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Debris slopes ventilation in the periglacial zone of the Tatra Mountains (Poland and Slovakia): The indicators

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ABSTRACT

This paper examines environmental indicators of debris slopes ventilation in the periglacial zone of the Tatra Mountains. Geomorphological and meteorological influences on ground surface temperature anomaly, hoarfrost, air ventilation funnels and snow melt windows, were analyzed as well as locations of long-lying snow and permafrost patches. The results show that debris slope ventilation is a common phenomenon occurring in different periods of the year. Its range is influenced mainly by substratum porosity (ground and snow cover), and the difference between the pressure inside and outside this medium (pore and atmospheric air temperature/dense; wind velocity). The height of the slope ('chimney') is less important. Some phenomena assumed to be evidences of slope ventilation are often connected with other factors influencing the thermal balance of the ground and the size of snow accumulation.

1. Introduction

In the upper part of the Earth's crust built of fissured, karstified or porous rocks, air exchange with the atmosphere takes place and exogenic processes occur. In the aeration zone groundwater circulates, weathering processes occur, thermal anomalies as well as accumulation of underground ice take place (Lukin, 1990a). In mountain areas, the underground cold accumulation seems to be the most important phenomenon which is connected with extrazonal occurrence of permafrost in caves (e.g. Yonge, 2004) and debris covers (e.g. Delaloye and Lambiel, 2005; Gorbunov et al., 2004; Lukin, 1990b) and specific ecosystems on the ground surface (Gude and Molenda, 2003; Lukin, 1990b; Morard et al., 2008; Ruzicka, 1999). Natural air circulation is applied, for example, to cool the bases of road and railway embankments in the areas of permafrost occurrence in order to protect them against degradation connected with climate warming (Cheng et al., 2008; Goering and Kumar, 1996). Evidences of blocky debris slopes ventilation were studied in the Prealps, the Alps (e.g. Delaloye et al., 2003; Morard et al., 2008; Phillips et al., 2009; Wakonigg, 1996), the České Středohoří-upland, the Lužické Hory Mountains (Gude et al., 2003; Zacharda et al., 2007), the Scandinavian Mountains (Heggem et al., 2005; Juliussen and Humlum, 2008), the Northern Caucasus (Lukin, 1990b), the Rocky Mountains (Harris and Pedersen, 1998), the mountains of Japan (Sawada et al., 2003).

In the Tatras the lower limit of permafrost determined by climatic conditions was delimited by Dobiński (1998) at the height of 1930 m.a.s.l., and the lowest located place of potential permafrost occurrence was found at the height of 1650 m.a.s.l. The possibility of winter ventilation of debris slopes in the Tatras, and the genesis of sporadic permafrost occurrence connected with this process were discussed by Gądek and Grabiec (2008), Gądek and Kędzia (2008), Mościcki (2008), Gądek and Leszkiewicz (2010), who indicated as the main reason anomalies of ground temperatures recorded in debris cones and rock glaciers of the periglacial zone of the Tatras. It was not proved, however, that ground temperature in these places was exclusively connected with ventilation process. Moreover, the obtained data indicated more important influence of slope exposition, local topography, local air circulation over the surface (Gądek and Kędzia, 2008), the ground structure and humidity (Mościcki, 2008).

In order to examine environmental indicators of debris mountain slopes ventilation the author took up detection and analysis of the potential abiotic aspects of air circulation inside the slopes in the Tatra Mountains. The works included: a) measurements and analysis of ground temperature variations in the upper and lower parts of the only debris slope in the Tatras, which was underlain by the permafrost outcrop, b) prospecting for the places where warm air flows from the inclined debris slopes, c) spatial documentation of snow cover decay, d) analysis of all the published data concerning the features and distribution of contemporary permafrost patches, e) analysis of geomorphological and meteorological influences on the identified phenomena.

1.1. Conception of ventilation system functioning within debris covers

Air exchange between the debris substratum and the atmosphere is connected with a difference in air density of different temperature (free convection) and wind influence (forced convection) (see Juliussen and

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Humlum, 2008). In coarse sediments of the inclined surface a "chimney effect" may originate — in this case the air movement in porous medium shows an advectional character (Cheng et al., 2008). The conception of air circulation mechanism within debris slopes was described by Lukin (1990b) and Delaloye and Lambiel (2005). According to these authors, during winter relatively warm air located inside the inclined debris cover moves up the slope. This forces penetration of the external cold air in the lower part of the slope deep into the ground even through a thick, although porous, snow cover. During summer this cold dense air flows gravitationally to the lowest parts of the slope, restraining possibilities of ground temperature increase. The efficiency of this process depends on ground permeability, intensity and duration of winter frost, content of water in the ground and its phase changes. The evidences of debris slope ventilation (Table 1) were observed both within the block covers with large porous spaces (e.g. Delaloye et al., 2003; Lukin, 1990b; Sawada et al., 2003; Wakonigg, 1996; Zacharda et al., 2007) and within debris cones where spaces between large rock fragments were filled with fine material (e.g. Delaloye and Lambiel, 2005; Heggem et al., 2005).

2. Regional setting

The Tatras are the highest mountain range in the Carpathians (Gerlach Summit: 2655 m a.s.l.). Their spatial range is delimited by the coordinates 19.54°E, 20.32°E, 49.11°N and 49.28°N (Fig. 1). The climate is transitional between maritime and continental influences. Most of the time it is controlled by maritime polar air masses coming from the Atlantic Ocean. The mean annual air temperature (MAAT) at the northern and southern Tatra foothills (ca. 850 m.a.s.l.) is 6 °C and 8 °C respectively. On the highest summits (above 2600 m.a.s.l.) MAAT is −4 °C (Hess, 1996). The mean total precipitation ranges from 1100 mm in the north foothills to 1900 mm in higher parts (Niedźwiedź, 1992). At the altitude of timber line (ca. 1500 m.a.s.l.) the mean values of seasonal number of days with snow cover and maximum snow depth, in the period 1927–1999 were 190 and 1.56 m respectively (Falarz, 2001). The modern climatic snow line runs above the Tatra ridge (Zasadni and Kłapyta, 2009). On the other hand, the orographic snow line at the northern side of the Tatras is delimited by a firn-ice patch in Mały Kocioł Mięguszowiecki nourished by snow avalanches, down to 1530 m.a.s.l.

The eastern part of the Tatras (The High Tatras) is built mainly of carboniferous granites and diorites overlaid with folded Mesozoic sediments in the northern side. In Pleistocene this area was glaciated several times (Baumgart–Kotarba and Kotarba, 2001; Lindner et al., 2003), and the youngest glacial landforms originated in Holocene (Baumgart–Kotarba and Kotarba, 2001; Gądek, 1998). The bottoms of many glacial cirques in the altitude zone of 1450–2000 m.a.s.l. are covered by rock glaciers built of granite-diorite blocks (e.g. Kotarba, 1992; Dzierżek and Nitychoruk, 1986; Nemčok and Mahr, 1974; Partsch, 1923;). They were usually interpreted as relict forms (Rączkowska, 2007). In fact, some of them are probably only inactive — inside their bodies Dobiński et al. (1996) determined layers of high electric resistivity, and on the surface low temperatures were recorded of the bottom of winter snow cover (BTS), which suggests a possible occurrence of permafrost (Dobiński, 1998; Kędzia et al., 2004; Kotarba, 2007). The results of geophysical investigations also suggest the occurrence of permafrost inside many debris slopes (Dobiński, 1998; Gądek and Grabiec, 2008; Mościcki and Kędzia, 2001). The inclination of these forms is in the range from 27° to 38°. Their height often increases to 200 m, and in some cases reaches 400 m (Lukniš, 1973). In the light of ground penetrating radar survey results, the maximum thickness of debris cones in the Polish High Tatras was estimated to range from about 20 m to over 45 m (Gądek and Grabiec, unpublished).

Table 1
Indicators of debris slope ventilation (based on: Lukin, 1990b; Delaloye and Lambiel, 2005; Zacharda et al., 2007; Juliussen and Humlum, 2008; Morard et al., 2008).

Indicators	Location on a slope	Season
Positive anomaly of GST	Upper part	All year
Funnelling of the snow cover	Upper part	Winter
Warm air outflow and condensation fog	Upper part	Winter
Snowmelt windows	Upper part	Spring
Hoarfrost	Upper part	Autumn, winter
Negative anomaly of GST	Lower part	All year
Azonal vegetation	Lower, middle or upper part	Perennial
Permasfrost	Lower and middle part	Perennial
Seasonally frozen ground	Lower and middle part	Winter
Residual snowpatch	Lower part	Summer, autumn
Outflow of saturated cold air and condensation fog	Lower part	Summer

Explanations: GST = Ground Surface Temperature.

3. Data and methods

3.1. Ground temperature

Monitoring of ground surface temperature (GST) and ground temperature at the depth of 30 cm (GT_{30}) was carried out within the hanging glacial cirque Medena kotlina (Fig. 2) at 2 soil/vegetation-free sites located in the upper (Mk_{up}) and lower (Mk_{down}) parts of talus slope of the N exposure. The ground surface contained blocky granite debris, sandy and clayey materials. The measuring sites were located in the places both without and with contemporary permafrost occurrence at the altitude of 2070 m.a.s.l. and 1990 m.a.s.l. respectively (Gądek and Grabiec, 2008).

The measurements were carried out from 1.10.2005 to 30.09.2006 using miniature data loggers Onset Hobo Pro which contained thermistors with a temperature range from −30 °C to +50 °C, a resolution of 0.02 °C and with an accuracy given by manufacturer of better than ±0.4 °C. During the measurement period, the upper thermistors were installed beneath a 3-cm thick debris layer in order to protect them from direct solar radiation and to secure good thermal conductivity with the ground surface. Temperature values were recorded every hour.

Based on the obtained data the following values were calculated: (1) mean daily GST and GT_{30}, 2) mean annual GST (MAGST) and mean annual GT_{30} ($MAGT_{30}$), 3) surface freezing index (FI_S) and surface thawing index (TI_S) (totals of negative/positive mean daily GST), 4) an approximate duration of a snow cover (number of consecutive days with GST ≤0 °C from first day with seasonal snow cover in Medena kotlina), and 5) the periods of the occurrence of a dry snow cover (number of consecutive days with GST <0 °C). Approximate meteorological conditions of thermal features of the investigated slope were determined based on the values of daily air temperature, precipitation, snow depth and maximum wind velocity recorded at the synoptic station Lomnicky Štit (WMO id: 11930) which is located about 700 m horizontally and about 600 m vertically from the measurement sites. It is the highest located meteorological station in Slovakia (2635 m a.s.l.) and the only one in the seminival belt of the Tatras. The data are derived from the Global Historical Climatology Network accessible from the NOAA website (http://www.ncdc.noaa.gov/cgi-bin/res40.pl? page = gsod.html). They include the periods when the analysed GST and GT_{30} values were recorded.

3.2. The outflow of warm air from debris slopes

During the investigations carried out in the autumn–winter seasons of the period 2006–2010 in glacial cirques of the Polish Tatras, places with the occurrence of hoarfrost and air ventilation funnels were found repeatedly. In every case, the position, date and the hour of observation were recorded, photographic documentation was