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Short Communication

Winter Ground Surface Temperature Regimes in the Zone of Sporadic Discontinuous Permafrost, Tatra Mountains (Poland and Slovakia)

Bogdan Gądek [1]* *and Stanisław Kędzia* [2]

[1] Department of Geomorphology, Faculty of Earth Sciences, University of Silesia, Sosnowiec, Poland
[2] Department of Geomorphology and Hydrology of Mountains and Uplands, Polish Academy of Sciences, Kraków, Poland

ABSTRACT

Ground surface temperatures in the zone of sporadic discontinuous permafrost in the Tatra Mountains were monitored over two winters at sites where either permafrost or deep seasonal frost had been previously posited. The results show that contemporary permafrost can exist beneath both thick and thin snow covers. We infer that its presence may relate more to local circulation of cold air over the surface and low summer solar irradiation than to elevation and snowpack development. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: permafrost; ground surface temperature; BTS; Tatra Mountains

INTRODUCTION

The Tatra Mountains are currently unglaciated mid-latitude mountains where periglacial forms and processes are active (e.g. Kotarba, 1992; Rączkowska, 2004). The presence of permafrost in the area was first reported by Dobiński (1997, 1998a, 1998b) based on the results of climatological and geophysical investigations. According to Dobiński, thawing and freezing indices provide evidence that sporadic discontinuous permafrost may occur at elevations of 1700 m a.s.l. with continuous permafrost occurring above 2500 m a.s.l. Contemporary permafrost is likely above 1930 m a.s.l. on north-facing slopes and above 2050 m a.s.l. on south-facing slopes. Permafrost mapping using the basal temperature of snow (BTS), direct current (DC) resistivity, infrared imaging and ground-penetrating radar methods in the glacial cirque of Kozia Dolinka (1940–2020 m a.s.l.) revealed only the occurrence of isolated, lens-like patches of permafrost on north-facing slopes (Mościcki and Kędzia, 2001; Kędzia, 2004; Lamparski and Kędzia, 2007). In contrast, massive ice was observed in the substrate at Medena kotlina at 2000 m a.s.l. (Gądek and Kotyrba, 2003).

Snow cover can be the key factor in determining the presence or absence of permafrost in sporadic discontinuous permafrost areas (e.g. Zhang, 2005). Individual measurements of the BTS (Haeberli, 1973) and/or monitoring of ground surface temperature (GST) at the snow-ground interface are simple techniques recommended for the investigation of mountain permafrost distribution and development (Hoelzle *et al.*, 1999; Ishikawa, 2003). This paper presents the first results of winter GST monitoring and briefly discusses the possibility of contemporary permafrost development in the alpine zone of the Tatra Mountains.

LOCATION AND METHODS

GST monitoring was carried out at 11 soil-free sites located in hanging glacial cirques (Medena kotlina, Kozia Dolinka, Świstówka Roztocka and

* Correspondence to: Bogdan Gądek, ul. Będzińska 60, 41-200 Sosnowiec, Poland. E-mail: bogdan.gadek@us.edu.pl

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Dolina Pięciu Stawów Polskich, Figure 1) where previous investigations had suggested either the presence or the absence of permafrost (Table 1). Miniature data loggers (Onset Hobo Pro), containing thermistors with an accuracy of better than ±0.4°C, were installed beneath a 3-cm thick debris layer. GST values were recorded every hour for 1–2 years: in Medena kotlina from 23 August 2003 to 2 October 2004, in Kozia Dolinka from 1 September 2003 to 30 June 2005, and in Świstówka Roztocka and Dolina Pięciu Stawów Polskich from 30 September 2003 to 29 July 2005. In summer 2004 the sites KC1 and KC2 were established in Kozia Dolinka and the site KG2 was removed. The data obtained were compared with snow thickness and air temperature measurements recorded at the nearest meteorological station on Hala Gąsienicowa (elevation 1520 m a.s.l.), located about 3 km from Kozia Dolinka (Figure 1).

RESULTS AND INTERPRETATION

GST values recorded at individual sites together with air temperature and snow depth from Hala

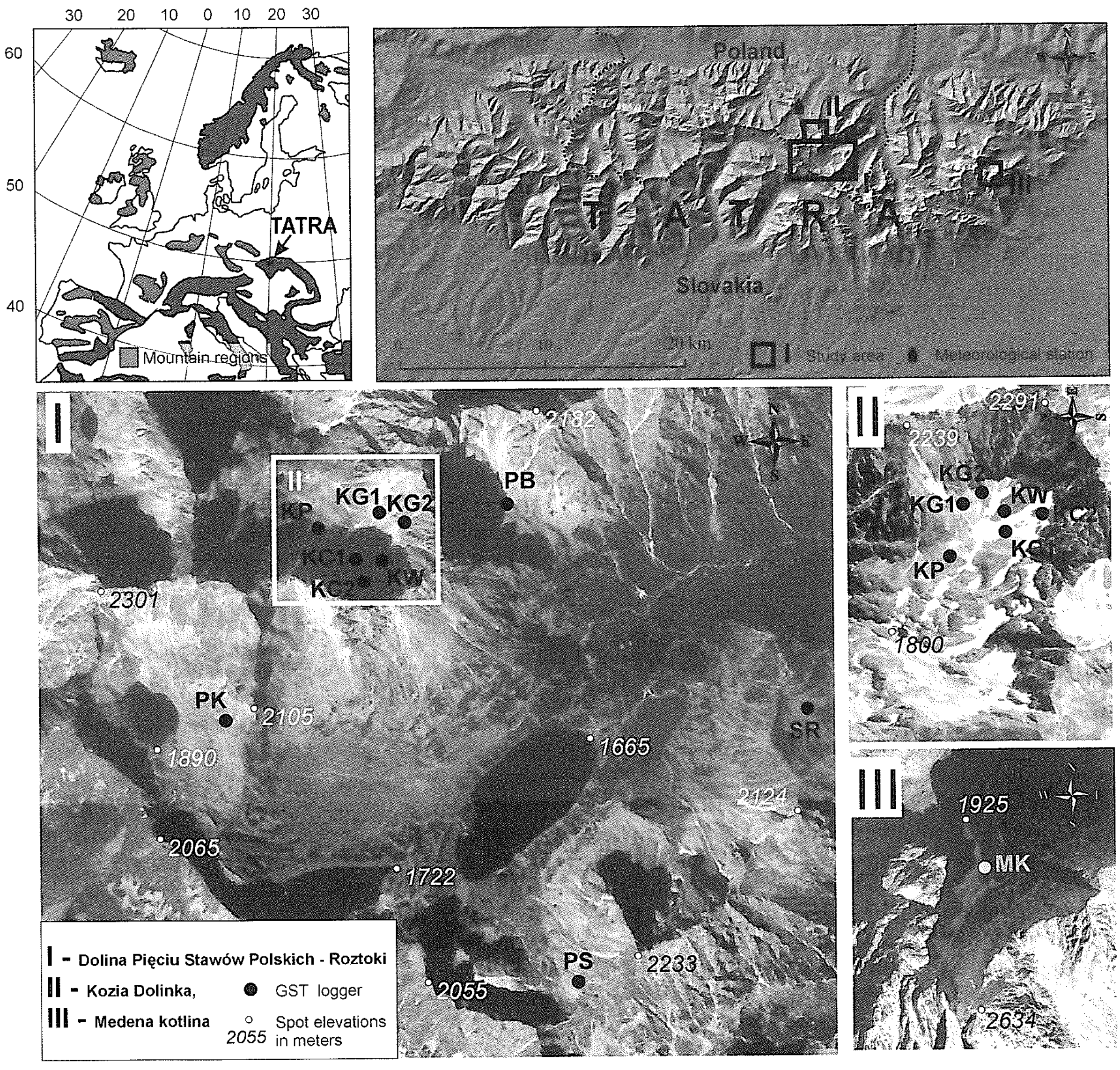

Figure 1 Location of the study area and measurement sites (orthophotomaps used by permission of the Urząd Marszałkowski Województwa Małopolskiego).

Table 1 Characteristics of GST measurement sites

Area	Site	Elevation (m a.s.l.)	Aspect	Landform	Permafrost occurrence based on the literature		
					Possible existence of permafrost	Methods of detection	Reference
Medena kotlina	MK	2030	N	Frontal-lateral moraine	Yes	Outcrop of massive ice	Gądek and Kotyrba (2003)
Kozia Dolinka	KW	1965	NW	Talus cone	Yes	DC resistivity sounding; BTS measurements; Infrared imaging; GPR survey	Mościcki and Kędzia (2001); Kędzia (2004); Lamparski and Kędzia (2007)
	KC1	1955	NNW	Hollow between talus cones	Yes		
	KC2	2020	N	Rock projection	No		
	KG1	1980	SSW	Talus cone	No		
	KG2	1990	WSW	Talus cone	No		
	KP	1940	WNW	Rocky threshold covered by moraine material	No		
Świstówka Roztocka	SR	1820	NNE	Debris tongue	Yes (relict)	DC resistivity sounding; BTS measurements	Dobiński (1997, 1998a)
Dolina Pięciu Stawów	PK	1930	SW	Moraine cover	Yes (relict)		
Polskich	PB	1785	SE	Deep hollow within debris tongue	Yes (relict)		
	PS	1980	N	Debris rampart	No previous study	—	—

DC = direct current; BTS = basal temperature of snow; GPR = ground-penetrating radar.

Gąsienicowa are shown in Figure 2. Mean annual ground surface temperatures (MAGST), in locations thought to have contemporary permafrost were negative, and in non-permafrost sites they were positive (Table 2).

The winter data indicate three stages of GST evolution, relating to the development of snow cover: (a) thin snow cover and short-term fluctuation of basal temperatures; (b) thick snow cover with stabilisation of basal temperatures; (c) and snowmelt, with a rapid increase in snow cover temperatures and basal temperatures. Although the snow cover thickness at individual sites was not measured, according to Haeberli (1973) it may be assumed that during stage (b) it reached at least 0.8 m.

The following three basic types of ground surface winter temperature regimes were observed:

(1) *Short-term GST fluctuations throughout winter.* GST values under a thin snow cover varied according to air temperature. The delay and amplitude of these changes depended on the

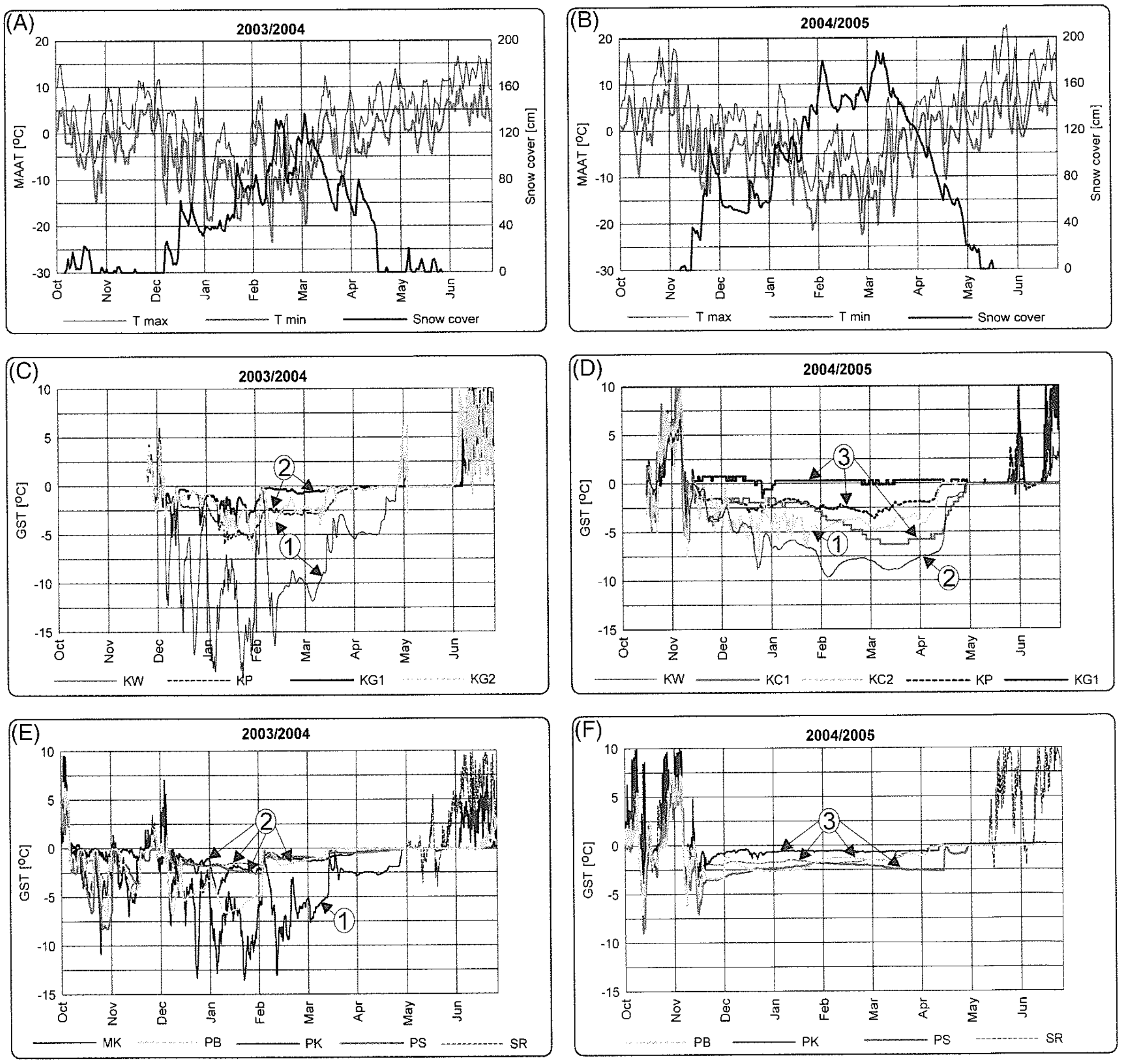

Figure 2 Winter air temperatures and snow depths at Hala Gąsienicowa (A, B) and winter ground surface temperature (GST) values in the sites studied (C–F). Numbers 1, 2 and 3 — types of GST regimes at individual sites (see Figure 3).

Table 2 Winter thermal regimes at ground surface measurement sites

Site	Type of winter GST regime		GST values in March (°C)		MAGST (°C)
	2003/2004	2004/2005	2003/2004	2004/2005	
MK	1	No data	−7 to 0	No data	−1.0
KW	1	2	−12 to −3	−8	−1.6
KC1	No data	3	No data	−6	No data
KC2	No data	1	No data	−5 to −2.5	No data
KG1	2	3	−0.5	0	2.3
KG2	1	No data	−4 to 0	No data	No data
KP	2	3	−3	−2	1.4
SR	2	3	−1	−1	1.9
PK	2	3	−1	−0.5	1.4
PB	2	3	−1	−1.5	0.3
PS	2	3	−1	−2.5	0.2

GST = ground surface temperature; MAGST = mean annual ground surface temperature.

thickness and density of the snow cover. This type of thermal regime was recorded at sites MK, KW, KG2 (winter 2003/2004) and KC2 (winter 2004/2005) (Figure 2). At permafrost locations MK and KW, the lowest GST values were −13°C and −20°C, respectively, whereas those at permafrost-free sites KG2 and KC2 were −4°C and −8.5°C, respectively. Stabilisation of GST values occurred at the beginning of spring 2004 at all the monitored sites due to snowpack ripening. Short-term cooling then occurred, accompanied by considerable snowfall (Figure 2).

(2) *Short-term GST fluctuations only at the beginning of winter.* This type of thermal regime typically develops beneath gradually increasing snow depths. In winter 2003/2004 this pattern was recorded at sites KG1, KP, SR, PK, PB and PS, and in the following year at site KW. At the end of winter, the basal temperature of dry snow cover (BTS) at sites free of contemporary permafrost ranged from −0.5°C (KG1) to −3°C (KP), and where permafrost occurred (KW) it was close to −8°C. At sites SR, PK and PB, where a high probability of relict permafrost exists according to previous investigations (Table 1), a GST of −1°C was recorded. It is important to note that in all cases the thick snow cover preserved the GST values that had existed at the beginning of this stage. In 2003/2004, for example, the stage of thick snow cover was established in February, just after a short thawing period had increased GST. GST values were stable until thaw in the third week of March, when they increased to 0°C everywhere.

(3) *Absence of short-term GST fluctuations throughout the period of dry snow cover.* Thermal regimes typical of the effect of thick snow cover were recorded during the snowy winter of 2004/2005 at KC1, KG1, KP, SR, PK, PB and PS. Some variations in GST, however, were identified among these sites. The initial GST values were 0°C and close to −0.5°C, respectively, at south-facing KG1 and PK and these temperatures were maintained until the end of the snow cover. At both sites, a decrease of GST values to −1°C was observed over several days at the end of December 2004, connected with snow cover subsidence (decrease in thickness and increase in density) and a significant decline in air temperature. At the other sites, slow changes of GST were recorded. These reflected periodic changes in air temperature with some lag relating to the thickness and density of snow cover. The largest changes of this type were recorded in the location with contemporary permafrost (KC1), where snow is usually several metres thick (Kędzia, 2004). After a 7-week stabilisation, the temperature at the bottom of thick snow decreased over 6 weeks from −2°C to −6°C. In all cases, the thick snow cover maintained the initial basal temperature values. On days with thaw, a rapid GST increase was sometimes recorded, which was followed by stabilisation at a higher value.

DISCUSSION

The field data show that locations with and without permafrost may exhibit similar winter GST regimes (Figure 3). Locations underlain by contemporary permafrost, however, were distinctly colder than non-permafrost sites. At the end of winters 2003/2004 and 2004/2005, temperatures beneath thick snow

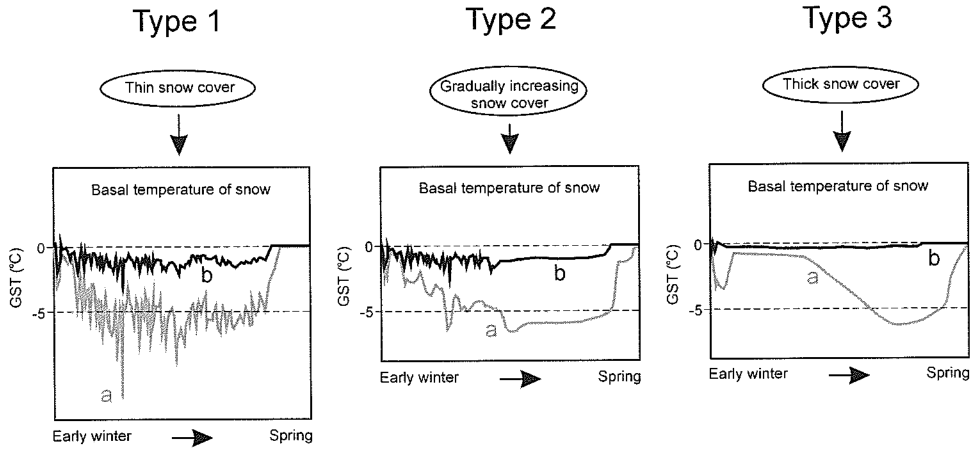

Figure 3 Type 1–3 temperature regimes at the base of the snowpack at (a) contemporary permafrost sites and (b) permafrost-free sites located in the alpine zone of the Tatra Mountains during winters 2003/2004 and 2004/2005.

cover (conventional BTS) were no higher than −5°C, whereas in non-permafrost sites the lowest BTS values were −3°C (Table 2). In the first winter, a late and thin snow cover developed whereas in the second the snow cover was early and thick. Thus in March 2005, BTS values higher than those of 2004 would have been expected (Brenning *et al.*, 2005). However, inter-annual variation of March BTS at individual loggers ranged from −1.5°C to +1°C (Table 2). The data confirm the statement, that the BTS method can be used as a general predictor of permafrost distribution but terms used in the 'rules of thumb' have not been fully quantified (Lewkowicz and Ednie, 2004, p. 77).

Winter thermal regimes of ground surfaces with (1) thin, (2) gradually growing and (3) thick snow cover (Figure 3) were similar to those observed by Ishikawa (2003) in the mountains in Japan. However, in the case of a gradual decrease of GST, reaching a minimum value at the end of winter (sites KC1 and PS), the reason was not subsurface lateral heat advection by cold air moving through blocky materials in a topographic depression (Ishikawa, 2003) since sites with this type of GST regime were located over sandy debris on convex (KC1) and concave (PS) slopes and winter values of ground temperature recorded at the depth of 50 cm were higher than those at the ground surface (unpublished field data). Thick snow cover at these sites resulted from surface relief (KC1) and avalanche accumulation (PS). The gradient of subsurface ground temperature evidenced a heat transfer to overlying colder snow layers. A distinct lag between GST and changes in air temperatures observed at the adjacent sites KC2, KW and KC1 with increasingly thick snow cover (Figure 2D) shows that at sites with little ground heat storage (KW and KC1), a thick and long duration snowpack acts as a thermal buffer but cannot entirely insulate the ground from the cooling influence of the atmosphere.

The GST values indicate contemporary permafrost in some north-facing slopes beneath both a thick, gradually increasing snow cover and under thin snow. GST values at sites KW and KC1 were distinctively lower than at site PS which had a similar elevation, aspect and snow cover. Similarly, temperatures beneath the rapidly growing snow cover at site KW were much lower than at the adjacent site KC2 (Figure 2D), located 55 m higher where snow was blown away. Winter ascending air circulation within the slopes (Delaloye and Lambiel, 2005) between these sites is excluded, because site KC2 was located on a granite ledge. This suggests that the occurrence of contemporary permafrost in the alpine zone of the Tatras may be more related to local circulation of cold air over the terrain surface and low summer solar irradiation than to elevation and snow cover development.

In Dolina Pięciu Stawów Polskich and in Świstówka Roztocka, low BTS values were not recorded at any site, despite previous DC resistivity soundings (Dobiński, 1997) which have suggested permafrost occurrence at a depth of 0.5 to 3 m. These locations are below the limit of contemporary permafrost occurrence in the Tatras, as delimited by thawing and freezing indices, and therefore they have been assumed to be sites of relict permafrost (Dobiński, 1998b). Their substrates consist of granite boulders with open voids which exhibit electrical resistivities similar to those of ice. The possible development of permafrost in these sites as a result of cold air

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circulation in the slope (e.g. Delaloye and Lambiel, 2005) is not reflected in the recorded GST values. There is also no indication of the development of air ventilation funnels through the snow in this area. The occurrence of permafrost at these sites should therefore be checked using methods such as refraction seismic survey, electromagnetic induction and ground penetrating radar (Vonder Mühll *et al.*, 2001).

CONCLUSIONS

1. Snow cover in the alpine zone of the Tatra Mountains does not usually insulate the ground from freezing, but depending on its thickness, density and the amount of heat in the ground, it decreases GST amplitudes and increases lags relative to air temperature changes. Even where snow cover remains several metres thick for several months, a slow decrease of bottom temperature is possible, reaching a minimum value at the end of winter.
2. Contemporary permafrost in the alpine zone of the Tatra Mountains is present within some north-facing slopes under both thick and thin snowpacks. It is inferred that its existence may relate more to local circulation of cold air over the surface and low solar irradiation (low summer ground heat storage) than to elevation and snow cover development.

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