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SOIL FREEZING AND ITS RELATION TO SLOW SOIL MOVEMENTS ON ALPINE SLOPES (OF THE TATRA MOUNTAINS, POLAND)

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Abstract: The paper presents preliminary results of studies on ground temperature and its spatial and temporal differentiation in the area above the timberline in the Tatra Mts. Studies of the mechanism and rates of slope-cover movements on a mature slope in the area are also discussed. Thermistors and data loggers were used in the studies. The ground was found to be frozen from December through to April/May, even at a depth of 0.5 m. In springtime there is a period about 10 days long during which vertical differences in ground temperature create conditions that favour solifluction. The presence of meltwater, as well as ground-temperature oscillations above and below zero, are also factors of importance in influencing the rate of slope-cover movements.

Keywords: *ground temperature, Tatra Mts., Poland, soil movements, solifluction.*
Cuvinte cheie: *temperatura solului, Munţii Tatra, Polonia, deplasări de teren, solifluxiune.*

INTRODUCTION

An understanding of the ground's thermology or thermal properties, and in particular the vertical distribution of temperature in the ground, is essential if the mechanism modelling slopes is to be determined (Washburn, 1979; Matsuoaka, 1998; Matsuoaka *et al.*, 1997). The need for a better understanding of this feature in Poland's Tatra Mountains was clear in the 1950s, when T. Gerlach and M. Klapa were commencing their work on different ice-related movements in soil (among other things) - from a base at the Observational Station of the Institute of Geography and Spatial Organisation, Polish Academy of Sciences, located at

1520m a.s.l. on Hala Gasienicowa. Besides standard measurements of ground temperature using traditional thermometers, their work used Danilin permafrost-meter mainly located at the upper altitudes in the Tatras (1963, 1966). The Station referred to remains the only one in the Polish Tatras making standard ground-temperature measurements. In turn, in the early 1960s, several one-day or several-day measurement series of air and ground temperatures were obtained within the framework of studies of the perinival climate, both in the Kozia Valley and below Gasienicowa Turnia (Hess, 1963).

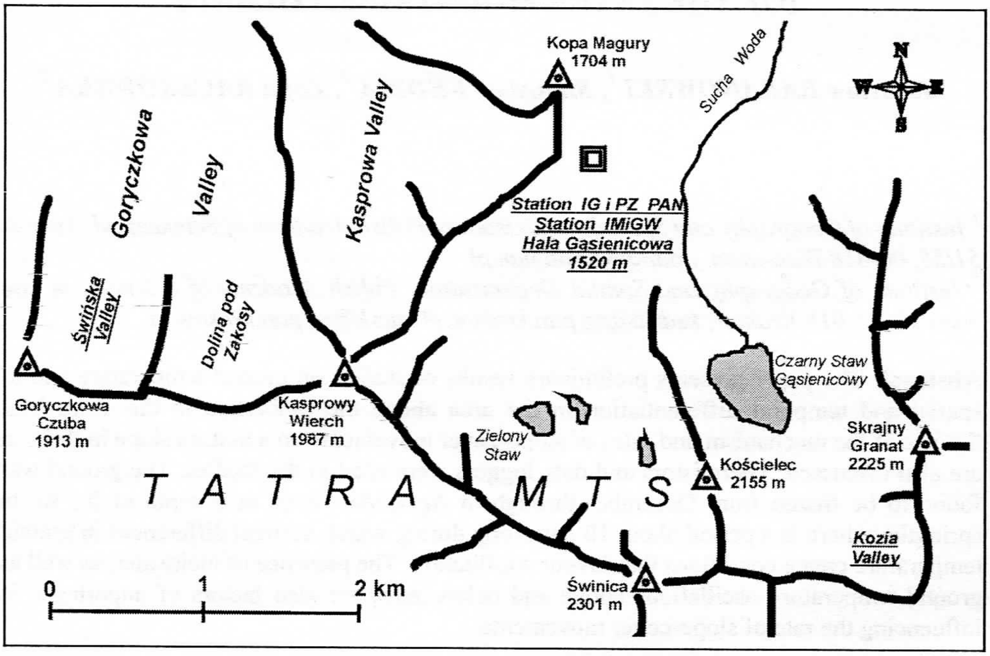


Fig. 1. Location of the study area.

At the end of the 1990s, measurements of ground temperatures using electrical thermometers (thermistors) - though not data loggers - were begun in the Kozia Valley, on the debris slopes below Kozi Peak at an altitude of 1970 m (by S. Kêdzia), as well as at the Hala Gasienicowa Station (by S. Kedzia together with M. Kotlarczyk). In 2001, J. Baranowski and Z. Raczkowska commenced with detailed research on ground thermal properties, using both thermistors and data-loggers. The work in question was located in the Œwiñska Goryczkowa Valley (Fig. 1). The ground-temperature measurement here takes place at two sites situated at 1720 and 1790 m a.s.l. (Fig. 2). The ground temperature in the Goryczkowa Valley in the autumn-spring period is measured by HOBO logger, at depths of 5, 25 and 50 cm (Fig. 4). The work in question began in autumn 2001, being supplemented by similar studies in the Kozia Valley (Fig. 4) from autumn 2003 onwards.

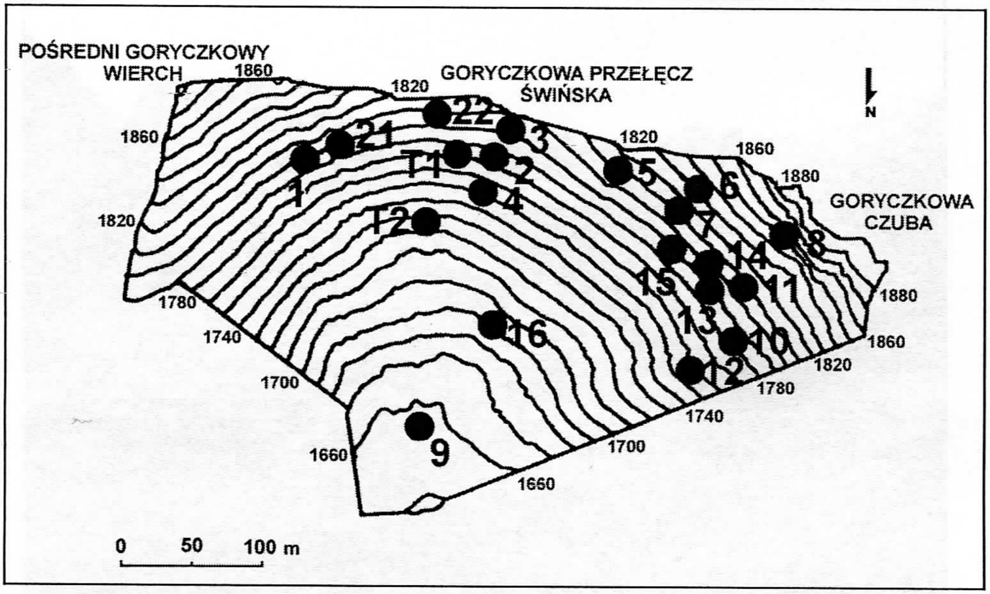


Fig. 2. Distribution of sites for the measurement of thermal properties of the ground and the shifting of slope cover in the upper part of the Goryczkowa Œwiñska Valley.

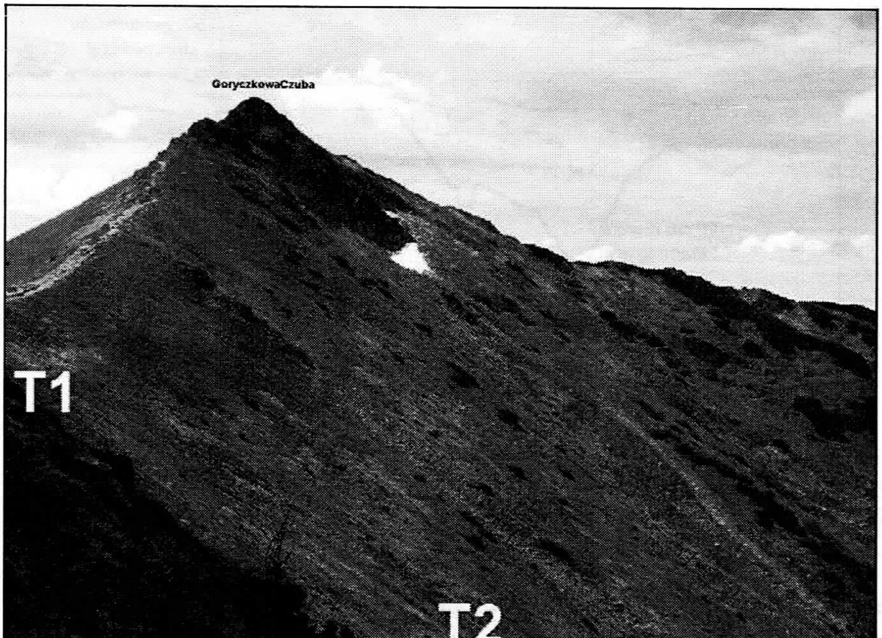


Fig. 3. General view of the Goryczkowa Valley. T1 and T2 indicate sites of ground temperature measurements.

Fig. 4. General view of the Kozia Valley.

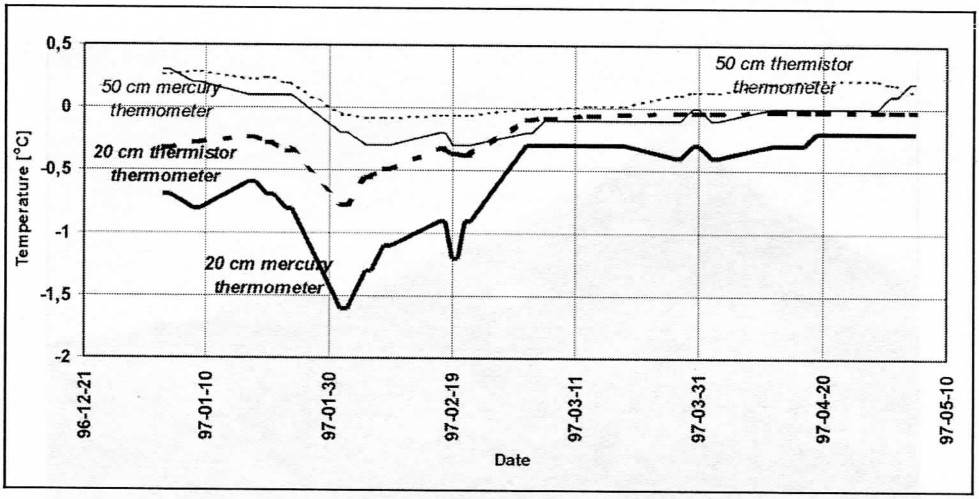


Fig. 5. Comparison of ground temperatures as indicated by mercury thermometers and thermistors.

The thermistors allowed for the determination of the real time taken for the ground at the selected depths to freeze and thaw. Standard measurements of ground temperature using mercury thermometers require disturbance of the snow cover as readings are taken, and these are associated with changes in insulating properties that distorts the natural distribution of temperatures in the ground. The greater depth and duration of the snow cover, the greater the changes of this kind also. The lack of vegetation on the measurement plot - a required condition at meteorological stations either impacting on ground temperature is. Fig. 5. presents differences in the temperatures read at Hala Gasienicowa using mercury thermometers, as well as thermistors at depths of 20 and 50 cm. The greatest differences - even attaining a value of around 1°C, are those from 20 cm down, while the smallest differences are in turn those at a depth of 50 cm. The length of the period for which the ground 50 cm down was frozen appears around twice as long when read off mercury thermometers, as opposed to thermistors. With this in mind, it was the latter that were chosen to determine the real ground temperature.

The aim of the work presented here has thus been to depict the "real" vertical differences in ground temperature, as well as the variability at the different depths through the year, at sites of differing altitude within the subalpine and alpine zones. A further aim was to use the greater familiarity with soil thermal properties in better appreciating the mechanisms by which mature slopes in the Tatras may be modelled.

GROUND THERMAL PROPERTIES AND THEIR VERTICAL AND TEMPORAL DIFFERENTIATION

From among the four sites studied, it was the Kozia Valley in which the surface layers of the ground remained frozen for longest (for around 8-9 months) (Fig. 6). In this area, the lower layers do not thaw at any time of the year, thereby generating a permafrost (Kêdzia, Moœcicki, Wróbel, 1998; Moœcicki, Kêdzia, 2001). The reverse situation applies at Hala Gasienicowa (Fig. 7), where the ground 50 cm down freezes for around 3 months, while that at a depth of 100 cm has not frozen even once since 1997 (the time the thermistors were installed). In contrast, at the upper site (T1) in the Goryczkowy Œwiñski Basin, the cool period of 2003/4 was characterised by first freezing of the ground at a depth of 50 cm in the final third of December - a situation that then persisted uninterrupted until the beginning of May (Fig. 8). The lowest temperature - of about -2.5°C was registered in mid March. In turn, the 50 cm depth at the lower (T2) site froze around a fortnight later than its T1 equivalent, also thawing slightly more than a month earlier. However, as at T1, the lowest temperature was reached in the second half of March (at a value of -0.5°C). Where the 25 cm depth was concerned, freezing occurred 1.5 months earlier at the upper site than the lower, though melting occurred at almost exactly the same time. Detailed analysis of the data for particular days reveals that superficial-layer temperatures most frequently fall below or rise above 0 °C at the beginning and around the end of the cool period. A similar situation applies to Hala Gasienicowa. The breakdown of temperatures looks different in the Kozia Valley at 1950 m a.s.l., however, in as much as that the permafrost layer is maintained, with the only defrosting occurring from the top down. In such places, the deeper (50 cm and 100 cm) layers remain frozen for the whole time in winter. Indeed, winter 2003/4 saw the temperature 50 cm down fall to a value as low as c. -17°C. Thus, the differences between the lowest registered ground temperatures 50 cm down at the Kozia-Valley and Œwiñska Goryczkowa-Valley (upper) sites were of as much as 10°C, despite the fact that the sites differed in altitude by only 160 m.

Cool-period temperature distributions in the ground are influenced very markedly by the depth of snow cover: the thicker the layer of snow the smaller and the later any changes in temperature that do occur. All the sites - be they high up or lower down - had year-round courses for temperature in which the single point representing the moment of snow-cover melting was very visible. At this point, the impact of the meltwater is to even out - at around 0 °C - the temperatures of both the disappearing snow cover and the ground. Fig. 9 presents the thickness and persistence of the snow cover at the Hala Gasienicowa Station of the Institute of Meteorology and Water Management. The date on which the ground 50 cm down at site T2 defrosts is coincident with the data of snow-melt. This despite the fact that patches of snow remain here until June.

GROUND THERMAL PROPERTIES AND MASS-MOVEMENT MECHANISMS

Mature slopes with a weathering cover are modeled by both soil-creep processes and by solifluction or frost related processes, as well as more rarely by debris flows. Determination of the processes responsible for the movement of slope covers is neither easy nor unequivocal if work is confined to geomorphological methods. A familiarity with ground temperatures may thus be helpful in seeking to draw distinctions. Research on the morphodynamics of mature slopes was done in the upper part of the Goryczkowa Œwiñska Valley, in which a map of morphodynamic surface types was produced at 1:1000 scale (Raczkowska, 1999). Each of the types it identified embraced a process or set of processes modelling a given fragment of slope, as well as an intensity of modelling defined qualitatively on a scale from I to IV - with the range being from inactive slopes to those subject to intensive transformation. At the same time, rates at which cover in this area moves have been measured since 1996, the sites involved being located on a slope of variable morphodynamics (Fig. 2). The work has involved a line of pegs separated by 1 m over total distances of between 10 and 15 metres. The mean sizes of the shifts reported over the period 1996-2003 were of between 0.0 and 5.3 cm/year in the cases of the different pegs (Table 1). The lines at sites 11, 12, 13, 14 and 16 did not change position. At sites 1, 2 and 4, individual pegs moved by up to 0.9 cm/year on average. In contrast, there were other sites at which lines shifted along their entire lengths. These were located on parts of the slope ascribed to modelling by solifluction or soil-creep on the basis of their surface morphology.

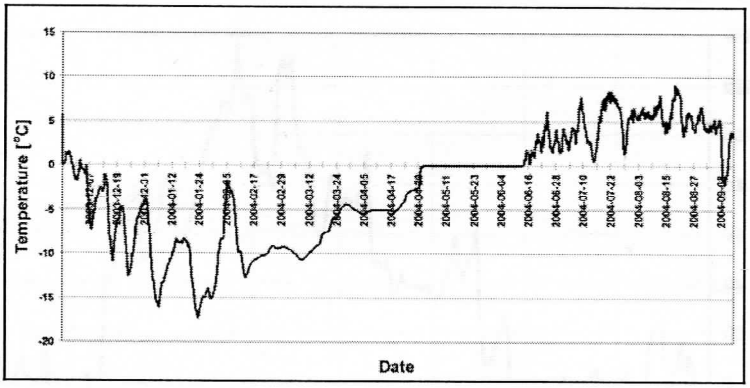


Fig. 6. Course taken by ground temperatures in the Kozia Valley in the 2003/2004 season.

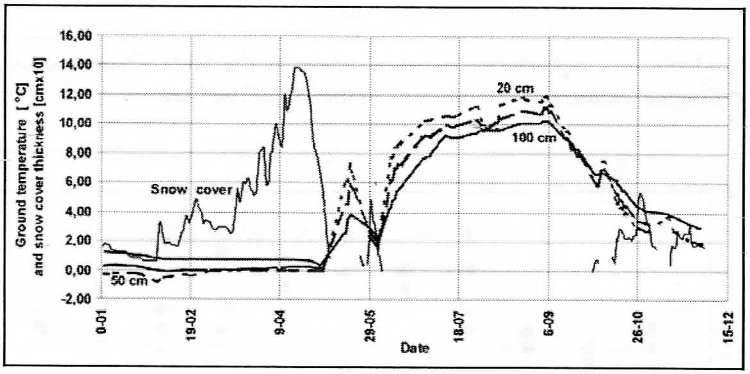


Fig. 7. Course taken by ground temperatures at Hala Gasienicowa, as exemplified by 1997.

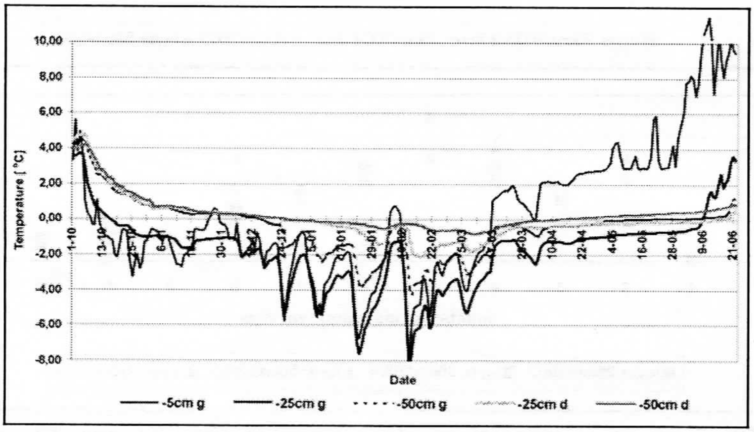


Fig. 8. Course taken by ground temperatures at sites in the Œwiñska Goryczkowa Valley between October 2003 and June 2004.

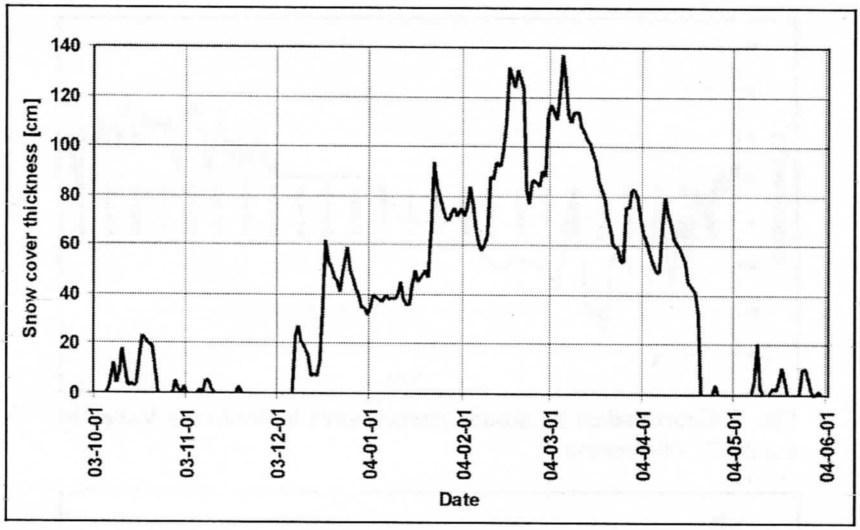
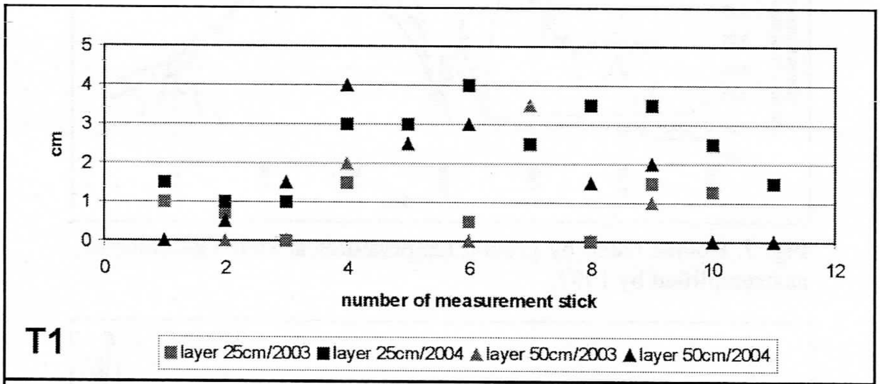


Fig. 9. Depth and persistence of snow cover at the Hala Gasienicowa IMH Meteorological Station (1520 m a.s.l.) in the 2003/2004 season.



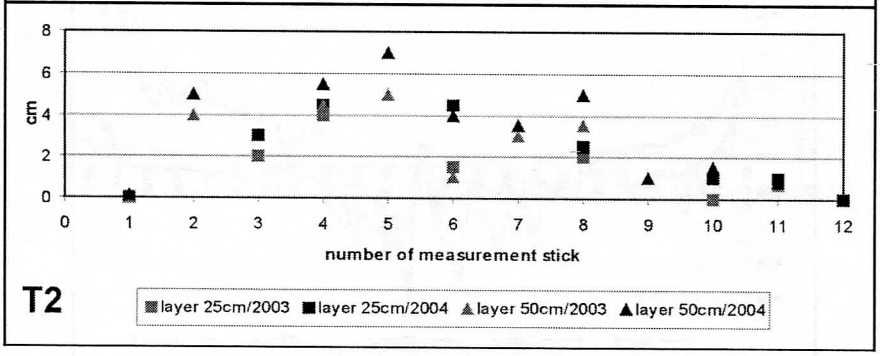


Fig. 10. Sizes of movements of slope cover at sites T1 and T2 in the Goryczkowa Valley in the period 2002-2004.

Thermal sites T1 and T2 were respectively at sites modelled by solifluction alone, or by solifluction plus creeping. Analysis of the data on the thermal properties of the ground over 3 consecutive years allowed for the identification - in spring - of a period lasting between several and some 20-25 days (depending on site) in which the surface layer is unfrozen, while the deeper layer remains frozen. Conditions suitable for solifluction are then present, offering confirmation of the mechanism for slope modelling determined geomorphologically. The actual time at which this period arose was found to vary, being in the second half of April 2002, and in the first half of May 2003.

Fig. 11. Snow patches at the beginning of June 2004, on the slope near site T1.

In 2002, a line of 0.5m wooden pegs and 0.25m nails was put in place on the slope on which the thermal sites were located. The rate of movement at the particular sites is seen to differ (Fig. 11), being almost twice as great lower down. At the upper site it is mainly the upper layer that moves, pointing to gelifluction as the additional causal agent. In contrast, both layers are being shifted at the lower site and the rate of movement is greater than that measured at site T1. At the lower site (T2), the period of intensive ground-temperature fluctuations above and below zero is somewhat time-shifted as compared with the upper site. Furthermore, what is probably a thicker snow cover ensures a longer and greater alimentation of slope cover by meltwater. Water from the melting snow has a major impact in shifting slope cover, since, while c. 75% of the water generated in this way soaks in, the corresponding figure for precipitation feeding groundwater is only 8% (Kosiba, 1949, *vide* Woœ, 1999). Site T2 is located on a slope from which snow disappears around the end of May (Raczkowska, Kozlowska, 1999), though patches even remain into June. In turn, at the time when thermal conditions in the ground favour the movement of cover, the upper site T1 was lacking a snow cover. To determine whether this process is the only one to generate a shift in cover, it would be necessary to make control measurements of the sizes of movements more than once a year, with the role of summer precipitation also being determined.

SUMMARY

The results presented for the aforementioned analysis of measured ground temperatures and rates of movement of cover appear to confirm the modelling of mature slopes in the Tatra Mountains by the processes already indicated on the basis of slope morphology. While ground temperature is an important factor underpinning shifts in cover, the underlying mechanism may only be fully explained if more detailed account is taken of the role of water - be this from precipitation or melting - as well as certain physical features of the cover.

While the courses obtained for ground temperatures at Hala Gasienicowa and on the slopes of the Œwiñska Goryczkowa Valley are similar, that obtained for the Kozia Valley is markedly different.

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