The effect of surface nocturnal cooling on maintaining the mountain permafrost in central Japan

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ABSTRACT: Meteorological observations were conducted to reveal the relation between surface nocturnal cooling during snow free periods and progressing ground freezing in the permafrost area of the cirque. Using an infrared thermal imager, the spatial pattern of surface temperature was observed on clear weather days in autumn. Debris slopes with permafrost cooled effectively by cold-air pooling due to basin-shaped topography, while the vegetated slopes and sidewalls of the cirque were rather warmer. According to year-round monitoring of ground temperatures at the permafrost site, snow melt was finished in early September. Frequent formation of strong nocturnal cooling after late September lowered ground temperatures within the active layer. The permafrost in the cirque is located in debris slopes with delayed snow melt due to large accumulations of snow. Thus, the ground surface in the area is affected by strong nocturnal cooling in autumn without heating by solar radiation and by warm rain during the summer.

1 INTRODUCTION

Mountain permafrost was recently discovered in the Kuranosuke Cirque (2720 m a.s.l.), Tateyama Mountains in central Japan (Fukui & Iwata 2000). Since the permafrost has a sporadic distribution in the cirque, it is thought that such low-latitude and altitude permafrost can exist under peculiar atmospheric and surface conditions.

The high sensitivity of the low-latitude mountain permafrost with respect to climatic factors such as snow cover duration and surface energy exchange during the snow free period makes knowledge about the spatial distribution patterns of mountain permafrost substantially important. A better understanding of both the processes of mountain permafrost formation or decay and the distribution of discontinuous mountain permafrost requires detailed information of the energy-exchange processes at the atmosphere/lithosphere boundary (Mittaz et al. 2000, Hoelzle et al. 2001). The influence of the seasonal snow cover on the ground thermal regime and on frozen ground has received considerable attention during the past few decades (Smith 1975, Goodrich 1982, Keller & Gubler 1993, Hoelzle et al. 1999). However, the spatial pattern of the thermal regime within the active layer involving surface cooling processes during the pre-snow-covered season tended to be given less attention since surface cooling processes show quite different behaviour due to complications with highly variable small-scale topography and surface conditions.

In the present study, meteorological observations were made to assess the relation between surface nocturnal cooling during the snow free season in autumn and progressing ground freezing in the permafrost area in the cirque. Using an infrared thermal imager, the spatial pattern of surface brightness temperature was observed on clear weather days of October 1999. In addition, the possible permafrost or non-permafrost area in the cirque is compared with spatial pattern of surface cooling based on thermal conditions of each surface. Finally, it discusses the required conditions to maintain permafrost in the cirque.

2 SITE AND METHODS

2.1 Site description

Kuranosuke cirque is located in Tateyama Mountains of central Japan (36°35’N, 137°37’E; Fig. 1, Photo 1), which mainly faces east-northeast. There is a perennial snow patch at the bottom of the cirque (ranging from approximately 2700 m to 2800 m a.s.l.), and debris slopes near the snow patch recognized as protalus ramparts (Sekine 1973, Ono & Watanabe 1986) where the permafrost is located at a depth of 1.5 m as investigation by digging showed (Fukui & Iwata 2000). In this cirque, inactive and fossil rock glaciers exist adjacent to a protalus rampart. The materials of the debris slopes consist of a surface layer with coarse blocks (10–20 cm) and non-porous sublayer (below 20 cm) with mostly...
sandy materials. In the lower part of the cirque, there is a partly vegetated surface.

2.2 Methods of observation

Spatial patterns of surface temperature (thermal image) were observed using infrared thermal imager (TVS-600, Nippon Avionics Co., Ltd.) during clear weather days in autumn (9 and 10 October 1999). The field of view (and pixel size) is 25.6° (320 pixels) vertical and 18.9° (236 pixels) horizontal. Pixel resolution is 0.71 m at a distance of 500 m. The images were measured five times during the period (9 October; 1130, 1640, 2050, 10 October 520, 1250 JST; Japan Standard Time). Emissivity of ground surface was assumed to be 1.0 regardless of the surface materials. This equivalent black body temperature (brightness temperature) does not show actual surface temperature, but allows to differentiate in terms of outgoing infrared radiation energy. Actually, thermal image remote sensing must be corrected for the influence of water vapor absorption of infrared radiation. However, the transmission function of the atmosphere is assumed to be 1.0 due to the short distance between the imager and cirque (less than 500 m) and very low humidity (Mori et al. 1995). In fact, averaged water vapor pressure observed at the Kuranosuke Hut (Fig. 1) shows only 2.4 hPa during 9 and 10 October.

At a permafrost site in the protalus rampart, year-round ground temperature observation was started from 9 October 2000 at six depths (0, 50, 100, 130, 160, 220 cm) using Pt 100 ohm sensor, which are recorded by multi-channel data logger (Kadec-US6, Kona system Co.). In addition, bottom temperatures of the winter snow cover (BTS) and mean annual surface temperature (MAST) were observed at some sites in the cirque using miniature data loggers (StowAway, Onset Computer Co.) since winter 1998.

3 RESULTS

3.1 Spatial pattern of brightness temperature

The spatial pattern of surface brightness temperature at 2040 JST is displayed in Fig. 2. The coldest area is found on the snow patch (point-A) with less than −7°C. The debris slopes (B) surrounding the snow patch show strong cooling as well, just looking like cold air accumulation around the snow patch. The area to the left of the debris slope (C, rock glacier) also showed relatively strong cooling (about −5°C). The mountain peak (E) as well as ridges and vegetated surface at the lower part
of the cirque (D) exhibit weaker cooling with brightness temperature warmer than \(-3^\circ C\). This spatial pattern of surface temperature is primarily caused by differences in topography, such as slope inclination and direction, and surface materials. On the surface of snow patches and debris slope surfaces, effective cooling occurred due to strong radiative cooling without perturbing prevailing westerly winds due to topographic protection. On the other hand, on the mountain ridge and vegetated surfaces, temperature variations are rather suppressed due to efficient mixing with the ambient atmosphere.

3.2 Diurnal variation

In order to extract the characteristics of surface cooling and diurnal temperature variation on different surface conditions from each thermal image, the five characteristic points having \(10 \times 10\) pixels (\(7 \times 7\) m) were chosen. The diurnal variations of averaged brightness temperature at these points were exhibited in Fig. 3. Point-A (snow patch) showed the coldest site both during the daytime and nighttime. Surface temperature in the daytime was around \(0^\circ C\) because of snow surface. Point-B (protalus rampart) exhibited the colder temperature during nighttime, while one of the highest temperature during daytime. Point-C (rock glacier) was also cold during night, and daytime heating was lower than that of B. Point-D (vegetated surface) was the warmest of all site: A strong heating during daytime and a suppressed nocturnal cooling. Finally, Point – E (mountain top) had a small diurnal variation with both weak daytime heating and nocturnal cooling.

The spatial pattern of surface brightness temperature within each surface also shows diurnal characteristics (Fig. 3). At point – A, the temperature varied nearly homogeneously with less than \(0.6^\circ C\) of standard deviation both in the day and night. Relatively high spatial deviation conversely formed at point – E through the day. On the other hand, daytime temperatures had larger standard deviations at points-B, C and D, whilst they were low at night except for point-D. These results
indicate that the heating and cooling processes at each surface have distinct characteristics in conjunction with the surface conditions.

3.3 Comparison with temperature properties

BTS and MAST of five points are shown in Table 1. Points – B (protalus rampart) and C (rock glacier), both with debris surface, are possible sites of existing permafrost due to BTS lower than $-3^\circ C$ and MAST lower than $0^\circ C$. The vegetated and mountaintop locations, D and E, denote little possibility of existing permafrost. These year-round thermal properties correspond to the amplitude of diurnal variation. Thus, strong nocturnal cooling in autumn is one of the requirements to maintain the permafrost, although high diurnal heating simultaneously occurs.

Figures 4 and 5 show time variations of ground temperature at the permafrost site (point-B) during both autumn 2000 and 2001. The annual maximum temperature was only less than 6°C below 50 cm depth of ground temperatures (Figs 4 and 5). Frequent and strong nocturnal cooling that had daily minimum surface temperatures well below 0°C developed after both October and rapidly lowered ground temperature in the uppermost 160 cm of the active layer to 0°C. At the site, snow melt ended in early September in 2001 and 2002 (not shown), so that the frozen layer could persist until late summer and the surface cooled again in a short time after exposure of ground surface.

4 DISCUSSION

4.1 Spatial difference in cooling processes

The present preliminary study indicates that the differences in micro-scale topography and surface conditions are key factors determining the spatial pattern of surface nocturnal cooling which possibly relates to the presence or absence of permafrost in the cirque. The spatial pattern of surface nocturnal cooling is caused due to

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![Figure 4](image-url) **Figure 4.** Time series of ground temperature at the permafrost site in Kuranosuke cirque from 8 October to 31 December 2000.

![Figure 5](image-url) **Figure 5.** As in Fig. 4, but from 1 August to 31 October 2001.

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Table 1. Thermal characteristics on each surface.

<table>
<thead>
<tr>
<th>Point†</th>
<th>BTS*</th>
<th>MAST*</th>
<th>DR**</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Perennial snow patch</td>
<td>No data</td>
<td>No data</td>
<td>7.5</td>
</tr>
<tr>
<td>B Protalus rampart</td>
<td>24.4</td>
<td>21.0</td>
<td>16.7</td>
</tr>
<tr>
<td>C Rock glacier</td>
<td>25.7</td>
<td>20.7</td>
<td>13.0</td>
</tr>
<tr>
<td>D Vegetated surface</td>
<td>21.7</td>
<td>1.5</td>
<td>12.5</td>
</tr>
<tr>
<td>E Mountain top</td>
<td>21.3</td>
<td>No data</td>
<td>7.2</td>
</tr>
</tbody>
</table>

† See Photo 1 for the location of each point.

* BTS and MAST were observed in March 1999.

** DR: diurnal range of the surface brightness temperature which is difference value between 0520 and 1250 JST, 10 October 1999.
different cooling processes on each surface based on the physical and thermal properties of each surface and their relations with the influence of the ambient atmosphere.

It is well-known that longwave emissivity at the snow surface is generally greater than that of other surfaces (Keller & Gubler 1993, Zhang et al. 2001). Our results showed that surface brightness temperature on a perennial snow patch was lowest at night, thus more efficient radiative cooling occurred at snow surface due to high emissivity. Topographic protection from westerly winds prevailing after autumn reduces sensible heat exchange at basin-shaped topography in the cirque, together with cold-air pooling around the snow patch. Thus, in the area of and around the snow patch, the surface nocturnal cooling tends to be enhanced. That is, nocturnal net radiation and lateral cooling fluxes mostly divided into ground heat divergence at the snow patch (point – A) and surrounding debris slopes (points – B and C).

Since surface temperature deviation increased in daytime at each point in the cirque, it is indicated that heating in daytime is limited only to surfaces facing the direction of direct solar radiation. In addition, as indicated by Figs 4 and 5, surface heating can not easily be conducted into the ground where there are coarse surface blocks with lower thermal conductivity. Thus, even though the surface heating at the protalus rampart (point – A) is greater than at other sites, the actual heating of the active layer may be suppressed. Inversely, surface nocturnal cooling produces cold air, which can penetrate into the coarse block cover and effectively cool the subsurface ground.

On the other hand, the mountain ridge and vegetated surface exhibit warmer brightness temperatures. Diurnal range of surface temperature at the mountain ridge is the smallest (Fig. 3), thus it can be noted that energy exchange between surface and atmosphere efficiently occurred both during day and at night. On the vegetated surface in the lower part of the cirque, greater warming occurred in the daytime, while weak cooling occurred at night. Daytime warming might be caused by the relatively low albedo of vegetation. Reduced surface cooling indicates that the different emissivity of leaves lowers surface cooling and the low heat capacity of leaves induces temperatures approaching air temperature.

5 CONCLUSIONS

In the present study, meteorological observations were conducted to reveal the relation between surface nocturnal cooling during snow free period and progressing ground freezing at the permafrost area in the Kuranosuke Cirque of Tateyama Mountains in central Japan. The permafrost in the cirque is located in debris slopes with delayed snow melting due to large quantities of snow accumulation, so that the ground surface at winter and spring. In particular, in and around the snow patch of the cirque, the snow cover is maintained until late August on an annual basis. Thus, low ground temperature, and hence permafrost in the cirque, is protected from heating processes. In central Japan, precipitation is the important factor of heating as well as solar radiation because high amounts of precipitation during the warm season [e.g. 1370 mm near the Kuranosuke Hut from 4 June to 31 August 2001 (Iijima, unpubl)] penetrate into the soil and melt the frozen layer. Precipitation is certainly effective in transporting sensible heat to the base of the active layer and deepening seasonal thaw above permafrost bodies (Hinkel et al. 1993).

During snow free period after September, a migratory anticyclone with a dry atmosphere frequently begins to cover Japan and is closely associated with remarkable nocturnal cooling in mountainous area of central Japan (Iijima & Shinoda 2000). Under calm and dry synoptic conditions, the potential intensity of radiative cooling is enhanced during autumn (after September) owing to decreased downward longwave radiation with reduced air temperature and water vapor content in the air (Iijima & Shinoda 2002). As shown in Fig. 5, strong surface cooling frequently occurred during autumn through late November with a decrease to less than 0°C at the permafrost site in the Kuranosuke Cirque. In addition, thermal images (Fig. 2) imply that lateral fluxes such as cold-air accumulation contribute to enhanced nocturnal cooling at debris surfaces with coarse blocks on steep slopes.

Taking above mentioned considerations into account, the combined effect of prolonged snow accumulation until late summer and strong nocturnal cooling during snow free season of autumn characterized the maintenance of mountain permafrost in the Kuranosuke Cirque. In fact, an estimation of year-around ground heat flux using ground temperature data of 2001 at permafrost site (Fukui unpubl) shows an efflux of ground heat (∼0.18 MJ m⁻²) mainly due to cooling during autumn. Further quantitative analysis of spatial pattern of energy exchange system in the cirque, however, should be required based on comprehensive observation and modeling.
the area is affected by strong nocturnal cooling during autumn without heating by solar radiation and warm rain during summer.

Using an infrared thermal imager, spatial pattern of surface temperature were observed on clear weather days in October 1999. Strong nocturnal cooling is likely in relation to cold-air pooling in the cirque. Debris slopes with permafrost cooled effectively by cold-air pooling due to basin-shaped topography, while vegetated slopes that distribute at the sidewall of the cirque were warmer. According to year-round monitoring of ground temperature at the permafrost site during 2000 and 2001, snow melt ended in early September. Frequent formation of strong nocturnal cooling that had daily minimum surface temperature below 0°C was developed after late September, and lowered ground temperature within the top 1.6 m to 0°C with rapid response. Thus, the combined effect of a prolonged snow cover duration and strong nocturnal cooling after the snow free period during autumn characterized the maintenance of mountain permafrost in the cirque.

ACKNOWLEDGEMENTS

The authors wish to thank Prof. T. Mikami of Tokyo Metropolitan University for instruction in using infrared thermal imager. They are also indebted to many individuals for their observations and other support. This research was supported by the fellowship of the Japan Society for the Promotion of Science for Young Japanese Scientists and a scientific research grant from the Japanese Ministry of Education, Science, Sports and Culture (No. 07386).

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