui correspond au tendance du réchauffement climatique.

## 1 INTRODUCTION

Ivvavik National Park (INP) is located in the northern tip of Yukon Territory, bordering Alaska in the very north-west corner of Canada (Figure 1). The park includes the high relief British Mountains, coastal plains in north and east, and several big valleys, like Firth, Malcolm and Babbage River valleys. Stretched in the transitional zone between the arctic tundra and subarctic boreal forest, and with most of its terrain not glaciated, INP has unique geological and ecological values.

Permafrost is continuous in INP and it is an important factor shaping the landscapes and the ecosystems. Observations and modelling studies have shown in recent decades that permafrost is warming and thawing in most of the high latitude regions (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. 2008). Therefore permafrost degradation could be a major driver of the changes in the northern natural systems in the near future due to its response to climate warming (Canadian Park Service 1993; Drew and Shanks 1965; Wiken 1984; Rampton 1982; Norris 1997).

Each Canadian national park is required to report the state-of-the-park every five years. Permafrost condition and its changes are important measures for the state-of-the-park report in northern national parks. Permafrost observations are sparse in INP, and it is costly to access and monitor in the field in this large and remote area (INP covers 10168 km$^2$). However, satellite remote sensing can provide detailed information about land surface conditions, although permafrost can only be detected indirectly from satellite data (Duguay et al. 2005). Therefore, we proposed a modelling approach to map permafrost distributions using remote sensing information and field observations as the inputs for the model. In this paper, we evaluated the major controls on permafrost distribution in INP based on the modeled permafrost conditions at representative sites in the park. This result will provide bases for mapping permafrost in the park at high resolution using remote sensing based spatial modelling.

## 2 METHODOLOGY

### 2.1 The model

A process-based model, NEST (Northern Ecosystem Soil Temperature model), was used to simulate ground thermal dynamics and determine the permafrost status by integrating the thermal and hydrological effects of above- and under-ground conditions, including climate, vegetation, snow cover, organic soils, mineral soils, and bedrock (Zhang et al. 2003). 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. Lateral water flow is parameterized based on Zhang et al. (2002). The input data needed for the model include daily climate data, vegetation types, leaf area index, ground component, the thermal conductivity of bedrock and the geothermal heat flux. Active-layer thickness and the base of permafrost were determined based on the modelled ground temperature profile (If the ground temperature at 120 m deep was less than 0 $^{o}$C, the base of the permafrost was estimated by assuming the ground temperature increases linearly with depth, with the increasing rate determined by the geothermal heat flux and the thermal conductivity of bedrock).

The initial modelling conditions were estimated by running the model iteratively using the first year climate data and ground parameters until a stable ground temperature profile was achieved (Zhang et al 2003). In this study we used the average climate at the beginning of the 20$^{th}$ century to initialize the model assuming the ground thermal condition was in equilibrium with the climate at that time.

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 (Zhang et al. 2003; 2005; 2006; 2008).

## 2.2 Vegetation and ground conditions

Based on the permafrost related geo-physiographic features, we selected eight representative sites from three typical land types in the park to model their permafrost conditions. These three land types are mountain tops, river valleys, and coastal plain areas (including coastal plain and east lowland areas). They are simply referred as mountains, valleys and plains respectively afterwards. There are two representative sites in the mountains, two sites in the valleys, and four sites in coastal plains (Figure 1).

The vegetation and ground component for model input were setup based on the general conditions for each sites. An extensive field survey on vegetation and surficial ground conditions were conducted in July 15-31, 2008 jointly by Parks Canada Agency and Canada Centre for Remote Sensing. The observations included vegetation (type, height and coverage), drainage and soil conditions, and active-layer thickness. Figure 1 shows the distribution of the observation sites in INP. Other data sources for model input were from remote sensing products (land cover map and digital elevation model (DEM)) and literature (Canadian Park Service 1993; Drew and Shanks 1965; Wiken et al 1981; Welsh and Rigby 1971).

We modelled ground thermal dynamics (from which permafrost conditions, i.e. active-layer thickness and depth to the base of permafrost, can be determined) for all these sites based on their climate and typical vegetation and ground conditions. To simplify the situation, we selected the sites with slope less than 10° and did not consider the effects of slope and aspect, but we tested the effects of solar radiation directly.

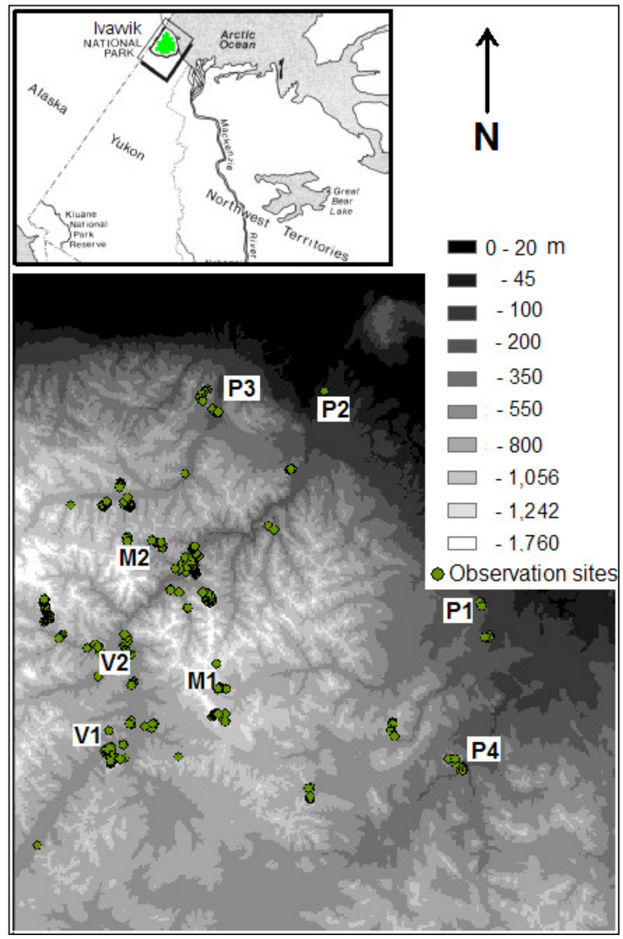


Figure 1. The distribution of the representative sites in Ivvavik National Park (labelled as M, V and P for mountain sites, valley sites and plain sites, respectively). The border of the map is 68°30'-69°40'N and 138°00'-141°00'W.

## 2.3 Climate data

The NEST model needs daily climate data as input and long-term climate data are needed to model the transient responses of permafrost to changes in climate (Zhang et al. 2008). There are only seven climate stations in INP. We used a monthly 1 km by 1 km grid climate dataset (McKenney et al. 2006) to determine the spatial patterns of climate across the park. Although this dataset spans from 1901 to 2007, its temporal patterns are erroneous before 1940s. Therefore we used a monthly half degree latitude / longitude grid dataset for 1901-2002 (Mitchell and Jones 2005) as long term template. Monthly climate data were down-scaled to daily data based on daily climate data observed at the climate stations. Since climate stations are sparse and observations usually contain gaps, we compiled two daily climate datasets (from 1956 to 2002) based on the daily station data using site-based difference correction. These two datasets represent daily climate patterns for coastal plain and for inland, respectively. Since the station observations began after 1956, we used historically averaged daily data as daily template for the period from 1901 to 1956.

The thermal conductivity of bedrock was set as 0.018 J/ (cm·k·s) and the geothermal heat flux was set as 0.05 w/m$^2$ based on observations by Majarowicz and Morrow (1998).

### 2.4 Modelling procedure and results analysis

To investigate the general permafrost distribution pattern in INP, we ran the NEST model for dominant ground and vegetation conditions for all the selected sites. Since various vegetation and ground conditions exist around valley sites (Drew and Shanks 1965), we ran the model with different vegetation and ground conditions to test their impacts. To examine the impacts of climate on permafrost distribution across the park, we ran the NEST model using different climate but with the same ground conditions. The sensitivity of permafrost to individual climate variables was analyzed as well. Observations from our field survey conducted in 2008 and from literature were used to validate the modelled results.

## 3 RESULTS AND ANALYSES

### 3.1 General distribution patterns of permafrost

Table 1 shows the range of Active-Layer Thickness (ALT) at different sites with locally typical vegetation and soil conditions. Since ALT differs greatly between peaty soil and mineral soils with high fractions of gravel, and such two soil conditions are common in these sites, we modelled permafrost under these two soil conditions separately for these three sites.

In the northern plain area of Ivavvik, soil or unconsolidated layer is usually deep. Peat can be up to 60 cm deep at some spots and significant amount of organic material can be found at 2 m deep at some locations (Canadian Parks Service 1993). Vegetation is dominated by shrubs and sedges. Plants can be very dense, and leaf area index can be up to 2.3 at some spots. The modelled ALT ranged from 25 cm to 50 cm. There are also sites with high fractions of gravel, but the plants are much denser and taller than at mountain sites. Active-layer thickness ranged from 60 cm to 200 cm at gravel sites (Table 1). Canadian Parks Service (1993, P5-7) and Wiken et al. (1981) reported that ALT ranged from 30 cm to 100 cm in coastal plain area, and our field observations shown that ALT ranged from 24 cm to 42 cm for peaty sites, and 76 cm for a gravel site. The modelled range of ALT was comparable with these observations. The active-layer thickness in the coastal plain area is generally shallower than in the mountain and valley areas, mainly due to the insulation effects of peat.

In the mountain areas, the ground is mostly gravel or weathered bedrock. Stone fraction can be up to 0.95. Soil is thin and the roots of the plants are usually limited within 20 cm deep. Vegetation is dominated by lichens and grasses, and their coverage is generally less than 50 %, rarely up to 70%. The modelled ALT ranged from 60 cm to 220 cm (Table 1). The field observed ALT ranged from 50 cm to 80 cm in July 2008. Some published results show that ALT ranged from 70 cm to 200 cm in this mountain area (Drew and Shank 1965; Canadian Parks Service 1993; Wiken et al. 1981). Our model results are comparable with these observations.

In the valley areas, because of lower elevation and locally warmer microclimate conditions, trees can grow further north in the valleys. Most of the area is gravel based deep unconsolidated and finer (with more clay) soil, with well drainage conditions. The modelled ALT varied from 60 cm to 120 cm, which is comparable with the reported ALT of 50 cm – 90 cm in this region (Canadian Parks Service 1993; Wiken et al. 1981). There are some spots with peat on the ground (usually less than 30 cm in thickness). The simulated ALT at peat conditions was less than 60 cm, which is comparable with our field observations of 25-50cm in July of 2008.

These modelling results show that permafrost existed at all the testing sites. That is consistent with the permafrost map of Canada (Heginbottom et al. 1995), which shows that permafrost is continuous in this area. The modelled depth to the base of permafrost ranged from 420 m to 520 m at different sites in INP. Temporally, the permafrost thickness was generally stable, changed about 20 m during the simulation period (1901-2002).

Table 1. Modelled active-layer thickness (ALT) at different sites with typical vegetation and soil conditions

| *Site name*[1] | *Vegetation* | *Dominant ground types and modelled ALT (cm)* | |
|---|---|---|---|
| | | *Peat* | *Gravel soil* |
| P1 | Sedges shrubs | 30-45 | |
| P2 | Shrubs grass | 25-50 | 100-180 |
| P3 | Shrubs grass | 25-50 | 130-190 |
| P4 | Shrubs grass | | 60-200 |
| M1 | Lichen grass | | 80-220 |
| M2 | Lichen grass | | 60-150 |
| V1 | Shrubs grass trees | 30-60 | 70-120 |
| V2 | Shrubs grass trees | | 60-120 |

[1]P1-4 represent for sites in plain areas, M1-2 for sites in mountain areas, and V1-2 for sites in valley areas.

3.2 Impacts of climate on permafrost distribution

The plain sites are about 1 ºC warmer than the valley sites, and the valley sites are about 1 - 2 ºC warmer than the mountain sites. The annual precipitation at the plain sites and mountain sites is similar, and it is about 30 - 37 mm more than at the valley sites (Table 2).

To understand the effects of these climate differences on permafrost, we ran the model for different sites with the same ground settings. The results showed the ALT at mountain sites was the shallowest (Table 2). Due to the climate differences, the ALT at plain sites were 18 cm deeper than at the valley sites; and the ALT at the valley sites were 39 cm deeper than at the mountain sites under gravel ground conditions. The differences were much smaller under organic soil conditions. The ALT at plain sites were 11 cm deeper than at the valley sites; and the ALT at the valley sites were 14 cm deeper than at the mountain sites.

Table 2. The average (over 1901 to 2002) air temperature (Ta), precipitation (PCP) and modelled active-layer thickness (ALT) based on two typical land conditions: gravel land and organic soil land.

| *Site name* | *Ta (ºC)* | *PCP (mm)* | *ALT (cm)* | |
|---|---|---|---|---|
| | | | *Gravel*[1] | *Organic*[2] |
| P1 | -11.3 | 146.6 | 210 | 79 |
| P2 | -11.8 | 136.8 | 186 | 69 |
| P3 | -12.5 | 115.1 | 168 | 60 |
| P4 | -11.6 | 161.5 | 204 | 77 |
| M1 | -13.1 | 147.8 | 155 | 55 |
| M2 | -14.6 | 118.6 | 115 | 37 |
| V1 | -12.5 | 107.7 | 174 | 60 |
| V2 | -12.4 | 98.8 | 173 | 59 |
| P mean | -11.8 | 140.0 | 192 | 71 |
| M mean | -13.9 | 133.2 | 135 | 46 |
| V mean | -12.5 | 103.3 | 174 | 60 |

[1]Gravel land: the vegetation was assumed as shrub with leaf area index as 0.75 and height as 0.43 m. We assumed that stone fraction was 0.6 at the top 0.2 m soil and increased to 0.9 at 0.6 m, and was 1.0 below 1.2 m (bedrock). For the remaining soil fraction, we assumed that the organic matter content was 17 % in the top 0.2 m, and then decreased to 3 % at 0.6 m.

[2] Organic soil land: the vegetation was assumed as shrub with leaf area index as 1.75 and height as 0.63 m. We assumed that stone fraction was 0.1 at the top 0.1 m soil, 0.2 at 0.2 m, and increased to 0.5 at 0.6 m, and was bedrock below 2.2 m. For the remaining soil fraction, we assumed that the organic matter content was 75 % at the top 0.1 m, 46 % at 0.2 m, and decreased to 6 % at 0.6 m.

3.3 Impacts of ground conditions on permafrost

To examine the impacts of ground conditions on permafrost, we ran the model with different vegetation and ground conditions at a valley site (V1), where various vegetation and ground conditions can exist (Drew and Shanks 1965). The results illustrated in Figure 2 show that changes in ground conditions from organic soil to peat (from I.D 13 to 14), from gravel soil to mineral soil (from I.D 2 to 3) and changes in soil texture from clay to loam (Among I.D 3, 4, 5 and 6) have the most significant impacts on ALT. Changing vegetation cover (LAI, vegetation type) and peat thickness could also influence ALT significantly (at I.D 2, 9, 12, 13, 15). Our test showed that the other conditions, such as snow drifting parameters and lateral flow parameters did not have significant impacts on ALT, therefore we did not show them in the figure.

The depth to permafrost base ranged from 430 m to 480 m for the above treatments.

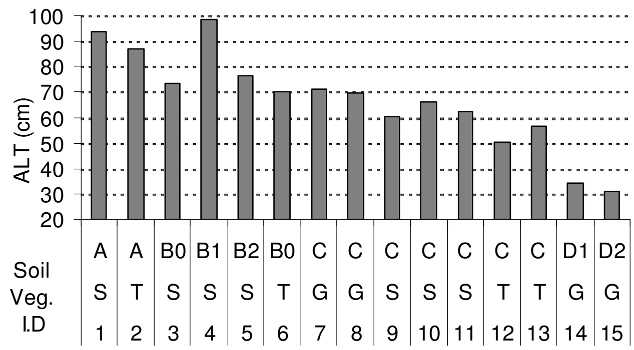


Figure 2. The simulated average active layer thickness (ALT), over 1901 – 2002, at the site V1 with different vegetation and ground conditions. The ground and vegetation settings for each run I.D was shown in table 3. The vegetation types are (Veg. = T is for forest, S for shrub, G for grass).

Table 3. Ground and vegetation parameters for Figure 2.

| I.D | Leaf area index | Canopy height (m) | Soil type [1] |
|---|---|---|---|
| 1 | 1.0 | 1.0 | A |
| 2 | 1.0 | 1.0 | A |
| 3 | 1.0 | 1.0 | B0 (silt clay texture) |
| 4 | 1.0 | 1.0 | B1 (sandy loam) |
| 5 | 1.0 | 1.0 | B2 (silt clay loam) |
| 6 | 1.0 | 1.0 | B0 (silt clay texture) |
| 7 | 0.5 | 0.5 | C |
| 8 | 1.0 | 0.5 | C |
| 9 | 0.5 | 0.5 | C |
| 10 | 1.0 | 0.5 | C |
| 11 | 1.0 | 1.5 | C |
| 12 | 1.5 | 8.5 | C |
| 13 | 1.5 | 1.5 | C |
| 14 | 1.0 | 0.5 | D1 (Peat 20 cm) |
| 15 | 1.0 | 0.5 | D2 (Peat 30 cm) |

[1] A: Gravel soil (Gravel fraction was 0.75, organic fraction was 0.16); B: Mineral soil (Gravel fraction was 0.4, organic fraction was 0.16); C: Organic soil (Gravel fraction was 0.4, organic fraction was 0.32); D: Peaty soil.

3.4 The long-term pattern of ALT and its response to climate factors

Figure 3 shows the simulated annual ALT from 1901 to 2002 and the long term trends. ALT fluctuated from year to year, and the sites with deeper ALT had a larger range of fluctuation. It shows a gradual deepening trend. This trend becomes significant after the mid 1980s, especially at the mountain sites and the valley sites (Figure 3). The deepening of ALT in recent two decades is consistent with the increase in air temperature (Figure 4).

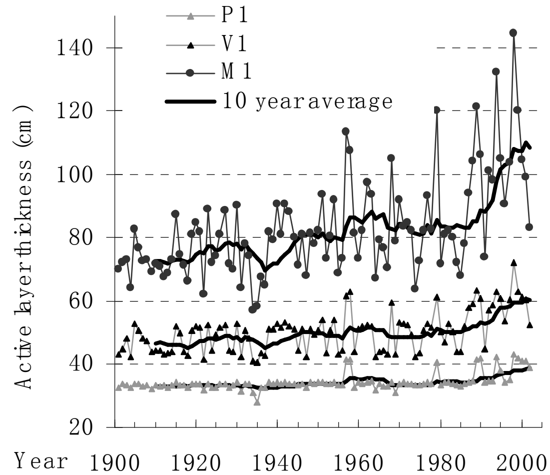


Figure 3. The long term trend of active layer thickness simulated at sites P1, V1 and M1. The ground conditions were set as peat for P1, mineral soil for V1 and more gravel for M1 (P1, in 0 – 20 cm: organic (fraction) = .85; in 20-30 cm: organic = .6; in 30 – 50 cm: organic = .4; in 40 - 80 cm: organic =.1, stone fraction = .2; 510 cm to bedrock. V1, in 0 -15 cm: organic (fraction) = .42, stone = .1; 15 - 80 cm: organic =.05, stone = .4; 80 – 120 cm: organic = .06, stone = .8; 410 cm to bedrock. M1, in 0 - 20 cm: organic (fraction) = .2, stone = .15; 20 - 50 cm: organic =.04, stone = .55; 50 cm to bedrock). Leaf area index = 1.0 and vegetation height = 0.5 for both V1 and P1. Leaf area index = 0.6 and vegetation height = 0.2 for M1.

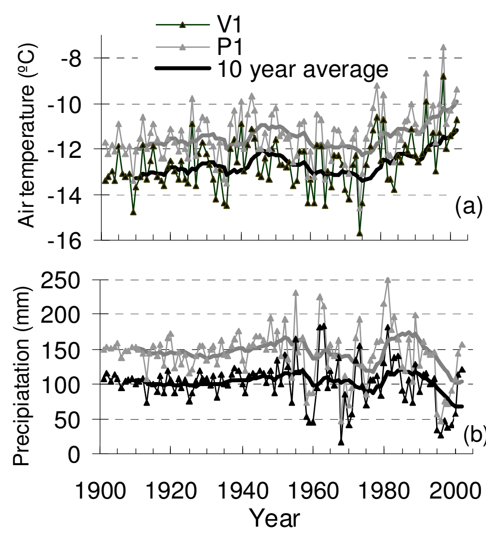


Figure 4. The annual air temperature (a) and precipitation (b) at a valley site V1 and a plain site P1.

To test the sensitivity of permafrost to individual climate factors, we ran the model by changing the air temperature, precipitation, wind speed and solar radiation arbitrarily at a valley site (V1) and a plain site (P1) (Figure 5). ALT is sensitive to changes in air temperature. Increasing air temperature by 1.0 ºC, the simulated average ALT increased by 14.1 cm (28.1 %) than lowering temperature by 1.0 ºC at V1 (soil). The ALT increase was 5.7 cm (16.6 %) for the 2 ºC difference at P1 (peat).

Changing solar radiation also caused significant changes in ALT. Increasing solar radiation by 20 % generated deepening of ALT by 7.7 cm at the V1 site and by 5.1 cm at the P1 site than decreasing solar radiation by 20 %. The simulated ALT did not change significantly with the changes in precipitation and wind speed (the result for wind speed was not shown in figure 5).

A 2.0 ºC increase in air temperature induced a decrease in permafrost base by 88 m at the V1 site and by 90 m at the P1 site. The permafrost base decreased by 21.5 m and 33.5 m at V1 and P1 sites respectively with an increase in solar radiation by 40 %. Changes in precipitation and wind speed had little effects on the base of permafrost.

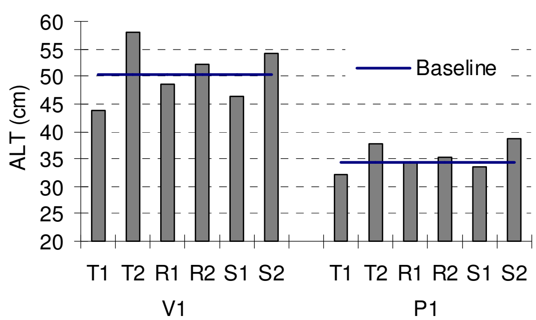


Figure 5. The sensitivity of active-layer thickness (ALT) to climate variables at P1 and V1 sites. The ground conditions were set as the same as in Figure 3. The average ALTs (over 1901-2002) were simulated by decreasing and increasing air temperature by 1.0 ºC (T1 and T2); decreasing and increasing precipitation by 50% (R1 and R2); decreasing and increasing solar radiation by 20 % (S1 and S2). The ALT simulated from original climate (T0) was presented as the baseline.

## 4 DISCUSSION AND CONCLUSIONS

This model-based evaluation of permafrost conditions in different sites in INP shows that ground condition is the dominant factor affecting the depth of ALT in INP. Although the coastal plain is warmer than the valleys and the valleys are warmer than the mountains, ALT in coastal plain area is much shallower than other areas due to its peaty soil conditions. In the mountain tops, although distributed with the lowest annual average air temperature, the ALT is the deepest due to its gravel and shallow soil condition. Vegetation could affect ALT as well. Under the same ground and vegetation conditions, the difference in atmospheric climate, predominantly air temperature and solar radiation, also affects ALT. Therefore, it is necessary to integrate climate, topography (i.e., slope and aspect), ground and vegetation conditions to map the distribution of permafrost in the park.

The significant effects of peat layer on ALT have been observed in the field (e.g., Smith 1975) and in modelling studies (e.g., Yi et al. 2007). Our modelled average ALT and its changes are in agreement with these studies. There are relatively few observations under rocky conditions due to the difficulties in probing the ground using steel rods. Our results show that high fraction of rock and thin soil above bedrock could have deep ALT. It may be caused by the high thermal conductivity and low heat capacity of the rocks. To develop a seamless permafrost map, all these conditions should be considered.

This modelling study shows that permafrost exists at all the testing sites, and permafrost is deep (more than 400 m). Our results also show that ALT increased significantly after the mid 1980s. This increase trend of ALT is mainly due to the changes in air temperature in this area (Figure 3 vs. 4). This pattern is consistent with observations and modelling studies reported recently (e.g., Smith et al. 2005; Zhang et al., 2008; 2008).

Our next step is to develop spatial maps of vegetation and ground conditions to map permafrost distributions in INP based on spatial modelling, in which the topographical factors would be integrated to better present the spatial pattern of permafrost status.

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