Spatial mountain permafrost modelling in the Daisetsu Mountains, northern Japan

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ABSTRACT: This paper discusses the spatial modelling of mountain permafrost on the summit areas of the Daisetsu Mountains, Northern Japan. GIS analysis using a precise DEM with 2 times 2 m unit elevation grid-cells was applied. The model was developed based on the estimation of cumulative annual freezing and thawing indices (CFTIs), considering spatial and temporal thermal-insulation effects by snow cover. The areas with negative CFTI were assumed to indicate the presence of permafrost. Combination of DC resistivity imaging and shallow ground temperature measurements were carried out in order to estimate the extent and thickness of permafrost and to validate the model output. The results of these field measurements indicated predominant controls by snow cover for permafrost occurrences and showed good agreements with the modelled permafrost distribution.

1 INTRODUCTION

In the Daisetsu Mountains, Hokkaido, Northern Japan, areas underlain by mountain permafrost are limited. Most of permafrost occurs in the summit areas, where mean annual air temperature (MAAT) is below 0°C and where winter-frost penetration is not impeded by thick snow cover (Fukuda & Kinoshita, 1974; Fukuda & Sone, 1992). This pattern of permafrost distribution is significantly different from that in European mountains, where glaciers occur and mountain permafrost has been found on the steep slopes even beneath thick seasonal snow. The amount of potential solar radiation is the most important factor controlling the occurrences of permafrost in European mountains (Funk & Hoelzle, 1992; Hoelzle, 1992; Hoelzle and Haeberli, 1995).

Spatial modeling of mountain permafrost in the Daisetsu Mountains requires different approaches from those adopted in European mountains. Snow-cover distribution is assumed to be the most important controlling factor. Accordingly, Ishikawa & Sawagaki (2001) have described possibilities to spatially model snow cover.

This paper presents the next steps of spatial permafrost modelling in the Daisetsu Mountains. The model outputs were validated by DC resistivity imaging and shallow ground temperature (SGT) measurements along seven survey lines. This paper also focuses on the permafrost geometry at depth as evaluated by the combined uses of these indirect field observations.

2 STUDY AREA

The study area is Mt. Hakuun-dake and its surroundings, is located in the northern part of the Daisetsu Mountains, central Hokkaido, northern Japan (Fig. 1).

The climate of this area is characterized by low air temperature during winter, high amounts of snow fall and strong uni-directional westerly winter wind. At the eastern slope of Mt. Koizumi-dake, mean annual air temperature (MAAT) at 2000 m a.s.l. between August 1998 and August 1999 was −4.7°C.

Mean monthly wind speed was 8.6 m/s at an elevation of 2000 m a.s.l (Sone & Takahashi, 1986). Owing to snow drift, snow tends to accumulate mainly on the east-facing leeward slopes, whereas snow cover is nearly absent on the flat summit areas even in winter. This snow cover distribution is reflected in the distribution of vegetation. Plant species belonging to alpine wind-blown dwarf scrub (WB) community are present on windward areas of bare ground, whereas plants belonging to alpine snow-hostile scrub (SH) community, which consists predominantly of Pinus pumila shrubs, tend to be present on the margins of windward bare ground and under the patches of winter snow cover. Plant species belonging to alpine snow-bed communities (SB) and alpine snow meadows (SM) communities are present in the areas where thick snow cover accumulates during winter and remains until summer or early autumn. Plants are rare in areas where considerably lower amounts of solar radiation are received owing to snow remaining until late autumn.
Subsurface materials are mainly composed of andesitic sandy gravels which derived from weathered bedrock and scoria. The presences of permafrost has been confirmed by direct excavation, ground temperature monitoring, DC resistivity sounding and shallow seismic refraction at the Mt Koizumi-dake site (13 m permafrost thickness and 1.8 m active layer; Fukuda & Kinoshita, 1974) and Hokkai-daira plateau (7.1 m permafrost thickness and 1.4 m active layer; Fukuda and Sone, 1992), where plants belonging to WB community are distributed.

3  SPATIAL PERMAFROST MODELLING

3.1 Overview

As a proxy indicating permafrost distribution, the cumulative annual freezing and thawing indices (CFTIs) on the ground surface with the thermal insulation effect of snow cover were considered. Negative CFTI suggests the occurrence of permafrost.

A precise topographic map was drawn based on photogrammetrical procedures (using Leica SD2000 scale 1:5000 with 2 m contour interval) and was interpolated into the 2 times 2 m unit grid-cells. General purpose GIS software Arc/View ver.3.2 was used for spatial modelling.

3.2 Modelling

Annual changes in the thickness of snow cover at grid cells were determined as shown in Fig. 2. In normal years, air temperatures turn to be below 0°C in mid-October and thus snow starts to accumulate at this time. By the end of April, subzero air temperatures predominate. Accordingly, during 15 October and 1 May of the next year, the thickness of snow cover is assumed to increase linearly such that:

$$\text{SC}_{m,n+1} = \text{SC}_{m,n} + \left( \frac{\text{SCM}_m}{198} \right)$$  \hspace{1cm} (1)

where \( \text{SC}_{m,n} \) is the thickness of snow cover at grid cell \( m \) and at Julian day \( n \), \( \text{SCM}_m \) is the maximum thickness of snow cover simulated at grid cell \( m \). The number 198 represents the duration between 15 October and 1 May and corresponds to the duration with snow accumulation. Between 1 May and 15 June, the thickness of snow cover at every grid cell is assumed to remain constant, because most of the incoming energy is used for the phase change of the snow cover. Until 15 June, the thickness of the snow cover decreases. Referring to the observation of snow-patch disappearance by Miyamoto (1999), the snow cover almost completely disappeared at 31 August in the simulated area and that the thickness of snow cover at each grid cell decreases following a linear trend:

$$\text{SC}_{m,n+1} = \text{SC}_{m,n} - \left( \frac{\text{SCM}}{79} \right)$$  \hspace{1cm} (2)

where \( \text{SCM} \) is the maximum thickness of snow cover estimated for all grid cells. The number 79 represents the duration between 15 June and 31 August. If \( \text{SC}_{m,n} \) reaches zero at a grid cell, calculation by equation (2) will not be carried out at this grid cell. From 1 September to 15 October, all grid cells were assumed to be snow free.

According to temporal changes in thermal insulating effects and the evolution of the snow cover as described above, the temporal ground surface temperature (GST) changes can be divided into four stages: (I) snow free stage, (II) dry snow, (III) wet snow, and (IV) snow melting. The GSTs at each stage were determined as follows.

(I) The snow-free stage corresponding to a period from late summer to the onset of snow accumulation. Daily mean values of GSTs are close to those of air temperatures.

(II) The dry-snow stage lasts from early winter until spring when the ground surfaces are covered with dry snow, which insulates the ground from winter frost penetration as long as the snow cover is thick enough. The amplitudes of daily...
and annual variations in GST decrease with increasing thickness of snow cover.

(III) The wet snow stage occurs between late spring and early summer when GSTs remain at 0°C at all sites with snow cover.

(IV) Snow melting takes place from early to late summer and GSTs beneath the snow cover remain at 0°C. On the other hand, daily mean GSTs is close to daily mean air temperature at sites where snow has disappeared.

Finally, CFTI at grid cell \( m \) is calculated by the following equation;

\[
CFTI_m = \sum_{n=1}^{365} GT_{m,n},
\]

where \( CFTI_m \) is the CFTI at grid cell \( m \) and \( GT_{m,n} \) is the daily mean GST at day \( n \) and grid cell \( m \). \( GT_{m,n} \) is approximated as the daily mean air temperature at day \( n \) (\( AT_n \)) multiplied by the snow-insulating index (\( SII_{m,n} \)) at grid cell \( m \) at day \( n \) as follows;

\[
GT_{m,n} = SII_{m,n} \times AT_n.
\]

\( SII_{m,n} \) depends on the thickness of snow cover and is determined by considering the ratio between daily mean air temperature and daily mean ground surface temperature (MRAG) as related to the simulated snow-cover thickness (Fig. 3). Assuming linear correlation, \( SII_{m,n} \) was approximated such that:

\[
SII_{m,n} = -0.4 \times SC_{m,n} + 1 \quad (0 \leq SC_{m,n} \leq 2.5) \quad (5)
\]

\[
SII_{m,n} = 0 \quad (2.5 < SC_{m,n}). \quad (6)
\]

Daily mean air temperatures were computed on the basis of field measurements carried out during August 1998 and July 1999 and served as input for the modelling.

![Figure 3. Relation between MRAG (see text) and the simulated thickness of snow cover between 15 March and 30 April, during which the snow cover is the thickest in a year. See Fig. 1 for in-situ monitoring sites.](image)

![Figure 4. Distribution of estimated cumulative freezing and thawing indices through a year (1998–1999).](image)

![Figure 5. Correlation between simulated and measured cumulative freezing and thawing indices (CFTIs) on the ground surfaces. See Fig. 1 for in-situ monitoring sites.](image)

4 FIELD EVIDENCES OF PERMAFROST OCCURRENCE

4.1 Field survey methods

DC resistivity imaging gives detailed information on subsurface structures both horizontally and vertically, and is known to be suitable for investigating mountain permafrost under condition of complicated topography/subsurface structure (Hauck & Vonder Mühll, 1999; Vonder Mühll et al., 2001; Ishikawa et al., 2001). For electrode configuration, Wenner-Schlumberger
array was used. The inverted resistivity models were processed by RES2DINV ver.3.4. Several iterations were conducted until root mean square (RMS) errors converged and reached a minimum.

It is difficult to determine the occurrences of permafrost based on resistivity values alone, because resistivity varies with subsurface materials, ground water condition and porosities. In order to obtain more realistic interpretation on permafrost occurrences, shallow ground temperatures (SGTs) down to 1.0 or 1.5 m depths and their profiles were observed in autumn when ground temperatures reach their seasonal maximum in value.

Along all survey lines, a total of 54 plant species was identified. Combination of these species determines the vegetation communities and qualitatively indicates the local thickness and durations of the snow cover.

4.2 Results and interpretations

**HOK#1 (Fig. 6)**

Along this entire line, plants belonging to WB grow, suggesting virtually near-zero snow accumulation even in winter. All SGT's seem to decrease with increasing depth. Extrapolation of these profiles toward greater depths indicates probable permafrost occurrence below 1.5 m along the entire survey line. High resistivities ranging 64 to 256 kΩm were found by DC resistivity imaging. The interpretation of this zone as permafrost agrees with results obtained by Fukuda and Sone (1992).

**HOK#2 (Fig. 7)**

Obvious differences in DC resistivities and SGTs were found along this line, according to the differences in vegetation cover. SGTs decrease with increasing depth between 10 and 40 m distance, where WB plants exists, whilst isothermal profiles were recorded between 50 and 80 m distance where SB and SM plants predominate. DC resistivities between 10 and 40 m distance are several hundred kΩm, considerably higher than those recorded between 50 and 80 m distance. This suggests that permafrost only exists between 10 and 40 m distance and in WB communities but is absent underneath SB and SH plants along the remaining parts of the survey line.

**HOK#3 (Fig. 8)**

Survey line HOK#3 is perpendicular to HOK#2, with the two survey lines crossing at 70 m distance. WB plants are dominant between 0 and 60 m, and 100 and 150 m distance, whilst mainly SH and SB plants grow along the rest of this line. SGTs are isothermal between 15 and 45 m, and between 75 and 105 m, while slightly decreasing with increasing depths at 65 m and between 120 and 145 m. High-resistivity zones with values exceeding 64 kΩm exist between 10 and 25 m, around 65 m and between 120 and 145 m. Such zones are found in areas where SGTs shows a slight decrease with depths. Along this
line, permafrost with a slightly thicker active layer underlies the wind-blown ground.

**KZ#2 (Fig. 10)**
Along this entire line, plant distribution is primarily *WB*. SGTs do not show obvious decrease with increasing depths and these values at maximum depths are not as low as would be anticipated. High resistivity zones with values exceeding than 64 kΩ m are observed throughout underneath this line, suggesting the presence of permafrost below a relatively thick active layer. The thick active layer may be due to higher amounts of solar radiation received at this location on the south-facing slope.

**KZ#4 (Fig. 11)**
Plant distribution is primarily *SB* between 10 and 50 m distance. There is no vegetation cover between 50 and 150 m. Such plant distribution suggests that much snow accumulates during winter and remains until summer. SGTs are near-isothermal throughout this line and show high values at the maximum depth reached. The DC resistivity tomogram does not show any subsurface frozen materials.

**KZ#5 (Fig. 12)**
Along this line, *WB* plants exist between 0 and 30 m distance, whilst *SB* and *SM* plants predominate between 45 and 150 m. Some of the plant species belonging to *SH* occur between 30 and 50 m. SGTs decrease with increasing depth between 10 and 30 m, whilst showing isothermal conditions between 35 and 140 m. At 20 m distance, frozen materials can be identified below a depth of 110 cm. High-resistivity zones with values exceeding 64 kΩ m underlay the survey line between 10 and 40 m and can be attributed to the presence of permafrost.

### 4.3 Summaries
The field evidences described above reveal that the permafrost distribution is strongly controlled by accumulation and duration of snow cover both in winter and summer. Lower ground temperatures and/or higher resistivities are found beneath the sites with *WB* plant, which is an indication of nearly total absence of snow accumulation during wintertime. On the other hand, permafrost is absent beneath areas with high amount of snow accumulation.

### 5 MODEL VALIDATIONS
The relation between calculated negative CFTIs and permafrost occurrence as derived from SGT measurements can now be analyzed (Figs 6–12 and Fig. 13). Along the line of HOK#1, permafrost is found throughout the line by SGT and DC resistivities. At the lines
HOK#2, HOK#3 and KZ#5, permafrost areas approximately correspond to areas with negative CFTIs. At the line KZ#4, no permafrost is found where positive CFTIs were calculated. At the lines KZ#1 and KZ#2 higher SGTs occur in spite of negative CFTIs. However, DC resistivity imaging indicates the occurrence of permafrost along these lines. The CFTI distribution shows good correlation with permafrost occurrence in the summit areas of the Daisetsu Mountains as surveyed by DC resistivity imaging and SGT measurements.

6 CONCLUSIONS

Permafrost distribution in the summit areas of the Daisetsu Mountains are strongly controlled by snow cover and complicated even over small areas. For spatial modeling of such permafrost, GIS analysis and precise DEM can be used. CFTIs are spatially calculated, considering the thermal insulation effects by snow cover, negative CFTI should indicate the occurrence of permafrost as demonstrated by the results from field surveys combining SGT measurements and DC resistivity imaging.

REFERENCES