Ground and Near-Rock Surface Air Thermal Regimes in the High Mountain of the Picos De Europa (Cantabrian Mountains, NW Spain)

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ABSTRACT: Even when the influence of climate on the geomorphological dynamics of mountain areas is well known, the ground and near-rock surface air thermal regimes of the highest altitude Cantabrian massifs still being poorly understood. This study, based on the examination of the thermal data obtained through the use of air and soil temperature dataloggers, aims to characterize the thermal regime of one of the most representative high mountain massifs of the Cantabrian Mountains: the Western Massif of the Picos de Europa. Results show the severe climatic conditions that prevail in the highest areas, where the snow cover lasts for 8 months on average, exerting an important insulating role of the soil. Thus, except on the uncovered rocky walls, the number of freeze-thaw cycles per year is low (0–16), with these cycles having a short duration and a low thermal amplitude. Significantly differences on annual thermal regimes have been confirmed; with two main phases (continued thaw phase and isothermal phase) and two minor transition phases at the ground, and only two main phases in near-rock surfaces (continued thaw phase and phase with a high number of FTCs).

KEYWORDS: Cantabrian Mountains, climate, high mountain, soil, periglacial, thermal regime

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Introduction

In periglacial environments, ground temperatures are a key driver of geomorphological processes. Considering the extent of the changes that currently affect the high mountain cryosphere (as well as the associated impacts and risks), derived from climate change (Hock et al., 2019), knowing and understanding the thermal regime of these environments is of the greatest scientific interest (Oliveira et al., 2018). Currently, in mountain regions of mid-latitudes (as is the case of the mountains of the Iberian Peninsula), periglacial processes are limited to the highest altitudinal belts, above 2,000 to 2,500 m (Oliva, Gómez-Ortiz, Salvador-Franch, et al., 2016). In these environments, the annual evolution of the snow cover has important implications for the ground thermal regime and, consequently, for the associated periglacial morphodynamics. In winter, snow cover plays an important role as thermal insulation of the soil (Frauenfeld et al., 2007; Ishikawa, 2003; Serrano et al., 2020; Serrano et al., 2019b; Zhang, 2005). On the other hand, the seasonal melting of snow generates an intense geomorphological dynamic linked to the abundance of water, which triggers fast and slow slope movements. The thermal regime also determines the permanent or seasonal existence of ice on the ground and rock outcrops, and influences the associated geomorphological processes.

In the main high mountain sectors of the Iberian Peninsula, research on the soil thermal regime has mainly focused on the mountain regions where the highest altitudes are reached, such as the Spanish Pyrenees (e.g. Lugon et al., 2004; Serrano et al., 2020; Serrano et al., 2019b) and Sierra Nevada (e.g. Gómez-Ortiz et al., 2001; Oliva, Serrano et al., 2016). Other Iberian mountainous environments, such as the Sierra de Guadarrama in the Iberian Central Range (e.g. Andrés & Palacios Estremera, 2010; Muñoz-Jiménez et al., 2007) and the Cantabrian Mountains, have also been studied in this sense. In the Cantabrian Mountains, in the last decades significant progress has been made in the knowledge of the active periglacial dynamics of the highest areas (e.g. Castañón & Frochoso, 1994, 1998; Gallinar-Cañedo et al., 2022a; González-Gutiérrez, 2002; González-Trueba, 2007; Pellitero, 2012; Ruiz-Fernández et al., 2014; Sanjosé-Blasco et al., 2020; Santos-González, 2010; Serrano & González-Trueba, 2004; Serrano et al., 2019a). Likewise, studies have multiplied on the climatic conditions that favor periglacial morphodynamics: changes in the soil thermal pattern throughout the year, the snow cover duration (SCD), the number of days and/or freeze-thaw cycles (FTC), and the influence of soil granulometry, air temperature, wind and solar radiation. The studies by Castañón and Frochoso (1998), González-Trueba (2007), Santos-González et al. (2009), González-Trueba and Serrano (2010), Pellitero (2012), Pisabarro et al. (2015, 2017), Ruiz-Fernández et al. (2014, 2017), Gallinar-Cañedo et al. (2022b) and Melón-Nava et al. (2022) have made the main contributions.

The study of the soil thermal regimes has prompted a debate about the existence of marginal permafrost in some high-altitude sectors of the Cantabrian Mountains (Melón-Nava et al., 2022; Ruiz-Fernández et al., 2017). Firstly, the results of some studies focused on the Picos de Europa area contributed to the debate: Several research showed the existence of buried ice patches covered by debris, with typical landforms of environments with permafrost, or with seasonally frozen soils such as small frost mounds (Castañón & Frochoso, 1998; González-Trueba, 2007; Ruiz-Fernández et al., 2017; Serrano et al., 2011), and ice caves (Gómez-Lende & Serrano, 2021). However, it is necessary to continue deepening the knowledge of the climatic conditions of the high Cantabrian Mountains, due to its implications in the periglacial morphodynamics and, in this sense, the important role played by snow must also be considered (Gallinar-Cañedo et al., 2022b; Pisabarro, 2020).

Both because of the global and local implications, we need to continue deepening the knowledge of the thermal regime in the main mountain area in the northwestern part of the Iberian Peninsula. This study focuses on the study of the ground and near-rock surface air thermal regimes of one of the most representative high mountain massifs of the Cantabrian Mountains: the Western Massif of the Picos de Europa. Its objectives are: (1) to obtain the main thermal parameters; (2) determine the annual SCD; (3) quantify the number of FTCs; (4) establish the annual ground and near-rock surface air thermal regimes.

Study Area

The Western Massif of the Picos de Europa (also called "El Cornión") is the second highest mountain massif of the three that make up the Picos de Europa mountain (Peña Santa de Castilla, 2,596 m; Figure 1). Like the Central and Eastern massifs, the Cornión is essentially composed of Carboniferous limestones, which are organized in an approximately E-W oriented imbricate thrust faults system (Farias, 1982; Marquínez, 1978). Calcareous rocks have been profoundly transformed by karstification (Ballesteros et al., 2011; Miotke, 1968; Ruiz-Fernández, García-Hernández, & Fernández-Fernández, 2019; Ruiz-Fernández & Poblete Piedrabuena, 2012; Ruiz-Fernández & Serrano, 2011; Santos & Marquínez, 2005), Quaternary glaciers (Moreno et al., 2010; Ruíz-Fernández & García-Hernández, 2018) and fluviotorrential activity (Ruiz Fernández & Poblete Piedrabuena, 2011), and modified by relict and current periglacial morphodynamics (Ruiz-Fernández, García-Hernández, & Fernández, 2019; Ruiz-Fernández et al., 2017).

From the climatic point of view, the high lands of the massif are defined by very abundant precipitation (over 2,000 mm/year), as well as by low temperatures. Muñoz-Jiménez (1982) places the annual 0°C isotherm in the area at 2,400 to 2,500 m, and points out that in the Picos de Europa there are about 85 annual days of snowfall (70% of the total precipitation). According to the Köppen classification, the high sectors of the Picos de Europa have a Dfsc climate type (Muñoz-Jiménez, 1982). In the Western Massif of the Picos de Europa, as in other mountainous areas of the Cantabrian Mountains, human presence has been traditionally connected with livestock farming, with a growing tourist activity linked to leisure and mountain sports (García-Hernández et al., 2022).

Materials and Method

Characteristics and location of temperature dataloggers

Between 2005 and 2011, Hanna instruments HI141AH (air temperature datalogger) and HI141BH (soil temperature datalogger) with an accuracy of ±0.4°C, were installed. The temperature dataloggers were placed in different locations of the Western Massif of the Picos de Europa, with contrasting topoclimatic and geomorphological conditions (Figures 1 and 2; Table 1). The soil temperature dataloggers were placed inside different surface deposits at 10 cm depth, except in one case, in which data was taken simultaneously at 10 and 50 cm depth (Table 1). On the other hand, the air temperature dataloggers were located on rock surfaces at different heights (Figure 2; Table 1). All of them were programed to take measurements at 2-hr intervals and for successive 1-year periods (4,380 data per sensor each year, 4,392 in 2008, which was a leap year).

Data processing

The air and soil temperature data have been treated using basic descriptive statistics techniques, in order to obtain the following values: average annual temperatures (AT), absolute maximum temperatures (AMax), and absolute minimum temperatures (AMin). The different temperature regimes that occur throughout the year have been identified, and both the annual SCD and the number of FTCs (one of the most determining factors in current periglacial morphodynamics) have been calculated. To calculate the number of FTCs, it has been considered that a cycle has occurred when the temperature rises above 0°C, falls below 0°C and returns to be above 0°C again (since it is frequent that the temperature drops to 0°C but does not exceed 0°C, and vice versa). However, we must consider that, as Hall (2004, 2007) points out, the water freezing temperature can vary significantly.

Method applicability

This methodology has been widely used in the last two decades, both in mountain areas and in polar zones, in order to establish the relationship between periglacial landforms and processes, and temperature regimes (e.g. Andrés & Palacios Estremera, 2010; Andrés et al., 2010; Castañón & Frochoso, 1998; González-Trueba & Serrano, 2010; Matsuoka, 2006; Melón-Nava et al., 2022; Salvador-Franch et al., 2010; Santos-González et al., 2009; Serrano et al., 2020; Serrano et al., 2019a); to determine the existence or non-existence of permafrost, and the evolution of associated forms (e.g. Gómez-Ortiz et al., 2001; Hoelzle et al., 1999; Ishikawa, 2003; Kneisel, 2010; Luetschg et al., 2004; Lugon et al., 2004; Melón-Nava et al., 2022; Serrano et al., 2001, 2010), and even to examine the effects of soil temperature on the composition and distribution of vegetation (e.g. Muñoz-Jiménez et al., 2007). Some of the data related to the temperature regime of the Forcadona buried ice patch (the remnant of a Little Ice Age glacier) and its

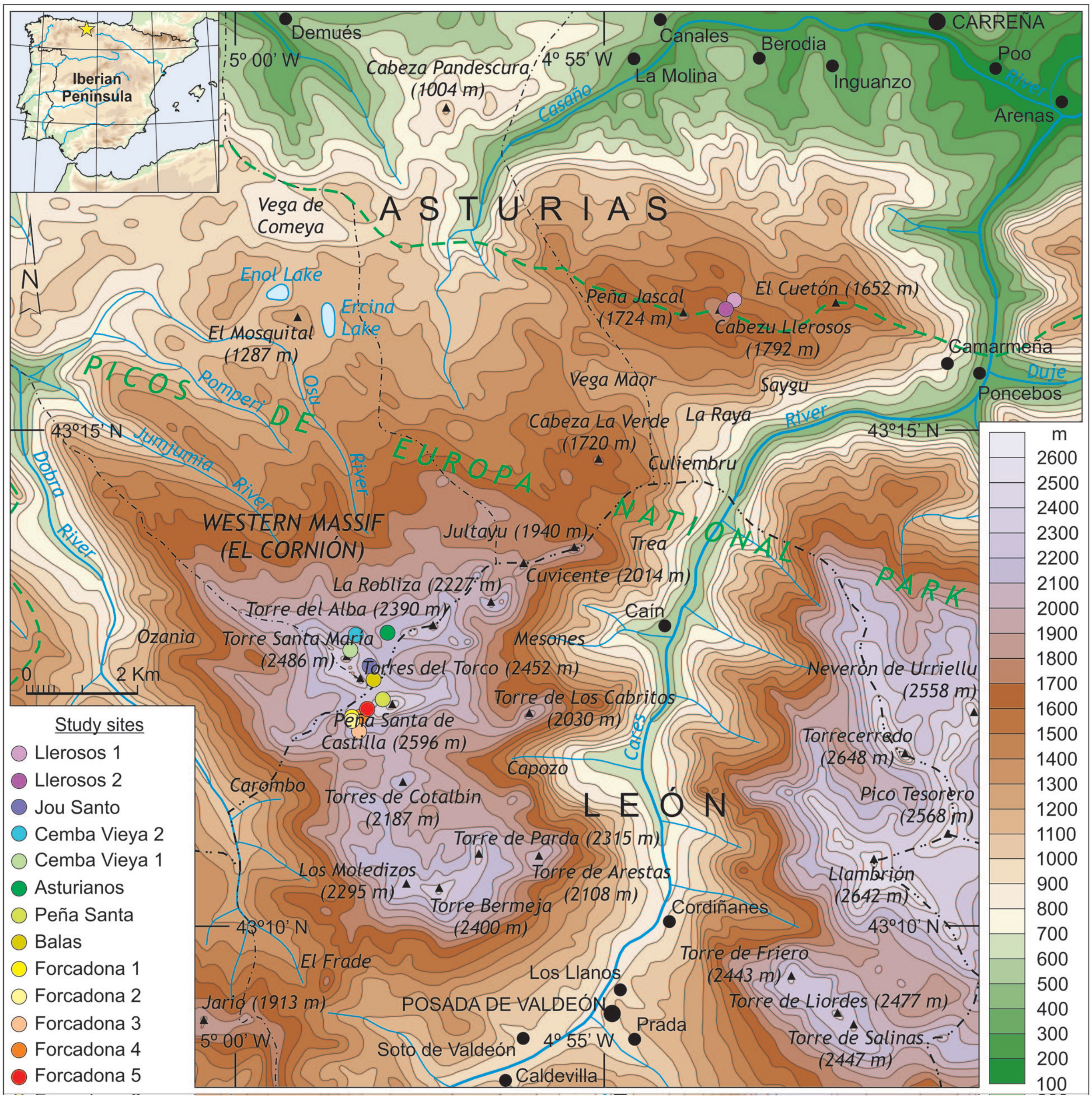

Figure 1. Location map of the study area within the Iberian Peninsula, and the specific sites mentioned in the text.

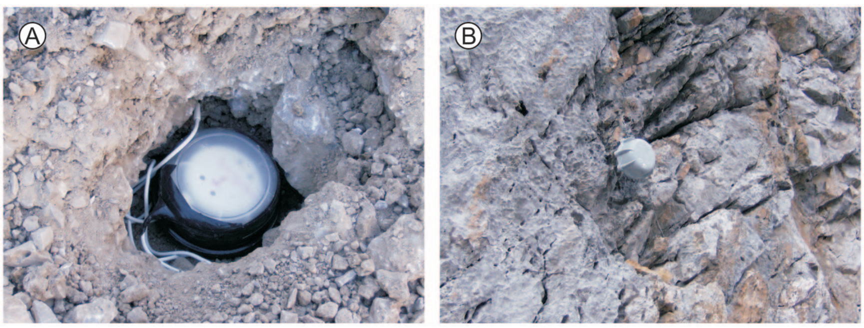

Figure 2. (A) Soil temperature datalogger placed in the debris that covers the Forcadona buried ice patch (04/11/2007). (B) Air temperature datalogger placed on a rocky wall in the Fuente las Balas area (04/11/2007).

Table 1. Thermal Data in Different Locations of the Western Massif of the Picos de Europa Between 2005 and 2011.

SITE	ALTITUDE (m)	ASPECT	GEOMORPHOLOGICAL CONTEXT	SLOPE ANGLE (°)	SOIL CHARACTERISTICS	MONITORING PERIOD	TYPE	DEPTH (cm) / HEIGHT (m)	TOTAL MEASUREMENTS
Llerosos1	1,680	East	Talus cone	24	Incipient edaphic processes	06/11/2005 to 21/10/2006	Soil temp.	–10	4,193
Llerosos2	1,780	East	Debris in culminating area	6	Incipient edaphic processes	06/11/2005 to 21/10/2006	Soil temp.	–10	4,193
Jou Santo	2,020	South	Debris cover	18	Absence of edaphic processes	16/10/2005 to 16/10/2006	Soil temp.	–10	4,380
Cemba Vieya1	2,190	North	Lateglacial moraine	21	Absence of edaphic processes	16/10/2005 to 16/10/2006	Soil temp.	–10	4,380
Cemba Vieya2	2,250	North	LIA moraine	23	Absence of edaphic processes	16/10/2005 to 16/10/2006	Soil temp.	–10	4,380
Asturianos	2,120	South	Till on glacial threshold	28	Absence of edaphic processes	22/10/2006 to 19/07/2007	Soil temp.	–10	3,238
Peña Santa	2,360	North	Debris cover	32	Absence of edaphic processes	22/10/2006 to 04/04/2008	Soil temp.	–10	6,360
Balas	2,131	Northwest	Rocky wall	90	----------	04/11/2007 to 24/10/2009	Rock-air interface temp.	+4 / +10	8,626
Forcadona1	2,227	North	Buried ice patch	7	Absence of edaphic processes	04/11/2006 to 04/11/2007	Soil temp.	–10	4,380
Forcadona2	2,227	North	Buried ice patch	7	Absence of edaphic processes	04/11/2006 to 04/11/2007	Soil temp.	–50	4,380
Forcadona3	2,235	Northwest	Talus cone	30	Absence of edaphic processes	04/11/2007 to 07/08/2011	Soil temp.	–10	16,386
Forcadona4	2,236	North	LIA moraine	23	Absence of edaphic processes	04/11/2007 to 24/10/2011	Soil temp.	–10	17,386
Forcadona5	2,215	Northwest	Rocky wall	90	----------	04/11/2007 to 24/10/2011	Rock-air interface temp.	+4 /+16	17,386

Table 2. Thermal Characterization of the Monitored Stations.

SITE	2005/2006					2006/2007				
	AT	AMAX	AMIN	FTC	SCD	AT	AMAX	AMIN	FTC	SCD
Llerosos1	5.5	16.4	0.2	0	6					
Llerosos2	6.8	22.2	0.3	0	6					
Jou Santo	3.7	24.8	−1.8	1	8					
Cemba Vieya1	4.5	25.6	0.1	0	7					
Cemba Vieya2	3.3	17.5	−0.5	3	8					
Asturianos						-----	21.5	−3.9	9	5 dis
Peña Santa						2.4	13.8	−0.7	8	7
Forcadona1						−0.04	2.9	−3.3	16	11
Forcadona2						0.07	1.2	−0.9	5	11

Note. The SCD is expressed in months. MT, AMax, and AMin are expressed in °C.

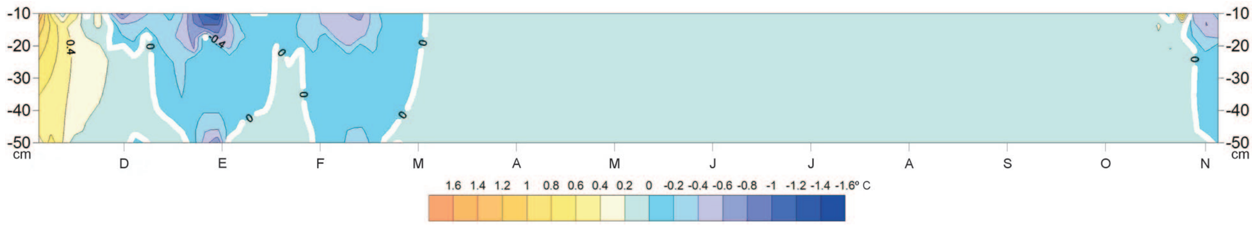

Figure 3. Thermal evolution of the layer of debris that covers the Forcadona buried ice patch between November 2006 and November 2007.

surroundings, have been dealt with in detail in Ruiz-Fernández et al. (2017), although with a very different purpose: to relate them to the geomorphological and topographic particularities of that sector. In this study, the data will be used to characterize the ground and near-rock thermal regimes in a much larger area (Western Massif of the Picos de Europa).

Results and Discussion

Thermal values: Average, maximum, and minimum temperatures

AT at 10 cm soil depth fluctuated between 6.8°C obtained in the vicinity of the top of Cabezu Llerosos Peak (1,680 m) in 2005 to 2006, and −0.04°C recorded in the debris that cover the Forcadona ice-patch (2,227 m) in 2006 to 2007 (Table 2). On the other hand, at a depth of 50 cm within these debris, the AT in the period 2006 to 2007 was 0.07°C. Although the data do not allow us to confirm the existence of a permafrost regime at the mentioned depth, they suggest that in deeper layers of the debris cover negative temperatures could be reached permanently (Ruiz-Fernández et al., 2017). In this sense, Figure 3 shows the thermal profile of the debris that covers the Forcadona ice patch at a depth of −10 and −50 cm, between November 2006 and November 2007. The profile clearly shows the impact exerted by the air temperature at shallower depths. This effect is progressively attenuated at depth, where the isothermy is increasingly marked until the temperature is situated at values about 0°C (between 0.2°C and 0°C). The existence of permafrost in the debris that covers the buried ice patches of the Picos de Europa has already been proposed in previous works (Castañón & Frochoso, 1998; González-Trueba, 2007). Recently, Melón-Nava et al. (2022) have pointed out the probable existence of permafrost in another sector of the High Cantabrian Mountains (The Hoyo Empedrado glacial cirque).

In the case of the rock-air interface, the AT fluctuated between 4.3°C at the Fuente de Balas station (2,170 m) in 2007 to 2008 season, and 2.3°C in the vicinity of La Forcadona (2,215 m) in the 2008 to 2009 (Table 3). The soil AMin were not excessively low, fluctuating between 0.3°C (summit of Cabezu Llerosos, 1,780 m, 2005–2006 season) and −6.3°C on the north face of Peña Santa de Castilla (2,360 m) in the 2007 to 2008 season. In the Central Massif of the Picos de Europa (Jou de los Cabrones, 2,050 m) at 10 cm soil depth, Castañón and Frochoso (1998) obtained an AMin of −6.8°C between September 1995 and September 1996. On the other hand, the dataloggers installed on the rocky walls (without the insulating effect of snowfall), recorded lower AMin: between −8.5 and −14.3°C in the Forcadona sector, in the 2008 to 2009 and 2009 to 2010 seasons, respectively (Tables 3 and 4).

Table 3. Thermal Characterization of the Monitored Stations (continuation).

SITE	2007/2008					2008/2009				
	AT	AMAX	AMIN	FTC	SCD	AT	AMAX	AMIN	FTC	SCD
Peña Santa	--------	3.3	−6.3	3	------					
Forcadona3	0.8	15.3	−5.5	6	8.5	0.4	0.5	0.3	0	12
Forcadona4	0.4	10.3	−5.1	12	8.5	0.09	0.1	−0.3	2	12
Balas	4.3	25.8	−10.6	119	------	3.2	23	−8.7	24	5
Forcadona5	3.5	26.6	−12	130	------	2.3	21.6	−8.5	21	6

Note. The SCD is expressed in months. MT, AMax and AMin are expressed in °C.

Table 4. Thermal Characterization of the Monitored Stations (continuation).

SITE	2009/2010					2010/2011				
	AT	AMAX	AMIN	FTC	SCD	AT	AMAX	AMIN	FTC	SCD
Forcadona3	0.7	9.6	−3.5	5	9.5	1.7	15.2	−2.4	2	8.5
Forcadona4	0.8	12.8	−3.5	3	9	2.4	13.8	−0.5	1	8
Forcadona5	3.0	23.4	−14.3	63	------	3.4	22.9	−12.4	37	-------

Note. The SCD is expressed in months. MT, AMax, and AMin are expressed in °C. .

During the study period, the AMax of the soil ranged from 25.6°C (reached in a glacial moraine located at 2,190 m in the Cemba Vieya area) in the 2005 to 2006 season, and 0.1°C in a debris slope in the Forcadona (2,235 m) in the 2008 to 2009 season. The AMax of the near-rock surface ranged between 26.6° and 22.9°C in the vicinity of the Forcadona, in the 2007–2008 and 2010 to 2011 seasons, respectively (Tables 3 and 4).

Snow cover duration

The snow cover exerts an important thermal control of the soil, isolating it from the air temperature. Thus, the soil experiences a marked isothermy with temperatures slightly above 0°C (zero-curtain effect). Soil isotherm can last for many months, until the snow cover disappears (Frauenfeld et al., 2007; González-Trueba & Serrano, 2010; Haeberli, 1973; Haeberli & Patzelt, 1982; Ishikawa, 2003; Santos-González et al., 2009; Serrano et al., 2020; Serrano et al., 2019b). Snow cover deeper than 40 cm leads to an isothermal soil temperature regime (Zhang, 2005). This isothermal situation of the soil makes it possible to accurately calculate the annual SCD. Based on the results of this study, we can affirm that the annual SCD is about 8 months on average, although with important interannual variations, as well as between some places and others according to the topoclimatic conditions (Tables 2–4). In fact, in the areas of higher altitude and sheltered from solar radiation, permanent snowfields (north face of Peña Santa de Castilla, area of Forcadona, and Cemba Vieya) or delayed melting snows remain, in which the snow lasts 11 and up to 12 months a year (Tables 2 and 3).

In the study by González-Trueba and Serrano (2010), focused on the Central Massif of the Picos de Europa, these authors reported similar data. Specifically, they point out that the snow cover lasts 8/9 months on average above 2,000 m, while around 1,500 m its duration drops to 6 months. On the other hand, in the Ubiñas Massif (central sector of the Asturian Massif), Gallinar-Cañedo et al. (2022b) argue that the SCD is between 6 and 8 months above 1800 m altitude. In other sectors of the Cantabrian Mountains, such as the Sierra de Gistredo and the Peña Prieta Massif, similar data have also been found for the SCD (Melón-Nava et al., 2022; Santos-González et al., 2009).

Freeze-thaw cycles

FTCs occur in surface deposits, although they are markedly attenuated due to the protective role of snow cover. During the study period, only between 0 and 16 cycles per year have been recorded (Tables 2–4). The low number of FTCs that occur in the soils of the high mountains of Picos de Europa has also been revealed by González-Trueba (2007). In contrast, Castañón and Frochoso (1998) detected a total of 52 FTCs in the Jou de los Cabrones (Central Massif of the Picos de Europa) at an altitude of 2,050 m and a depth of 10 cm in the ground. In the same way as Castañón and Frochoso (1998) and González-Trueba and Serrano (2010) in their studies of the Central Massif, the results of this study show a low thermal amplitude in the FTCs, which also tend to last only between one and a few days (short duration cycles). Although they have been rare, longer FTCs have also been recorded, with negative temperatures lasting weeks and even months (e.g. between December 25, 2005 and March 31, 2006, the temperature recorded by a datalogger placed at the bottom of the Jou Santo depression was below 0°C).

In other places in the Asturian Massif, such as the Gistredo Massif and Peña Prieta, Santos-González et al. (2009) detected a maximum of 12 to 27 FTCs per year between 2003 and 2007, at similar depths (10–15 cm) and at altitudes between 1940 and 2280 m. In other Iberian mountain ranges, such as the Sierra de Guadarrama, the number of days with soil temperature oscillations below and above 0°C fluctuated between 2 and 41 during the years 2002 to 2007, at the same depth as in the present study (10 cm) and at 2,212 m altitude (Andrés & Palacios Estremera, 2010).

In contrast, a higher number of FTCs is recorded in vertical or subvertical rock surfaces: Between 20 and 60 on average, and even more than 100 in the 2007 to 2008 season (specifically, 119 FTCs at the Fuente las Balas site and 130 at the Forcadona site, Table 3). This is a good indicator of the existence of frost shattering as a weathering agent in the monitored sectors.

Ground and near-rock surface air thermal regime and its implications in the periglacial morphodynamics

In the high mountain of the Western Massif of the Picos de Europa, two main thermal phases can be distinguished throughout the year: the continuous thaw phase and the isothermal phase, as well as two other short-term transition phases that take place between the previous ones (Figure 4).

Continuous thaw phase. It ranges from late spring or early summer to mid-autumn, and is characterized by strong thermal oscillations between day and night and the absence of FTCs.

Transition phase I. It is characterized by the beginning of the FTCs (first frosts of the season) and by the first snowfalls (appearance of the snow cover). Thus, after a few weeks the thermal stabilization of the soil occurs, while the regime of the rocky walls and ridges continues to be controlled by atmospheric dynamics.

Isothermal phase. It is the longest by far, as it extends from mid-autumn to late spring (or even into summer in the case of the highest sectors). It is defined by the presence of the snow cover, which isolates the soil from the atmospheric thermal influence (isothermy is reached). However, small imbalances caused by melting, wind action, rain-on-snow events or snow avalanches can occur. These alterations can reduce the depth of the snow cover, consequently generating FTCs in the soils. In general, these cycles are short, lasting one or a few days, although much longer cycles have also been recorded, with negative temperatures lasting weeks and even months.

Transition phase II. The isothermy in the soil is maintained until the disappearance of the snow cover. From then on, the ground thermal regime is once again controlled by atmospheric conditions, which implies a rapid increase in temperatures and the return to daily fluctuations.

As shown in the results, the soil thermal pattern is controlled by the regional atmospheric dynamics, but also by the appearance, depth and evolution of the snow cover. However, it should be considered that the aforementioned pattern undergoes numerous variations in the Western Massif itself, depending on topographic conditions, in addition to those caused by interannual climatic variability. On the other hand, the thermal regime of the sectors not covered by snow (ridges and rocky walls) essentially depends on the thermal evolution of the air, although the influence of topoclimatic factors must not be ignored.

This soil thermal pattern, made up of four main phases, has also been identified in other high mountain sectors of the Cantabrian Mountains (Central Massif of the Picos de Europa, Ubiñas Massif, Fuentes Carrionas) in several specific studies (Gallinar-Cañedo et al., 2022b; González-Trueba, 2007; González-Trueba & Serrano, 2010; Pellitero, 2012; Pisabarro et al., 2015, 2017; Ruiz-Fernández et al., 2014, 2017). In other Iberian mountain sectors, such as the Corral del Veleta area (Sierra Nevada), Salvador-Franch et al. (2010) described a similar soil thermal pattern. In the Pyrenees, Serrano et al. (2019b), Serrano et al. (2020) differentiate ground thermal patterns controlled by atmospheric temperature, by snow cover and by the existence of frozen ground conditions.

On the other hand, in the rocky walls (near-rock surface) only two thermal phases are differentiated throughout the year: a phase of continuous thaw (late spring or early summer to mid-autumn) and a phase with a high number of FTCs (the rest of the year).

Currently, in the highest sectors of the Western Massif of the Picos de Europa (and the rest of the massifs that make up the Picos de Europa) an active periglacial morphodynamics is present (Figure 5). This morphodynamics is linked to the thermal characteristics detected in this study, and controlled mainly by two factors: (1) the annual evolution of the snow cover, and (2) the existence of frozen ground following FTCs of essentially daily rhythms. Based on the spatial distribution and altitudinal variations of the active periglacial processes and landforms, two belts can be distinguished within the periglacial environment of the Western Massif of the Picos de Europa: (1) the nivoperiglacial belt and (2) the cryonival belt.

The nivoperiglacial belt develops between 1,800 and 2,200 m and is defined by an attenuation of cold processes. Active processes are related to the snow cover and the availability of meltwater (snow avalanches, debris flows, solifluction features, nival karst, etc.; Figure 5A and B), as well as those dependent on FTCs (frost shattering, pipkrakes, etc.). This belt is widely represented in other mountainous areas of the Asturian Massif and the Cantabrian Mountains such as the Puerto de San Isidro (Rodríguez, 1995) the Massif of the Saliencia Syncline (Rodríguez, 2009), the Ventana Pass

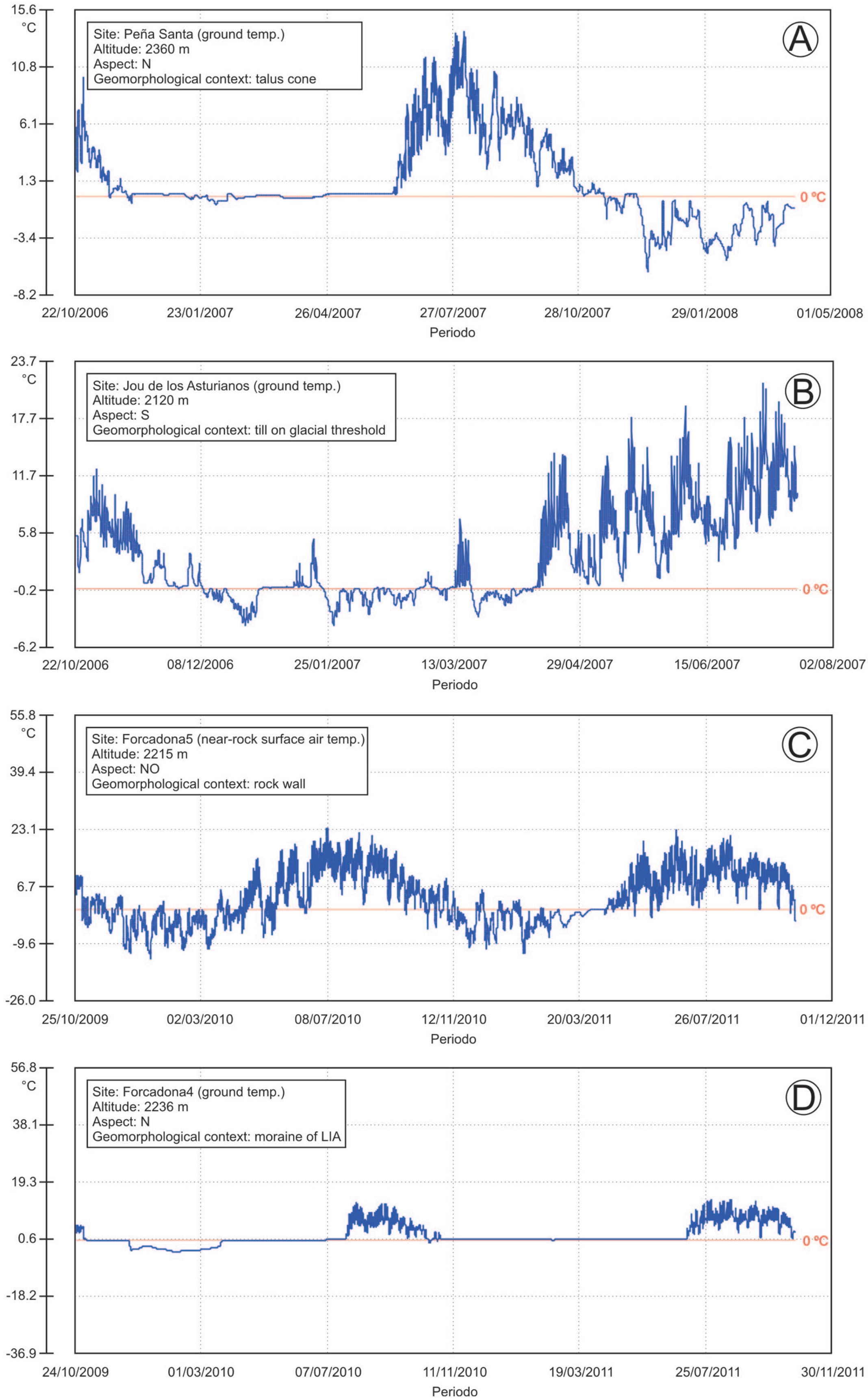

Figure 4. Ground (A, B, and D) and near-rock surface air (C) annual thermal regime in the monitorized areas of the Western Massif of the Picos de Europa.

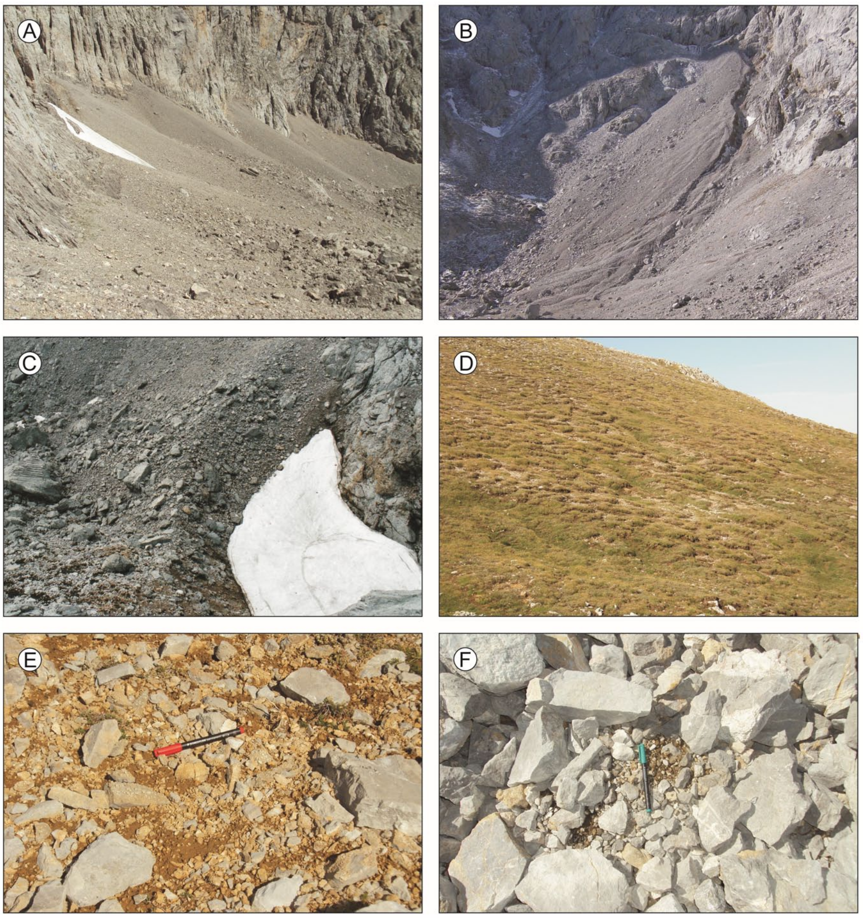

Figure 5. Examples of periglacial landforms in the Western Massif of the Picos de Europa. (A) talus slopes in the Peña Santa de Castilla area; (B) talus slope with debris flows in Jou Santo (the erosive channel and the characteristic digitations of the distal part are observed); (C) pronival rampart in Jou de los Asturianos area; (D) slope with solifluction lobes in Los Moledizos glacial cirque; (E) stone stripes near of Torre Bermeja; (F) stone-sorted circle on the Forcadona buried ice patch.

(González-Díaz et al., 2021) and the Ubiñas Massif (Gallinar-Cañedo et al., 2022a).

On the other hand, the cryonival domain, located above 2,200 m altitude, is characterized by more rigorous thermal conditions that allow greater effectiveness of frost shattering (especially on the rocky walls), nivation (Figure 5C) and the existence of cryoturbation processes. Cryoturbation generates patterned ground features such as stone stripes and stone-sorted circles (Figure 5E and F). In this environment, karstic dissolution is very intense, favored by the abundance of snow-fields and their long duration (many subsist for up to 10 and 11 months and some are even permanent). In turn, solifluction landforms (solifluction lobes, terracettes, ploughing blocks) are abundant (Figure 5D). Finally, snow avalanches and debris flows generate an efficient movement and redistribution of particles downslope. Therefore, the cryonival belt is a very dynamic environment, although with a very small extension, since many peaks of the massif exceed 2,200 m in altitude, but very few reach or exceed 2,400 m. In addition, there are very few deposits in these levels, since they are very abrupt areas dominated by vertical rocky walls. In addition to the Picos de Europa (Brosche, 1978; Castañón & Frochoso, 1998; González-Trueba, 2007; Ruiz-Fernández et al., 2014; Serrano & González-Trueba, 2004), the cryonival belt is present mainly in other sectors of the Cantabrian Mountains such as the Fuentes Carrionas Massif (Pellitero, 2012) and the Ubiñas Massif (Gallinar-Cañedo et al., 2022a).

Contributions like this, applied in this case to a mountain area, are key to delving into the relationship between the soil and the spheres of air and water/snow (Rodrigo-Comino et al., 2022; Zhang, 2005). In the current context of environmental change, the parameters discussed here are important indicators to know the evolution and health of the soil and the ecosystems (Brevik et al., 2015; Rodrigo-Comino et al., 2020; Steffan et al., 2018).

Conclusions

At the present time, the high mountain of the Western Massif of the Picos de Europa is characterized by severe climatic conditions, with low mean annual ground and near-rock surface air temperatures and high precipitation (mostly snow precipitation). The snow cover lasts about 8 months on average, although with important interannual variations depending on the topoclimatic conditions. The snow cover insulates the soil from the air temperature, which determines the low number of FTCs in the superficial formations. On the other hand, the number of FTCs is much higher on the rocky walls, unprotected from the snow cover.

The existence of significantly different annual thermal regimes at the ground and near-rock surface air has been confirmed; with two main phases (continued thaw phase and isothermal phase) and two minor transition phases in the first case, and only two main phases in the second case (continued thaw phase and phase with a high number of FTCs).

Under the thermal regime described, a functional periglacial morphodynamics is developed related to the annual evolution of the snow cover (precipitation, permanence of the snow cover and its melting) with different geomorphological implications, as well as with the formation of ice on the ground and in rock outcrops based on the presence of FTCs that, mainly, we can consider daily.

Author Contributions

Study conception and design: JRF, CGH. Field work and data collection: JRF, CGH, MOA, MVB, DGC, BGD. Analysis and interpretation of results: JRF, CGH, MOA, MVB, DGC, BGD. Draft manuscript preparation: JRF, CGH. Figures and tables preparation: JRF, MOA, MVB. All authors read and approved the final manuscript.

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Availability of Data

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