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GROUND THERMAL REGIME IN THE VICINITY OF RELICT ROCK GLACIERS (CANTABRIAN MOUTAINS, NW SPAIN)

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Abstract – Ground temperature data obtained from 2002 to 2007 in sites near relict rock glaciers in the Cantabrian Mountains, at altitudes between 1500 and 2300 meters is analysed. Snow cover lasted between 3 and 9 months and had a strong influence on the thermal regime. When snow was present, the soil was normally frozen in the first 5 to 10 cm, but daily freeze-thaw cycles were rare. In well developed soils located at sunny faces frost penetration rarely reached more than 10 cm. On the contrary in shady and windy faces with scarce snow cover, frost penetration reached, at least, 40 cm. In persistent snow patches the temperature was stable at 0 ºC, even in relict rock glaciers, where subnival winter air fluxes appear to have been very rare.

Key words: Thermal regimes, periglacial processes, relict rock glaciers, Cantabrian Mountains.

Resumo – REGIME TÉRMICO DO SOLO PRÓXIMO DE GLACIARES ROCHOSOS FÓSSEIS NA CORDILHEIRA CANTÁBRICA (NW DE ESPANHA). Apresentam-se dados da temperatura do solo obtidos entre 2002 e 2007 na Cordilheira Cantábrica entre 1500 e 2300 metros de altitude. A cobertura nival, presente entre 3 e 9 meses, influencia em grande medida o regime térmico. A sua presença favorece a congelação do solo à superfície mas reduz a frequência dos ciclos de gelo-degelo. Os solos húmidos e bem desenvolvidos em vertentes soalheiras limitam a congelação, que apenas alcança alguns centímetros. Em áreas com pouca insolação e cobertura nival pouco importante, a frente de congelação ultrapassa, pelo menos, os 40 cm. Nos sectores com uma cobertura nival muito prolongada e persistente, a temperatura mantém-se constante em torno dos 0ºC, inclusivamente em acumulações de blocos, onde raramente foram observados fluxos internos de ar.

Palavras-chave: Regime térmico do solo, dinâmica periglaciária, glaciares rochosos fósseis, Cordilheira Cantábrica.

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Résumé – Regime thermique du sol dans des glaciers rocheux fossiles de la Cordillere Cantabrique (Nord-ouest de l'Espagne). On présente des enregistrements de température du sol, réalisés entre 1500 et 2300 m d'altitude. La couverture nivale, qui dure de 3 à 9 mois, influence fortement le régime thermique. Sa présence favorise le gel superficiel du sol mais réduit le nombre des cycles gel/dégel. Dans les sols d'adret, humides et bien développés, la congélation ne pénètre que sur quelques centimètres d'épaisseur. Là où l'insolation et la couverture nivale sont faibles, le front du gel atteint au moins 40 cm. Là où la couverture nivale est persistante, la température se maintient vers 0ºC, même dans les accumulations de blocs, où l'on a rarement détecté une circulation de l'air.

Mots Clés: Régime thermique du sol, dynamique périglaciaire, glaciers rocheux fossiles, Cordillère Cantabrique.

I. INTRODUCTION

In a geomorphological context, ground temperature is more relevant than that of air. The relation between both is not linear (Thorn *et al*., 1999), and is mainly controlled by radiation, snow cover, relief, type of substrate, moisture and vegetation. For that reason, under the same conditions of temperature, a mosaic with great variety of ground temperatures may occur. Beneath coarse blocky materials, as rock glaciers, the thermal dynamics is more complex (Humlum, 1997; Harris and Pedersen, 1998).

In the Cantabrian Mountains there is a limited network of meteorological observatories and they are located at valleys floors. Therefore, air temperatures are poorly characterized. Regarding ground temperatures, the research by Castañón and Frochoso (1998) and González-Trueba (2006) on the high altitudes (2100-2500 m) of Picos de Europa is the only reference allowing for a first approximation to the ground thermal regime in the area.

In this paper we analyse the ground temperature regimes of ten sites at altitudes between 1500 and 2300 meters. The objective is to improve the knowledge on the present-day thermal regime in the Cantabrian chain, emphasising on the differences induced by the substrate, aspect, snow-cover and other geographical factors.

II. STUDY AREA AND METHODS

The present paper is framed within a wider study on the environmental characteristics of relict rock glaciers of the Cantabrian Mountains (fig. 1). Nowadays, active marginal periglacial features are present above 1900 meters, like terracettes, ploughing boulders and gelifluction lobes, whereas other forms are relict. The large interannual variability of the thermal regime implies analysing several years in order to draw conclusions about ground temperatures.

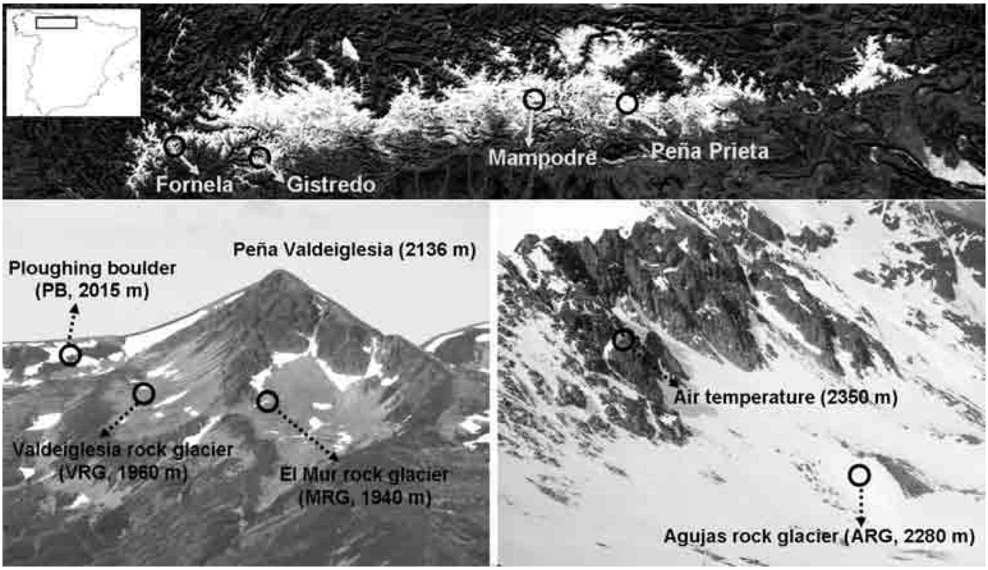

Fig. 1 – Location of the study area. Gistredo massif on the left corner and Peña Prieta massif on the right (TOP: NASA/GSFC, MODIS rapid response image).

Fig. 1 – Localização da área em estudo: Maciço de Gistredo no canto esquerdo e maciço de Peña Prieta no canto direito (TOP: NASA/GSFC, MODIS rapid response image).

At each site we have installed a small plastic box with one, two or three data-loggers (HOBO® H8 ProTemp/RH and H8 Temp, by Onset), storing hourly data at different depths in the ground. In many of the places 3 sensors have been set up, normally at the surface (-1 or -2 cm), -10 or -15 cm, and at -20 or -40 cm, depending on the ground characteristics. Data have been collected between 2003 and 2007, but not simultaneously at all sites during the whole period.

In this paper we consider a temperature oscillation below and above 0ºC as a freeze-thaw cycle, although water freezing can happen in a diverse temperature range (Hall, 2007) or even take several weeks to occur, even with negative temperatures (Sutinen *et al.*, 2008). On the other hand, water is not always present, since, for instance, in relict rock glaciers even with negative temperatures, the openwork structure mitigates water availability.

III. RESULTS

1. Summer temperatures

During the summer no ground freezing occurred, except, occasionally, in September, when shallow and short cycles were recorded. The sites where snow remained until July or even August (especially at Agujas Rock Glacier) are exempt from this regime, because the ground remained frozen until the snow melted.

Daily summer maximum temperature oscillations are of the order of 13 to 25 ºC at -2 cm, as opposed to 2 to 5 ºC at -20 cm and 1 to 2 ºC at -40 cm, depending fundamentally on the type of substrate. Fine soils have a large insulation effect, so thermal oscillations are lower than in boulderly terrains, like relict rock glaciers (fig. 2).

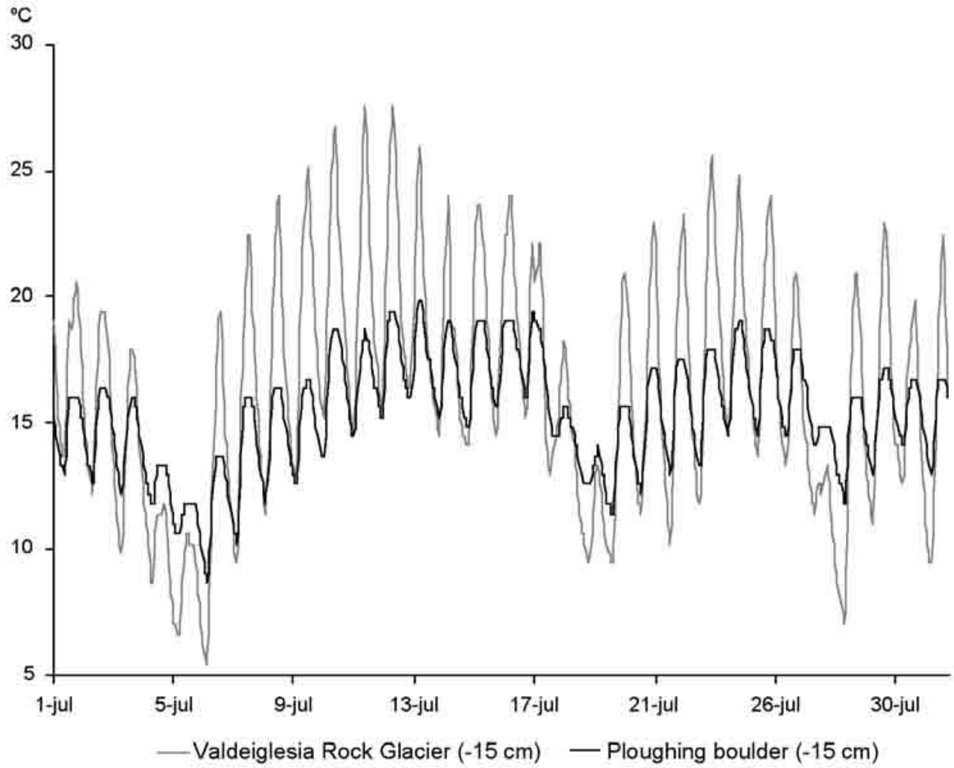

Fig. 2 – Comparison of ground temperatures during the summer at a site with fine-grained soil (Ploughing Boulder) and at a relict rock glacier site with openwork structure (Valdeiglesia Rock Glacier).

Fig. 2 – Comparação das temperaturas estivais do solo num local com solo fino (bloco lavrador) e num local com estrutura em open-work (glaciar rochoso de Valdeiglesia).

2. Autumn temperatures and freeze-thaw cycles

The first annual snow in the study area falls usually in October, but below 2000 m the snow mantle melts quickly and there, it only settles in November. In October the negative air temperatures result in ground freezing at surface levels.

In places showing a more stable snow cover, like Nevadín Snow Patch and Agujas Rock glacier, it is in autumn, before the permanent snow settlement, that freeze-thaw cycles occur. However, in other sites, cycles are more frequent in winter and in spring due to the more discontinuous snow cover. In any case, diurnal freeze-thaw cycles were very unusual in most sites in autumn and restricted to the first 5 or 10 cm of the ground. In the sunny faces, especially in the years with scarce snow and, above all, in the ploughing boulder site, there was a higher frequency of shallow frost cycles that did not reach deeper than 10cm. The differences in years with a high quantity of snow (2003-04 and 2004-05) stand out in Nevadín Snow Patch as opposite of other ones where snow is quite limited (2006-07) (table I).

Table I – Freeze-thaw cycles at the study sites.
Quadro I – Ciclos gelo-degelo nos locais de estudo.

		Altitude (m)	**Depth (cm)**	**2003-04**	**2004-05**	**2005-06**	**2006-07**
Nevadín Snow Patch		2040	-2	3	–	–	18
			-8	10	4	–	–
			-15	13	2	–	–
Valdeiglesia Sunny Face		2035	-2	–	18	–	–
			-15	19	–	–	–
			-20	–	2	–	–
Nevadín Sunny Face		2035	-2	41	–	8	–
			-5	11	0	–	–
			-10	13	–	3	–
			-20	–	–	3	–
Ploughing Boulder		2015	-2	36	37	–	–
			-15	6	10	5	17
			-40	2	–	–	–
Valdeiglesia Rock Glacier	Ridge	1960	-15	–	–	18	–
	Furrow		-15	–	–	12	–
El Mur Rock Glacier	Furrow	1940	-20	–	–	–	27
			-70	–	–	–	26
Poza del Puerto Sunny Face		1750	-5	–	–	–	3
			-30	–	–	–	0
Agujas Rock Glacier	Furrow	2280	-15	–	–	–	7
Recacabiello Rock Glacier	Ridge	1495	-15	–	–	–	27
Ferreira Rock Glacier	Ridge	1575	-15	–	–	–	33

The period of autumnal cooling influences clearly the temperatures of the rest of the winter, especially in the sectors where the snow cover is more stable and long-lasting, as Overduin and Kane (2006) have shown for Alaska. This influence is visible in Nevadín Snow Patch, where in 2003-04 temperatures were stable around 0ºC throughout the winter, whereas in 2006-07, due to the delay on snow cover settlement, temperatures well below 0 ºC were recorded, keeping the temperature at -2ºC after the establishment of the snow cover and reaching the frost penetration of the ground deeper depth. Generally, when there is an early snow cover (at the end of October for example) lasting well into the spring, it can even cause no episode of frost, not even at the ground surface, especially if the ground is wet enough, although air temperature can reach -10ºC or -15ºC (Nevadín Sunny Face, 2004-05) (fig. 3).

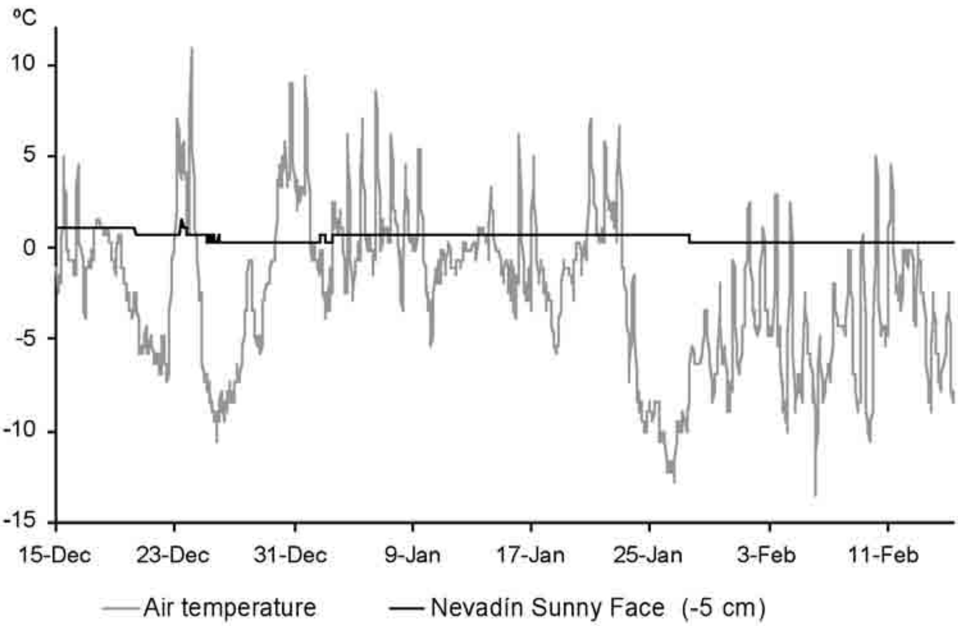

Fig. 3 – Comparison between air and ground temperatures in the Nevadín area during a period with snow cover.
Fig. 3 – Comparação entre temperaturas do ar e do solo em Nevadín num período com solo coberto de neve.

3. Temperatures during the period with snow cover

The study area is characterized by a snow cover with high temporal and spatial thickness variation as in other Iberian mountains (Vieira *et al*., 2003), varying between a 3 and 9 months in the study sites. Once snow establishes, ground temperature falls and stabilizes after a few days around 0ºC, producing the so-called zero curtain effect (Outcalt *et al*., 1990). The cause of this phenomenon lies in the latent heat emitted as a result of the energy leak when the water of the ground is being frozen. This isothermal curtain is typical at end of autumn and spring, but it can appear in winter and, occasionally, extend during almost the whole winter period, whenever there is enough humidity. Harris and Corte (1992) have shown that this effect is longer in wet fine-grained soils, as we have checked in different locations as Nevadín Snow Patch, Nevadín Sunny Face, Ploughing Boulder or Valdeiglesia Sunny Face.

A long freezing curtain effect is common in the Cantabrian relict rock glaciers, where the presence of water is unusual. Hanson and Hoelzle (2004) attribute this type of process to the deep melt inside an active rock glacier, although we have not checked the possible ice formation in spring in the relict rock glaciers analysed. Other authors in openwork structures of similar environments observe a similar phenomenon (Sawada *et al*., 2003; Zacharda *et al*., 2007). At all the relict rock glaciers large periods of zero curtain effect lasting until snow melt were registered.

Table II – Maximum and minimum rates of frost penetration in fine grained-soils at the study sites. NSF: Nevadín Sunny Face. NSP: Nevadín Snow Patch. PSF: Poza del Puerto Sunny Face. PB: Ploughing Boulder. VSF: Valdeiglesia Sunny Face.

Quadro II – Valores máximos e mínimos das taxas de penetração da congelação em solos finos.

	NSF	**NSP**	**PSF**	**PB**	**VSF**
Maximum (mm/h)	20	3,4	0,4	9	19,8
Minimum (mm/h)	0,9	0,1	<0,1	0,2	<0,5

The rates of frost penetration are very variable in the same locations in a monthly and yearly basis (table II) as Overduin and Kane (2006) showed for Alaska. Air temperature, ground structure and melt of the snow cover are some of the causes that induce this variability. Nevertheless, ground moisture is perhaps the most important, since with a high moisture content, more latent heat will be released and ground freezing will be slower (Taras *et al*., 2002). In this case, the type of substrate shows a great influence. Therefore, sensors installed in sunny faces covered by shrubs (Poza del Puerto Sunny Face) or in herbaceous vegetation sites with thick soil (Nevadín Sunny Face) show significantly slower frost penetration rates. This can be explained by the organic soil without pebbles, larger solar radiation and more frequent snow melting resulting on a continuous feeding of moisture to the ground. We have also noticed that frost penetration is faster if the ground has been frozen previously during the winter, even with temperatures that are not very low, such as in the end of spring. In this way, as recorded in several sites, rates are usually faster in consecutive freezing periods.

The period of ground freezing is very variable and depends mainly on the snow cover, and also on the possible delay of the frost penetration, and therefore the differences at depth can be very significant (table I). At similar altitudes we have observed large differences in ground freezing days. For instance, in 2003-04, 225 days were recorded at Nevadín Snow Patch and a mere 88 days at nearby Nevadín Sunny Face site. There are also relevant differences in the depth of frost penetration, which can be just below the surface (5-10cm) or exceed, at least, 40cm (Ploughing boulder, fig. 4).

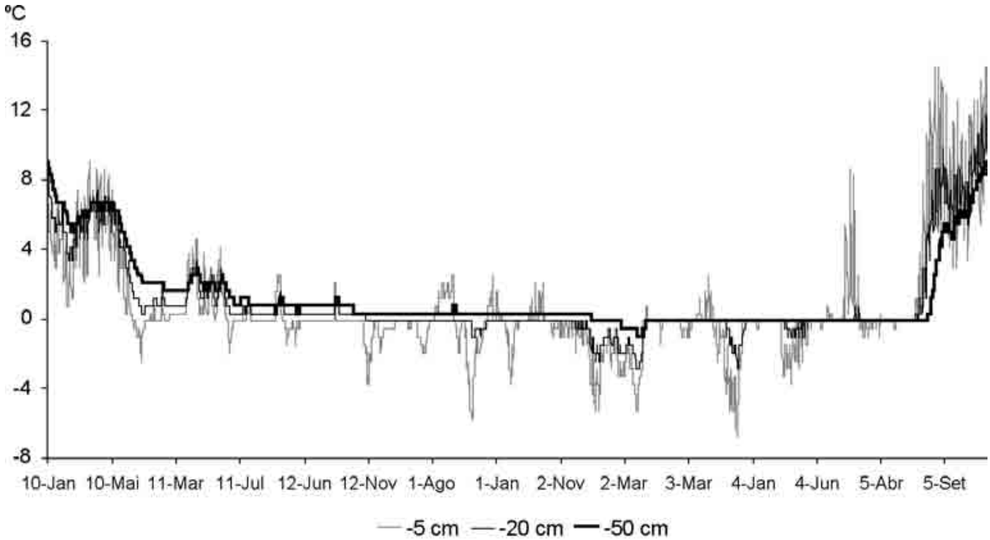

Fig. 4 – Ground temperature regime at the Ploughing Boulder site from October 2003 to May 2004.
Fig. 4 – Regime térmico no sítio do bloco lavrador entre Outubro de 2003 e Maio de 2004.

The period of ground thaw developed quickly and coincides with snow melt. Normally, the process lasts for a few hours until thawing affects all depths, except for isolated cases (i.e. at Ploughing Boulder in 2004, it took 3 days for thawing to reach -40cm). Furthermore, in a day of thaw it is usual to observe a ground temperature increase up to 6 or even 10ºC. Only when thawing occurred during winter and in shady slopes, ground remained frozen at depth for some days, whereas it thawed superficially (Ploughing Boulder, between January and April 2004; March 2005; January and February 2007; Valdeiglesia Sunny Face, March 2005).

IV. CONCLUSIONS

At the study sites in the Cantabrian Mountains freezing of the ground lasts longer and is deeper in north faces with scarce snow cover and where, because of the wind effect, the permanent snow cover is delayed until the beginning of the winter. These types of location are related to convex windy sites with northerly aspect and also to summits above 2000m, with gentle slopes. In these places frost penetration can reach deeper and gelifluction forms with reduced or subactual activity, as the gelifluction lobes and the ploughing boulders, are present. Therefore, it seems that the presence of these forms in N-NW slopes is due to the colder ground conditions with deeper frost than in sunny slopes (where the high solar radiation limits frost penetration) and than in shady slopes, which accumulate high amounts of snow (with an insulating effect).

The rates of frost penetration are very variable, even for the same location, with values between 0.1 and 2 mm/hour. The maximum frost penetration is difficult to estimate from the data. At the Ploughing Boulder site, freezing reached 40cm in 19 February 2004 and 3 January 2005. We estimate a depth of ground freezing between 50 and 100 cm at this place. It is likely that these values are very variable from year to year, having an influence on the sporadic mobility of the ploughing boulders. A deeper frost can be also related to the presence of the boulder which influences the thermal conductivity (Berthling *et al*., 2001).

Diurnal freeze-thaw cycles are more frequent in sunny faces with 30 to 40 cycles per year. However, this fact does not imply higher rates of geomorphological activity than in northern slopes, since these cycles are very shallow (2 to 10 cm depth) and only generate small forms related to needle ice. Relict rock glacier sites show a larger number of frost cycles but the boulders and absence of matrix prevent the movement. Unlike in active rock glaciers, we have rarely observed signs of internal air flow. Snow cover maintains ground temperature stable until snow melt, even in areas with big boulders and when the snow patches are already scarce. The small diurnal air temperature range of the high areas and the snow cover explain the small number of freeze-that cycles, which are probably more frequent at the valley floors, where strong temperature inversions occur.

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