GROUND TEMPERATURES, LANDFORMS AND PROCESSES IN AN ATLANTIC MOUNTAIN. CANTABRIAN MOUNTAINS (NORTHERN SPAIN)

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Abstract

Ground temperatures determine significant geomorphological processes in a wet and temperate mountain with a narrow high elevation range belt. Twenty five temperature data loggers were buried at a shallow depth in different locations and altitudes and at specifically cold locations at two massifs in the Cantabrian Mountains (North Spain), Picos de Europa and Fuentes Carrionas. This paper analyses the ground thermal regime and associated parameters (e.g. freeze index, duration and depth of freeze, freeze and thaw cycles) and correlates them with active geomorphological processes and landforms. The thermal regime varies in accordance to the topoclimatic conditions, and it was possible to determinate annual phases in function of snow cover behaviour. Main active processes and landforms stop their activity with a large snow cover which thermally protects the ground and in consequence, avoids the freeze and thaw cycles. During this period, the records allow to asseverate the evidence of seasonal freeze grounds in several locations. Permafrost was not discover on the ground at any of the thermometers except one located at the vicinity of a relict ice patch. With the help of geomorphological maps and previous works, we got to establish the relation between geomorphological processes, landforms, snow cover and ground thermal regime.

Key words: Ground Thermal Regime, Temperate High Mountain, Snow cover, Geomorphology, Cantabrian Mountains.

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1. Introduction

The Cantabrian Mountains are situated in the North fringe of the Iberian Peninsula (Fig. 1). They present an active periglacial belt that occupies the highest portions of the mountain, above 2000 m. The most representative elements of the cryosphere in the Cantabrian Mountains are mainly the snow cover, seasonal freeze ground, and, to a lesser extent, ice patches and ice caves. There are also lots of periglacial features inherited from colder Pleistocene and Holocene climate phases (Oliva et al. 2016). The cryosphere has been moderately studied in the Cantabrian high Mountain. The first works are focused on periglacial landforms, mainly slope deposits of Picos de Europa linked to the glacial features (Obermaier, 1914). Also, different periglacial phases were established through the study of deposits and landforms on the low areas of Cantabrian Mountains, which lead to their relative dating in the Lateglacial and Postglacial phases (Martinez-Álvarez, 1959; Hernández-Pacheco, 1959; Hazera, 1968; Mugnier, 1969; Frochoso, 1990; Díaz-Martínez, 1989; Serrano et al. 2013). Nival features have been also described, although to a lesser extent (Ugarte, 1992). These landforms will be best defined in the space and the time in following works. Pleistocene cryoturbation and gelifluction landforms (e.g. patterned ground, blockfields and blockstreams) have been described, showing the imprint of cold phases on glaciated and not glaciated areas (García de Celis, 2002; González-Gutiérrez, 2002; González-Trueba, 2007a,c; Rodríguez-Pérez, 2009; Santos-González, 2010; Pellitero, 2013, 2014; Ruiz-Fernández et al. 2014a). The presence of relict rock glaciers in the Cantabrian Mountains suggest permafrost environments during the Late Pleistocene glacial stages and the Holocene coldest phases. Firstly cited by Clarck (1981), most of the rock glaciers were developed during the Lateglacial stage (Younger Dryas), but also during the Last Glacial Maximum (LGM) and possibly the Holocene (Alonso 1989; García de Celis, 1991; Serrano and Gutiérrez, 2000; Gómez-Villar et al. 2004, 2013; Rodríguez-Pérez, 2009; Pellitero et al. 2011, Rodríguez-Rodríguez et al. 2016), showing a large amount of inactive features situated between 400 and 2300 m.

The study of present day periglacial processes and environments in Cantabrian Mountains began in the Picos de Europa, where the displacement of debris lobes was measured, confirming the existence of active processes (Brosche, 1994). So far, contributions have focused on the thermal regime and active processes description (Castañón and Frochoso, 1994, 1998; Serrano and González-Trueba, 2004; González-Trueba, 2007a; Santos et al. 2009; Pellitero, 2013; González-Trueba and Serrano, 2010b; González-Trueba et al. 2012, Ruiz-Fernández, et al. 2014b; Pisabarro et al. 2015).

These studies show the reduced number of freeze/thaw cycles (F/Tc) on the ground and the domain of processes related to the debris movement by gravity without ice activity.

Some deep-freeze active processes such as patterned ground (Brosche, 1994; Castañón and Frochoso, 1994; González-Trueba, 2007a, b; Serrano and González-Trueba, 2011; Serrano et al. 2011) and frost mounds (Castañón and Frochoso, 1998; González-Trueba, 2007a; Serrano et al. 2011) are located in specific locations where they show the existence of ice in the ground during the winter. The definition of mountain permafrost establish at least a mean annual ground temperature <-2ºC for at least two consecutive years in mountain environments (French, 2007; Dobinski, 2011). Cryokarst, which is likely related to permafrost in ice caves has been described in Picos de Europa (Gómez-Lende, 2015; Gómez-Lende et al. 2014, 2016). However, perennial frozen ground, if present, would be featured by discontinuities and instabilities due to the snow cover, slope and aspect (Harris et al. 2009; Gruber and Haeberli, 2009). Besides, the influence of ice-patches is also evident and only conserved in Picos de Europa (González-Suárez and Alonso, 1994, 1996; Frochoso and Castañón, 1995; Alonso and González-Suarez, 1998; González-Trueba, 2004, 2007; González-Trueba et al., 2008; Serrano et al. 2011) as a heritage of the Little Ice Age and implications on some periglacial processes. However, other periglacial processes can be associate with the concept of seasonal frozen ground (SFG) (French, 2007), also common in mountain environments.

The snow cover is a cryosphere transversal component that influences over surface waters, the physical soil comportment, the biogeochemical flows and the ecosystem dynamic (De Walle and Rango, 2008; Adam et al. 2009). It also determines partially the periglacial processes and affects the ground temperature and runoff regimes (Zhang, 2005; López-Moreno et al. 2009; García-Ruíz et al. 2011). In the Cantabrian Mountain the nivation has been studied describing landforms and deposits (González-Trueba, 2007a,b; González-Trueba and Serrano, 2010a; Pellitero and Serrano, 2012) and analyzing snow avalanches as a morphogenetic process (Castañón, 1984; Puente, 2006; González-Trueba, 2007; González-Trueba and Serrano, 2010a; Santos et al. 2010; Pellitero and Serrano, 2012; Pellitero, 2013; Hernández-Holgado, 2014). Only recently snow has been considered as a natural hazard in the area (Wozniak and Marquínez, 2004; González-Trueba, 2007; Vada et al. 2012; 2013; García-Hernández et al. 2014; Serrano et al. 2016).

With this background, the aim of the study is differentiate landforms and processes related to ice, snow or gravity, as well as to determine the ground thermal regime in different locations, establishing the magnitude and duration of the cold wave penetration by means of the Freeze Index (FI), timing of SFG, and F/Tc. The effectiveness of current thermal processes on the ground in a wet and temperate high mountain will be assessed through the relationship between these measurements and the active periglacial landforms found in the different mountain belts.

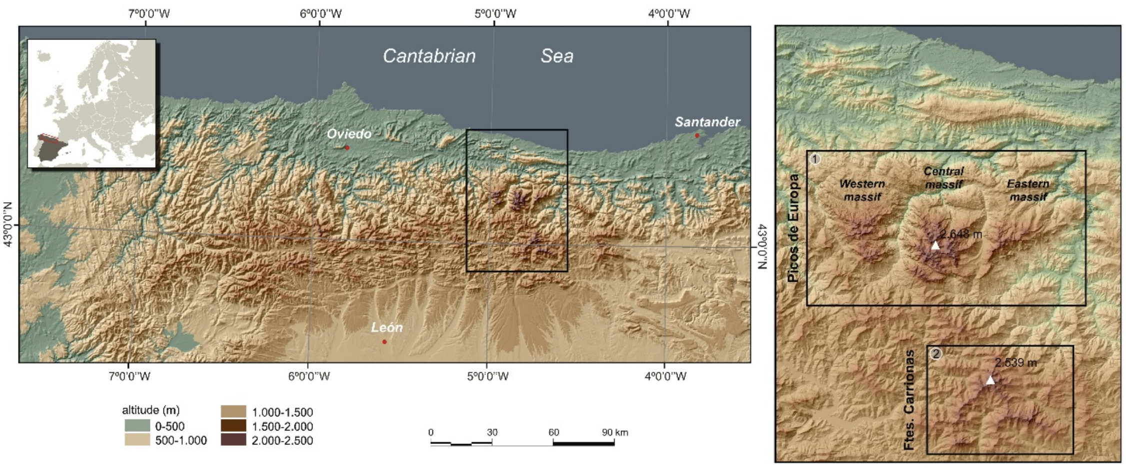


Figure 1. Location of Cantabrian Mountains and the massifs studied.

This paper deals with the two highest massifs in the Cantabrian Mountains (Fig.1), where the active periglacial landforms (e.g. frost mounds, debris flows, terracettes and solifluction lobes) are most common. In both cases the depth and extension of the cryogenic processes remains unknown and the study of the SFG is key to understand the geomorphological processes triggered in the high mountain belt.

Picos de Europa (PE) has the highest altitudes in the Cantabrian Mountains, up to 2648 m. It comprises an area of 150 km^2. Lithology is mostly calcareous, and limestones thickness reach about 2000 meters (Merino-Tomé et al. 2009) Relief is very abrupt and rugged by the development of glacio-karst depressions (Smart, 1986) (locally called “jous”) between ice-moulded horns. The seasonal snow cover generates superficial and underground karst processes, which are mostly directed by layers stratification and faulting. On relict glacial and periglacial deposits, snow melt and frost-heave play a role in the general deposit erosion. This also happens to bedrock over 1800 m. There is also relict glacial ice in several sheltered locations.

Fuentes Carrionas (FC) occupies about 175 km^2 with altitudes ranging from less than 1000 to 2536 m. It hosts a wide variety of rock outcrops, for example, limestones, conglomerates, granites, quartzites, sandstones and shales. Its structure is dominated by overthrusts, faults and narrow anticlines and synclines to the south, while the northern area is covered by the broad Curavacas syncline. In the centre of this area there is a small granitic stock (Rodríguez, 1994). Glaciers shaped most of the valleys and watersheds during Quaternary, and left till mantles from 1200 to 2300 m (Pellitero 2013; Serrano et al. 2013). Beyond the glaciated areas (and progressively higher on the transition between the Last Glacial Maximum to the Holocene), periglacial conditions led to the formation of rock glaciers, blockslopes and blockfields, patterned soils and solifluction lobes (Pellitero, 2014). During deglaciation slopes underwent a paraglacial phase, so mass movements, some of which are still active, began to develop.

During the Holocene glacial tarns started to fill with water and sediments, leading to the formation of lakes and peatbogs, fluvioglacial and fluvial terraces. Nowadays periglacial and nival processes such as gelifluction, gelifraction, the construction of pronival ridges and the occurrence of avalanches are still active, making FC, alongside PE, the only area in the Cantabrian Mountains with a periglacial belt (sensu Chardon 1984).

2. Methodology

Ground thermal regimes were obtained by thermal micro sensors I-bottom UTL - Geotest AG (Universal Temperature Logger) data-logger with centesimal accuracy and 0.05°C error level. They were buried between 0.1 and 0.2 meters depth, following Delaloye (2004) methodology. These thermometers allow monitoring ground temperatures between 4 and 6 times a day for an entire year. The locations are visible in figures 2, 3, 4 and the Table 1 includes the bedrock, deposit, coordinates, altitude and aspect. The thermometers were distributed in altitudinal belts where it was possible and close to active periglacial landforms. The data was taken between 2004 and 2007 in PE and between 2009 and 2012 in FC.

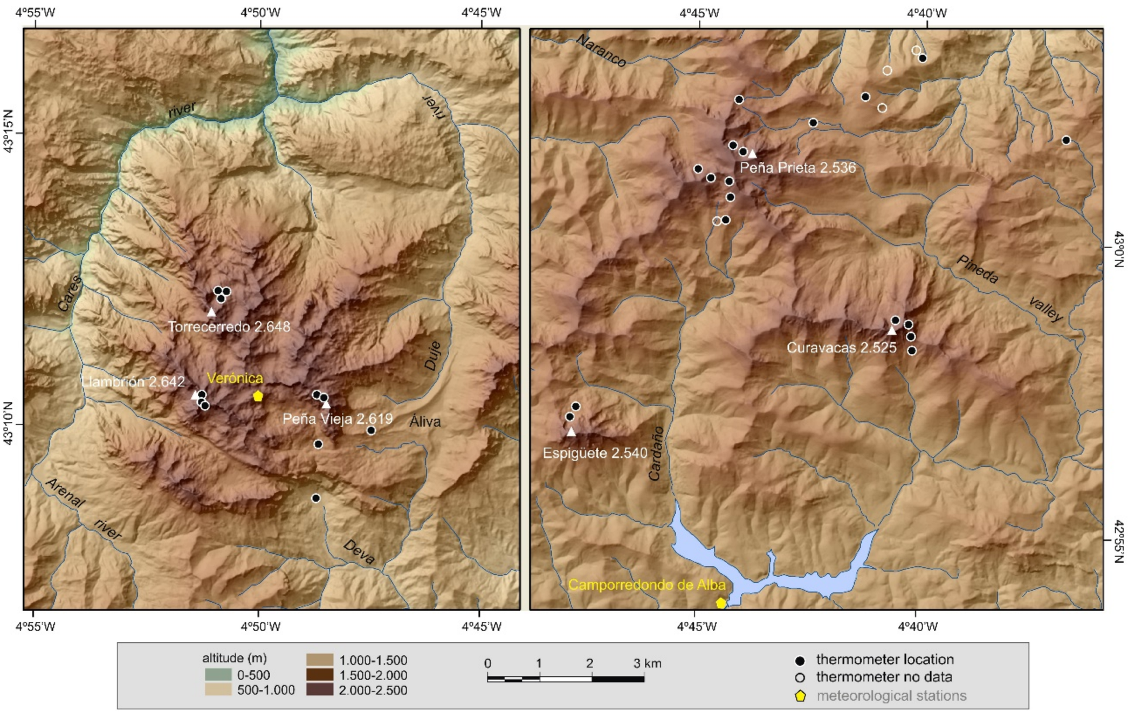


Figure 2. Left, massif of Picos de Europa and right, massif of Fuentes Carrionas.

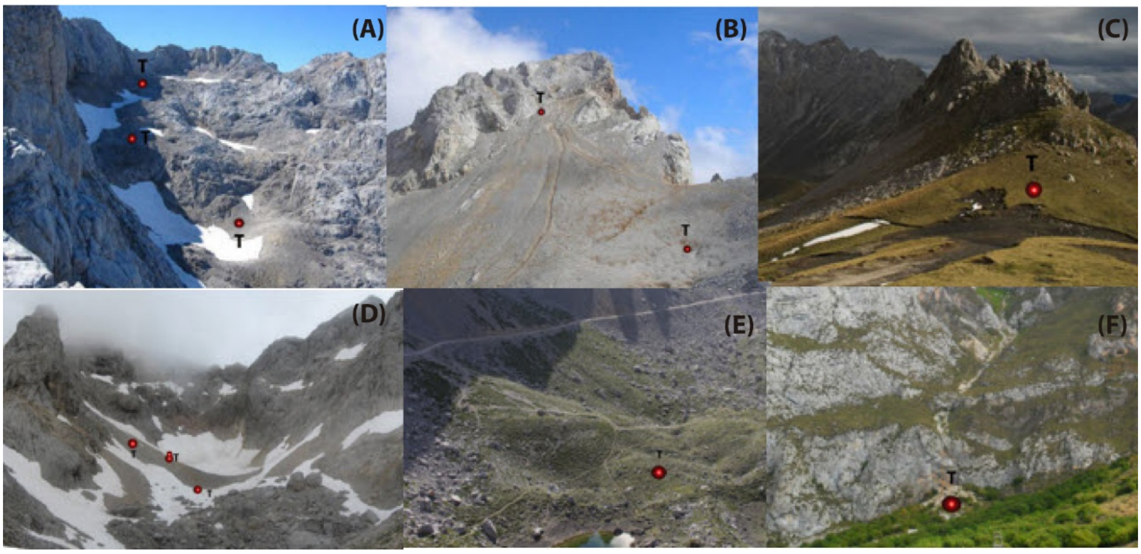


Figure 3. Locations of the thermometers in Picos de Europa massif. A) Jou Traslambrión, B) Peña Vieja, C) Áliva, D) Jou Negro, E) Lloroza, F) Fuente De.

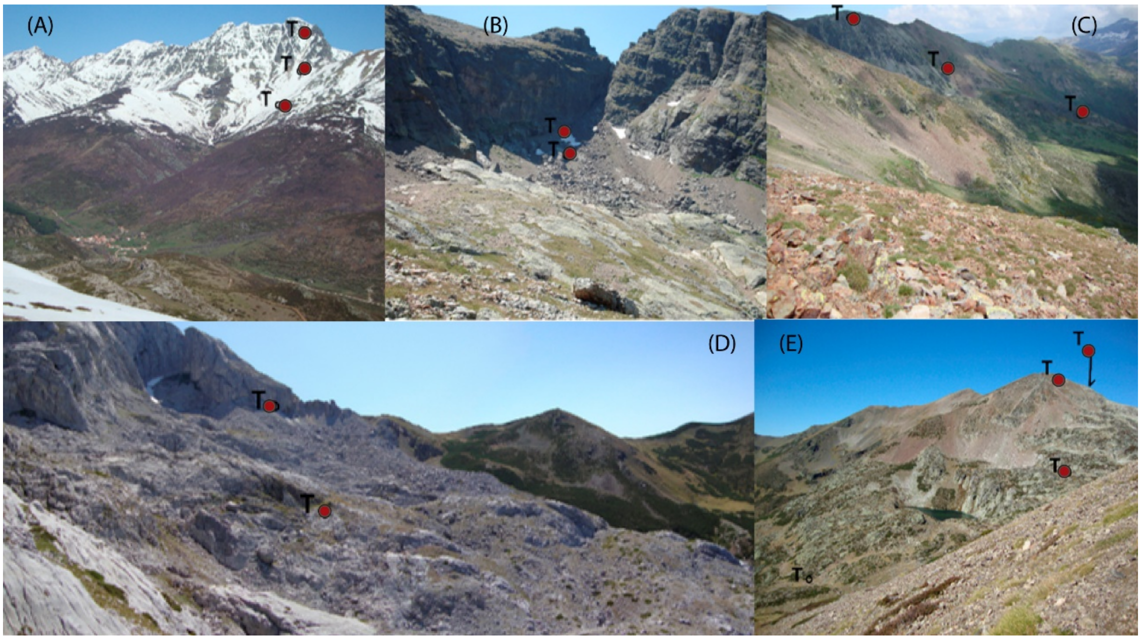


Figure 4. Locations of the thermometers in Fuentes Carrionas massif. A) South face of Curavacas peak, B) North cirque of Curavacas peak, C) West faced slope in Tio Celestino peak, D) North face of Espiguete peak and E) East face of Lomas peak.

Main data treatment consisted in obtaining representative statistical parameters of temperatures tendencies, phases, freeze/thaw cycles (days with temperatures below and over 0ºC) and temporal behaviours (Table 1). The phases of the ground thermal regime were developed in Pisabarro et al. (2015) and were useful to signal key moments of thermal instability (e.g. phases with many of the F/Tc). The freeze index (FI) (Fengqing and Yanwei, 2011), has been useful to compare SFG depths and its magnitude (French, 2007). Freeze depth is calculated following the Washburn (1979) method using the material conductivity (Eppelbaum et al. 2014) and the FI. The likelihood of SFG is analysed looking the phase 3 of the thermal regimes. If minimum temperature of the phase is <-0.5ºC the SFG is sure, if is between -0.5ºC and 0ºC, the SFG is likely and if the minimum is >0ºC is unlikely.

The inventory of periglacial landforms is a result of the previous literature and field work. Mostly of landforms were mapped at a 1:25000 scale in PE (González-Trueba, 2007; González-Trueba and Serrano, 2010b; González-Trueba et al., 2012; Serrano and González-Trueba, 2004) and 1:12.000 in FC (Pellitero, 2014). The inventory allows establish relationships between landform creation and the level of ground temperature at different belts and altitudes.

3. Results

3.1. Air thermal regimes

In PE, the mean annual air temperature (MAAT) is 3.6ºC at 2325 m., the atmospheric high freeze index is high and snowpack depths are around 2 m of thickness. The snow cover is stable between December/January to May/June. Atmospheric minimum temperature can get below -10ºC between October and March according to 2011 values (Fig.5).

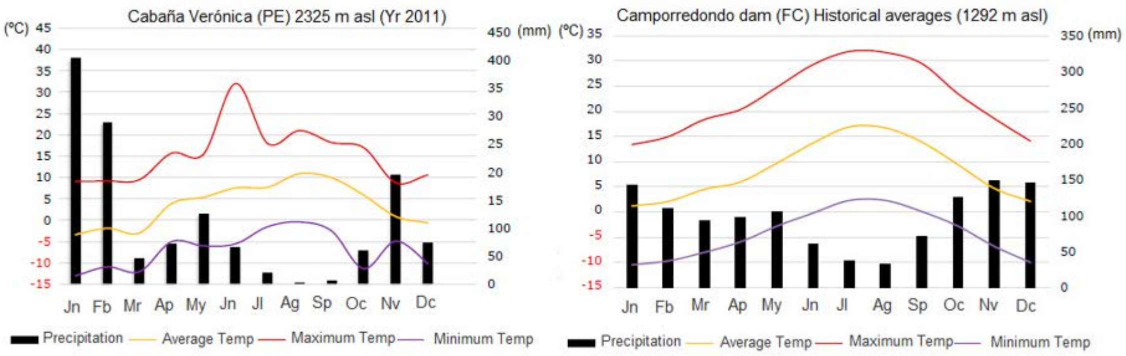


Figure 5. Air temperature and precipitation in Cabaña Verónica (PE) and Camporredondo dam (FC). Source OAPN (National Parks Autonomous Organism) and AEMET (National Meteorological Agency)

There are not high mountain weather stations in Fuentes Carrionas, but we can find several ones in the nearby valleys. Camporredondo de Alba (1295 m) has the longest lasting record among them, with more than 80 years of daily records of precipitation and temperature. Here, MAAT is 8ºC and the minimum daily temperature is below -5ºC between November and April and below 0º all months except summer (Fig.5).

Both massifs get the highest amount of precipitations between November and May, most of it as snow. Precipitations reach 1900 mm yr^{-1} in PE thanks to its proximity to the Cantabrian Sea., whereas in FC they are about 1000 mm yr^{-1} due to the shadow effect from the PE (Fig.5). Snow precipitation is highly variable depending on the year. First snow of the season usually falls in early autumn, but summer snow is possible, and dry years can delay snowfall up to March during dry and cold winters (González-Trueba and Serrano, 2010a).

3.2. Ground thermal values

3.2.1. Freeze magnitude

The number of days with temperatures below 0°C exceeds half of the year over 2100 m. At some particularly high locations the ground is kept frozen over 75% of the year. These areas also record sustained temperatures below -2°C. The -2°C threshold is considered the highest winter temperature to consider the existence of sporadic

permafrost (Haeberli, 1973; French, 2007). There are six locations where the -2°C limit is continuously exceeded, mainly in Lomas (FC) over 2400 m and Jou Negro (PE) over 2150 m. However, the low temperatures are not kept long enough to consider the existence of permafrost. The thermometers located at the moraine by the ice-patch in Jou Negro (Fig. 2) are the ones with highest freeze index, which is coherent with the existence of frost mounds at the site. This could show the influence of the nearby ice body and maybe other buried frozen bodies within the moraine (González-Trueba, 2007).
Below 2000 m. the FI is low in both massifs (between 55 and 0) and it descends under 100 below 2100 m. In general, FI is highly dependent on the snow cover, which keeps the soil around 0°C thanks to the zero curtain effect. This situation is especially marked in FC, where thermometers were placed at different orientations in order to highlight the snow accumulation changes. Here, over 2100 m, the snow mantle is stable and the FI is close to zero, especially at the N and E slope. However, on the W and S orientations, or at very steep slopes where the snow mantle is not stable, the FI exceeds 100. Therefore, the most exposed soils are the ones where the periglacial processes are more active. Frozen ground days are conversely maximum where the snow mantle is most stable, with values over 260 days near semi-permanent snow-patches.

Given the similarities between the studied massifs, the thermometer altitude and days below zero degrees have been correlated. There is a linear correlation between altitudes of both massifs and number of days Tg< 0ºC with p-value < 0.05 and $r^2 = 0.4592$ (Fig.6). This is interpreted a statistically significant correlation, but other factors, as the mentioned orientation, snow cover and situation near relict ice patches, must be also considered.

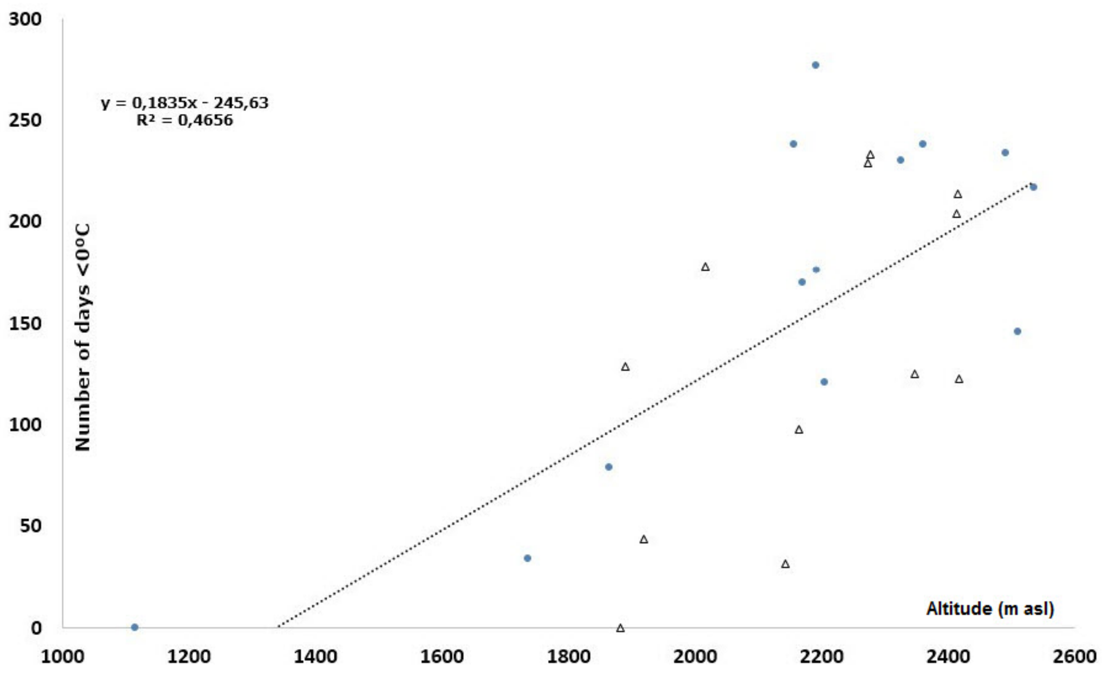


Figure 6. Correlation between thermometers in FC (triangles) and PE (points).

Table 1. Main parameters of the Picos de Europa and Fuentes Carrionas.

Name | Massif		Alt.	Asp	Lat °	Long °	Deposit & Bedrock	Year	Days < 0°C & Days<-2°C		FI	F/Tc	T°C (Phase 3)	SFG	Frozen ground depth (m)[1]	Conductivity (10^5 J °day) (Eppelbaum et al. 2014)
Espigüete	FC	1889	N	42,9517	4,7984	Terra rossa in doline/Limestone	08/09-11/12	129	1	30	6	0 to 0,5	Unlikely	0,29	2,05
Espigüete	FC	2016	N	42,9491	4,8011	Debris on active scree/ Limestone	2010/ 12	178	3	67	14	-3 to 0,5	Likely	0,39	2,05
Lomas	FC	1918	E	43,0032	4,7397	Soil on till sheet/Turbidite	2010/ 12	44	0	39	6	-0,5 to 0,5	Likely	0,28	1,44
Lomas	FC	2163	W	43,0097	4,7381	Soil on scree/Turbidite	2009/ 12	98	0	33	36	-1 to 0	Likely	0,27	1,44
Lomas	FC	2417	W	43,0150	4,7380	Blockfield/ Granite	2009/ 11	123	60	273	54	-7 to 0,5	Yes	0,72	2,32
Lomas	FC	2169	E	43,0132	4,7440	Soil on till sheet/ Granite	2010/ 12	170	0	67	24	-0,5 to -0,5	Likely	0,40	2,32
Lomas	FC	2412	E	43,0156	4,7502	Soil on scree/ Granite	2010/ 12	204	0	69	4	-0,5 to 0	Likely	0,41	2,32
Lomas	FC	2415	N	43,0158	4,7506	Solifluction lobe/ Sandstone	2010/ 12	214	11	109	8	-3 to 0,5	Yes	0,48	2,16
Curavacas	FC	1882	S	42,9683	4,6698	Soil on scree/Conglomerate	2010/ 12	0	0	0	0	-	Unlikely	0,00	4,32
Curavacas	FC	2143	S	42,9729	4,6711	Soil on scree/Conglomerate	2010/ 12	32	0	0	6	0 to 0,5	Unlikely	0,00	4,32
Curavacas	FC	2346	S	42,9756	4,6723	Soil over bedrock/Conglomerate	2010/ 12	125	14	77	4	-2,5 to 0	Yes	0,55	4,32
Curavacas (2)	FC	2272	N	42,9759	4,6786	Active scree/Conglomerate	2010/ 12	229	0	0	2	0 to 0,5	Unlikely	0,00	4,32
Curavacas (1)	FC	2277	N	42,9756	4,6786	Active scree/Conglomerate	2010/ 12	233	0	0	4	0	Likely	0,00	4,32
Llambrión	PE	2535	N	43,1736	4,8528	Till in rock bar/Limestone	2005/ 07	217	0	85	15	-0,5 to 0	Likely	0,42	2,05
Traslambrión	PE	2490	N	43,1748	4,8541	Till in rock bar/Limestone	2005/ 07	234	2	219	8	-1,5 to -0,3	Yes	0,62	2,05
Traslambrión	PE	2360	N	43,1792	4,8533	Top debris cone/Limestone	2005/ 07	238	0	59	3	-0,5 to 0	Likely	0,37	2,05
Jou Negro	PE	2205	N	43,2027	4,8499	Debris slope/Limestone	2005/ 07	121	2	113	10	-1,5 to -0,5	Yes	0,47	2,05
Jou Negro	PE	2155	N	43,2022	4,8521	Till in moraine/Limestone	2005/ 07	238	65	235	18	-1,1 to -0,1	Yes	0,64	2,05

Jou Negro	PE	2190	N	43,2019	4,8525	Till - patterned ground/Limestone	2005/07	176	63	461	40	-8,5 to 0	Yes	0,77	1,64
Jou Negro(Ta)	PE	2190	N	43,2019	4,8525	Till - patterned ground/Limestone	2005/07	277	1	138	36	-2,5 to -0,1	Yes	0,37	1,64
Peña Vieja	PE	2510	W	43,1747	4,8106	Debris slope/Limestone	2003/04	146	17	96	9	-1 to 0	Likely	0,41	1,64
Peña Vieja	PE	2325	W	43,1753	4,8122	Small sinkhole/Limestone	2003/05	230	0	20	15	-0,2 to 0,2	Likely	0,26	2,05
Lloroza	PE	1865	S	43,1597	4,8120	Moraine/Limestone	2005/07	79	2	55	8	-0,7 to 0,5	Likely	0,33	1,64
Áliva	PE	1735	E	43,1944	4,7714	Soil with debris/Shales	2005/07	34	0	3	6	0 to 0,5	Likely	0,15	1,44
Fuente Dé	PE	1115	S	43,1492	4,8098	Debris cone/Limestone	2005/07	0	0	0	0	-	Unlikely	0,00	2,05

[1] Washburn (1979); h (m) = $\sqrt{\frac{2K(FI)}{C_L}}$ +d; K (Conductivity J °day);
C_L (Latent Heat 3.34x10^{8}J m^3); FI (Freeze Index °day); d (Depth of the register 0.1m)

Frozen ground depth was not measured in this project, but it was estimated from the shallow-buried thermometer temperatures using the Washburn (1979) approach, taking into account that the used constants were calculated in laboratory conditions. The highest freeze depth was calculated for Jou Negro (PE) with 0.77 m. and Lomas (FC) with 0.72 m. The higher conductivity of the soil material in Lomas permits a higher potential for frost penetration in the ground regardless a lower FI. Anyway, these values entail that there is a considerable amount of soil susceptible to be mobilised during the thaw season. Not surprisingly, they coincide with the development of gelifluction lobes in Lomas (whose thickness is around 0.5 meters, see Fig. 11), which corroborates the effect of seasonal frost in the landform creation processes.

3.2.2. Freeze-thaw cycles (F/Tc)

The entire area presents F/Tc which are highly variable and dependant on the snow cover. F/Tc are more frequent on steep slopes, crest, wind-exposed areas and overhangs, where the snow cover is not stable. Sheltered situations reduce F/Tc to less than 18 cycles/year. F/Tc are generally higher in PE, especially in autumn and even summer (between 5 and 33 cycles in summer and autumn), whereas the F/Tc in winter and spring are similar in both massifs.

Table 2. Monthly distribution of F/Tc in PE and FC.

Picos de Europa	Alt.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	Year
Llambrión	2535							1		1	2	2	9	**15**	2006
Peña Vieja	2510					5						3	1	**9**	10/2003-10/2004
Jou Trasllambrión	2490							1			1	6		**8**	2006
Jou Trasllambrión	2360							1	2					**3**	2006
Peña Vieja	2325	13	1					1						**15**	2004
Jou Negro	2205					5						3	2	**10**	2006
Jou Negro (Ta)	2190							1	2	5	8	14	4	**34**	11/2005-11/2006
Jou Negro	2190	4							4	4	10	14	4	**40**	11/2005-11/2006
Jou Negro	2155				4	4						6	4	**18**	2006
Lloroza	1865			7									1	**8**	2006
Áliva	1720	1	1	3	1									**6**	2005
Fuente Dé	1115													**0**	2006
SubTotal		**18**	**2**	**10**	**5**	**14**	**0**	**5**	**8**	**10**	**21**	**48**	**25**		
Fuentes Carrionas	Alt.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	Year
Espiguete	1889						1							**1**	2009/10
Espiguete	2016				1						4	4		**9**	2010/11
Lomas E	1918	1	1	1									1	**4**	2010/11
Lomas E	2169				9	3						5	1	**18**	2010/11
Lomas E	2412						1				1			**2**	2010/11
Lomas W	2163	7	1	1									9	**18**	2010/11
Lomas W	2417	9	13	8								3	11	**44**	2010/11
Lomas N	2415					1					1	3		**5**	2010/11
Curavacas S	1882													**0**	2010/11
Curavacas S	2143		2	1										**3**	2010/11
Curavacas S	2346				1								4	**5**	2010/11
Curavacas N low	2272						1				1			**2**	2010/11
Curavacas N high	2277						**1**				**1**			**2**	2010/11
Subtotal		**17**	**17**	**11**	**11**	**4**	**4**	**0**	**0**	**0**	**8**	**15**	**26**		
TOTAL		**35**	**19**	**21**	**16**	**18**	**4**	**5**	**8**	**10**	**29**	**63**	**51**		

The highest amount of F/Tc in both areas happens in autumn, when the snow mantle is thin and brief. In spring/summer there are few cycles, between 1 and 5 over 2000 m., especially where the snow mantle can keep up to the late spring or early summer. Here, snowmelt coincides with the existence of already high atmospheric temperatures, which implies a higher thermal stress in a soil that very quickly passes from a zero-curtain winter effect, to summer high temperatures (see Fig. 7 Jou Negro or Peña Vieja). The few summer cycles correspond to night irradiation frost in clear summer nights at the highest elevations of PE, possibly with the influence of nearby ice-patches.

3.2.3. Ground thermal regimes: the climate at the soils

The analysis of the ground daily temperatures reveals at least four thermal phases, whose duration is variable depending on the topoclimatic peculiarities. Some of these theoretical phases can be subdivided given specific thermal situations (Figs. 7 & 8).

The **high temperatures phase (1)** usually lasts from May or June until the beginning of the autumn in early October. During this season the ground is in contact with atmosphere and temperature is over 0ºC. There is a strong variability between days and nights, in which frost is possible. The difference between consecutive daily temperatures is also highly variable, so it can reach up to 10ºC.

Transition Summer-Winter (2). During this season, which is usually short and not clearly defined in all cases, but mainly happening between October and early December, temperatures get or even descend below 0°C. There is a great ground thermal instability, which is originated by the first seasonal snowfall and the sudden temperature drop over 2000 m. Snow mantle is settled in favourable aspects (E and N, see Fig. 8), provoked by precipitations and lower temperatures driven by the advection of Atlantic depressions and fronts. Nevertheless, the snow mantle is still ephemeral in exposed areas, where the soil still gets the atmospheric influence, so some F/Tc happen here, and the temperature oscillations gradually become colder. It is also possible that sudden temperature increment, caused by the irruption of stable tropical air, melts most of the snow (see November 2011 in Fig. 8). Only N and E faces over 2150 m. escape the general snowmelt situation, mainly because many of them remain in the shadow during this season.

Isothermal equilibrium (3). The onset of phase 3 is marked by a uniform 0ºC, due to the snow curtain effect. Its duration in Picos de Europa (Fig.7) varies between 3 and 9 months depending on the altitude, with large differences between years depending on the snow mantle thickness. In 2006 the cold wave was larger in general but Jou Trasllambrión and Jou Negro (2490 and 2205 m) had their lowest temperatures in 2007, probably due to the snow instability or because of inner thermal fluxes within the vicinity of buried ice. There are not frozen grounds below 1800 meters in PE. In FC the ground thermal regime is much differentiated depending on the orientation and altitude. N and E faced areas (over 2000 m. in the glacial cirques and elsewhere over 2150 m.), where snow accumulates and its mantle is stable between October and May-June, the F/Tc are reduced to the autumn thermal freeze below the snow mantle and the melt in late spring. The spring season snowmelt water saturates the surface and enables solifluction. At the W/S faces, the snow mantle is more unstable due to enhanced solar radiation and wind blow-out. As an example, thermometers at the S face show very distinctive behaviour depending on the height. At 1900 m. on the S face there are not F/Tc and the snow cover is not sufficient to create the curtain effect. At 2150 m. there are F/Tc but temperatures in winter are near the 0ºC, which show the curtain effect. Finally, the thermometer installed over 2400 meters (Fig. 8) shows a strong freeze, with a Tg <-7 ºC on a snow disappearance situation in January 2011. These events imply a deep freeze and therefore enhanced gelifluction and frost shattering.

Snowmelt (4). This is a sudden episode in which the thermal transfer from the atmosphere (which is often several degrees over 0ºC) attains the ground. In N faced cirques, as Jou Negro, Trasllambrión (PE) or Curavacas (FC) this can happen at the onset of summer, during late June, so there is a sharp increase to the Tg in accordance with the Ta. Temperature rises between 10°C and 20°C during a single day, which prevents new F/Tc in summer. Finally, late snowfall can lay a spring snow mantle which installs the curtain effect again for several days, which enables new late F/Tc. This happened in May 2010 at the W face of Pico Lomas.

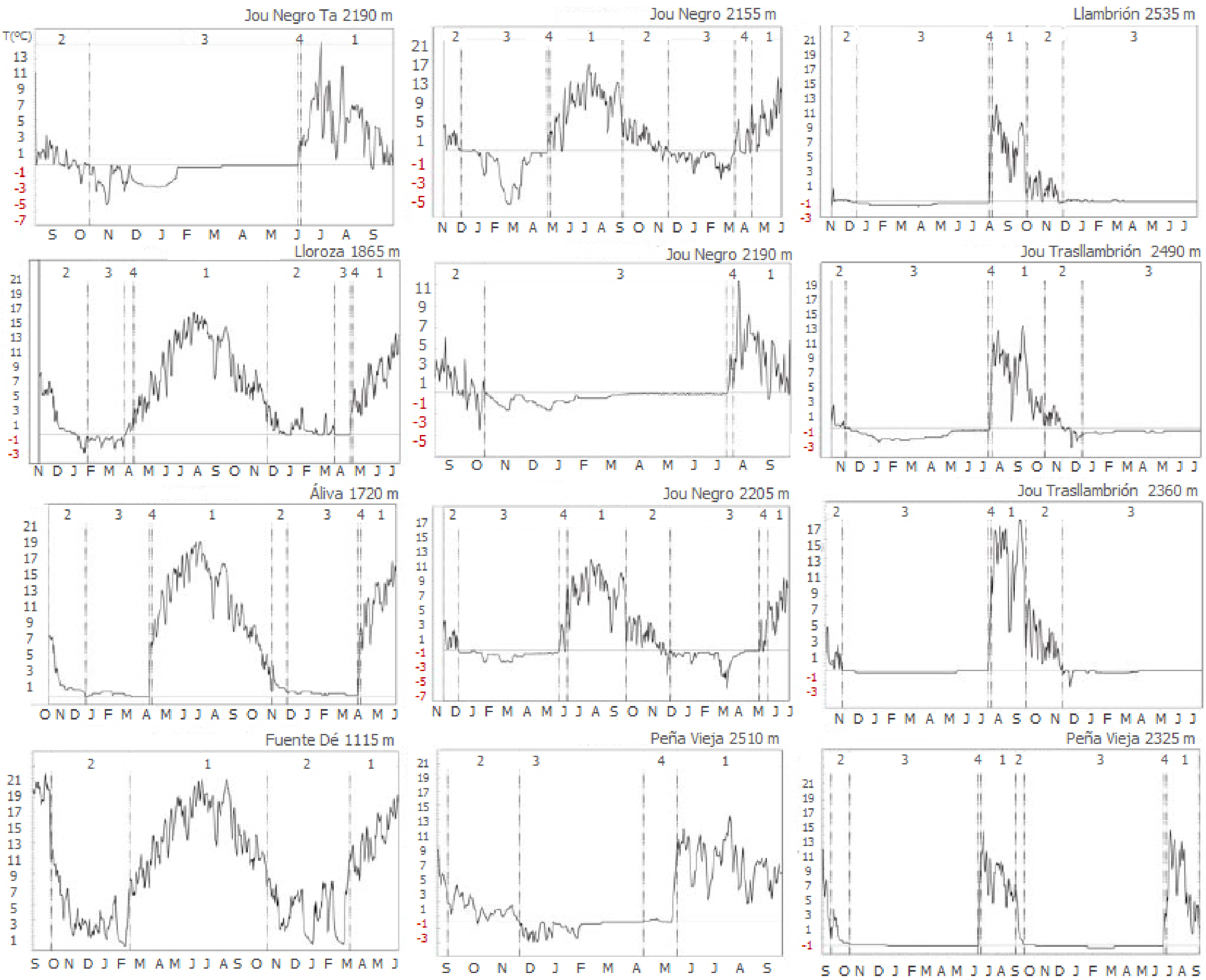


Figure 7. Ground thermal regimes of Picos de Europa including the number of phases.

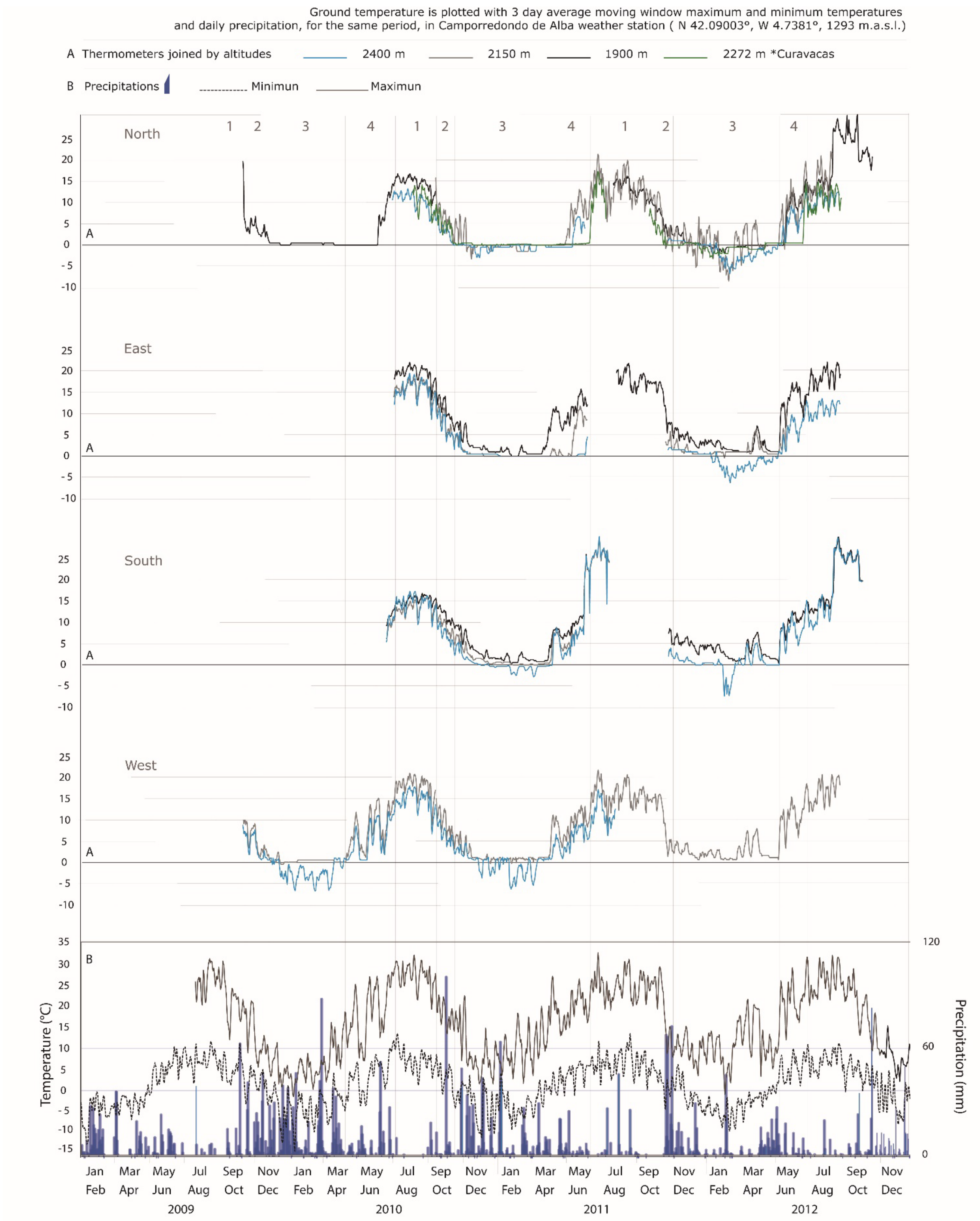
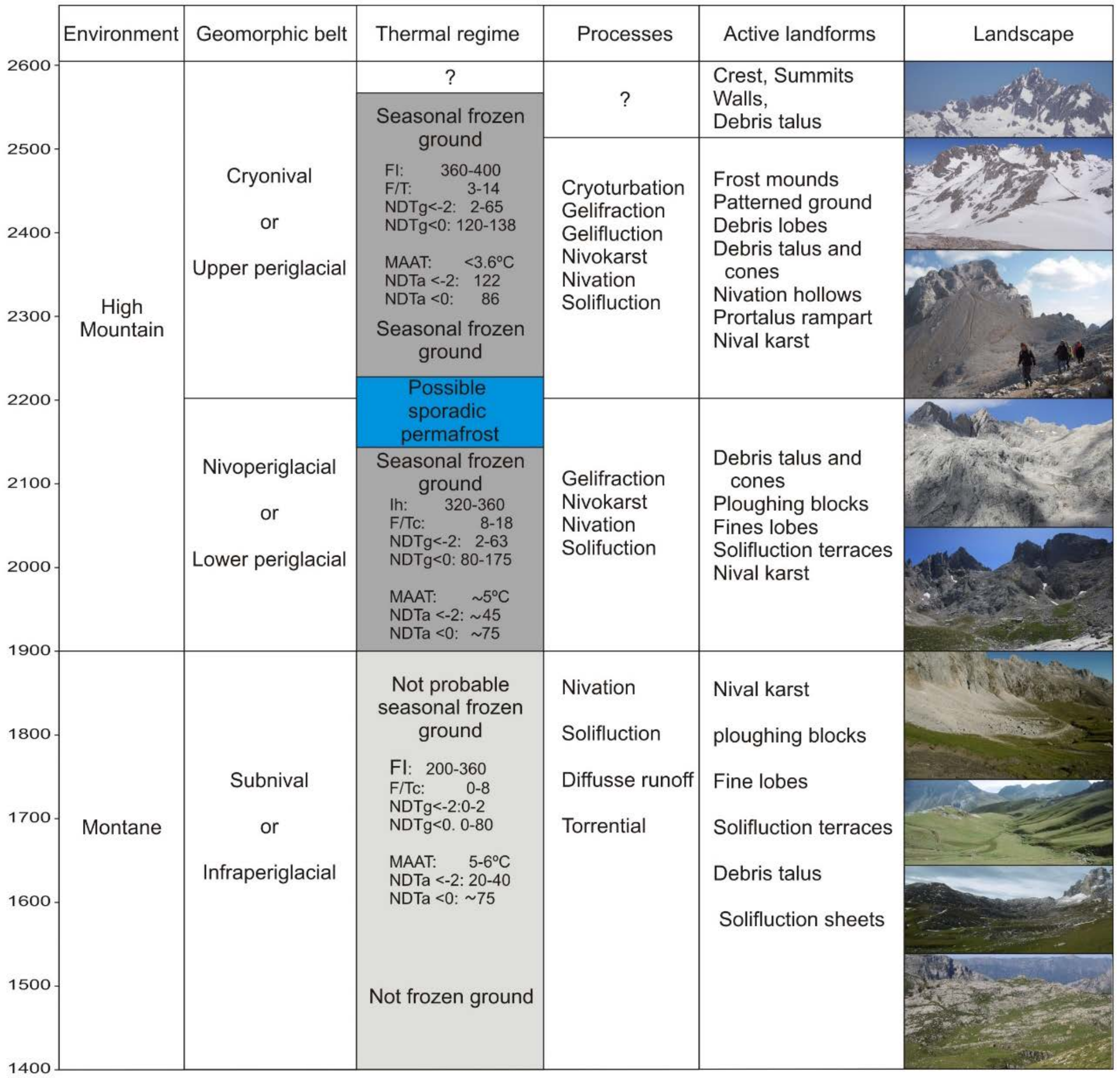


Figure 8. Ground thermal regimes of Fuentes Carrionas at different altitudinal belts including the number of phases and the relation with the weather station.

3.3. *Landforms and processes*

The ground thermal regime in different altitudes denotes several altitudinal steps. Depending on the altitudinal belt, the processes and landforms change (Figs. 9 & 10). In Fuentes Carrionas SFG appears at 1900 m. on the N face, whereas on the S face there are SFG over 2100. In Picos de Europa the SFG area is between 1900 m. to the top of data records (2535 m.). The distribution of the slope landforms in PE are characterized by processes of low intensity, except debris flow and snow avalanches. Landforms are linked to the gravity, freeze-thaw cycles, thermal cracking, creeping, solifluction and water saturation by rainfall and snow melt, often with close interrelationship with vegetation. Therefore, it is possible differentiate the altitudinal distribution of landforms.



FI, freeze Index. F/Tc, freeze/thaw cycles. Nd, number of days. Tg, ground temperature. Ta, air temperatures. MAAT, mean annual air temperature

Figure 9. Environments, thermal regime, processes and active landforms in PE.

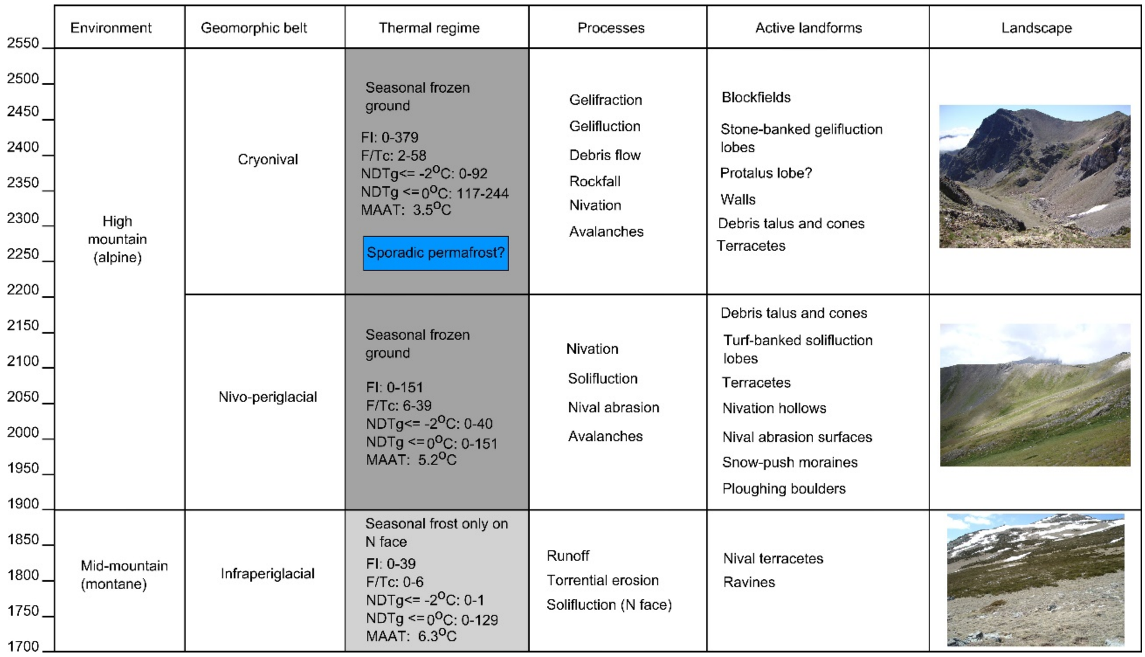


Figure 10. Environments, thermal regime, processes and active landforms in FC.

The **debris talus and cones** are one of the fastest sediment transfer in both massifs. They develop at an altitudinal range between 1800 m. and the peaks, although in some exceptional occasions they develop as low as 1200 m. Their exact location is very much directed by tectonics for the lowest ones, which are usually located under fault scarps (Serrano and González-Trueba, 2004; González-Trueba, 2007; González-Trueba and Serrano, 2010b; González-Trueba et al. 2012; Serrano et al. 2014). Over 2000 m. talus locate preferentially on N faces, and they are fed by frost shattered clasts, debris flows and avalanches (Serrano and González-Trueba, 2004, Serrano et al. 2014). The vertical development of these landforms is quite varied, between 100 and 900 meters.

The snow patches are snow accumulations that melt between June and August, and they can even endure the summer. They are located usually on glacio-karstic depressions or glacial tarns. Due to their specific thermal regime, water saturation and slow ground creep, they form a complete array of singular landforms. **Nivation hollows** are created by snow creep and snow-melt runoff, in a context where persistent snow mantle also prevents plant colonization to happen. We can also find protalus ramparts **and snow-push moraines** at the foot of patches. **Protalus ramparts** are originated by the slide of material along the snow-patch and its accumulation at the foot, whereas **snow-push moraines form also** by rock pucliking and polishing at the foot of the snow-patch and subsequent transport at the foot of an unstable snow mantle (Kirkbride 2015). Nivation hollows and snow-push moraines have been mapped in PE between 1900 and 2400 m. (González-Trueba

2007), although active landforms of this type are located over 2100 m. only on shadowed areas, being very active over 2400 m. In FC these landforms are found over 1900 m. and on slopes ~20º of inclination, also on N faces. Associated to these snow-push moraines there are also nival stone pavements and snow polished bedrock, with striate and partly detached material (Fig. 11). These landforms show a snow mantle basal drag on the bedrock.

The debris lobes and stone banked solifluction lobes are coarse grained regolith masses that flow down. Their size is <1 m deep, ~ 4 o 5 long and ~2 m wide, and they usually appear clustered in groups. In FC they are located mainly at the W face of Tres Provincias Peak over 2300 m. on a ~35º slope. Here, there is not a wall to provide material to the regolith, and the snow cover is never too thick due to wind-blow of snow, so frost can penetrate deep in the ground (table 3). Similar landforms can be found at the W, S and N slopes in Peña Prieta, over 2300 m. In PE these landforms can be found in Peña Vieja, over 2400 m, where displacements between 1.3 and 1.6 cm yr^{-1} have been measured (Brosche, 1994) and in Jou Negro on till at 2240 m. (González-Trueba, 2007; Serrano et al. 2011).

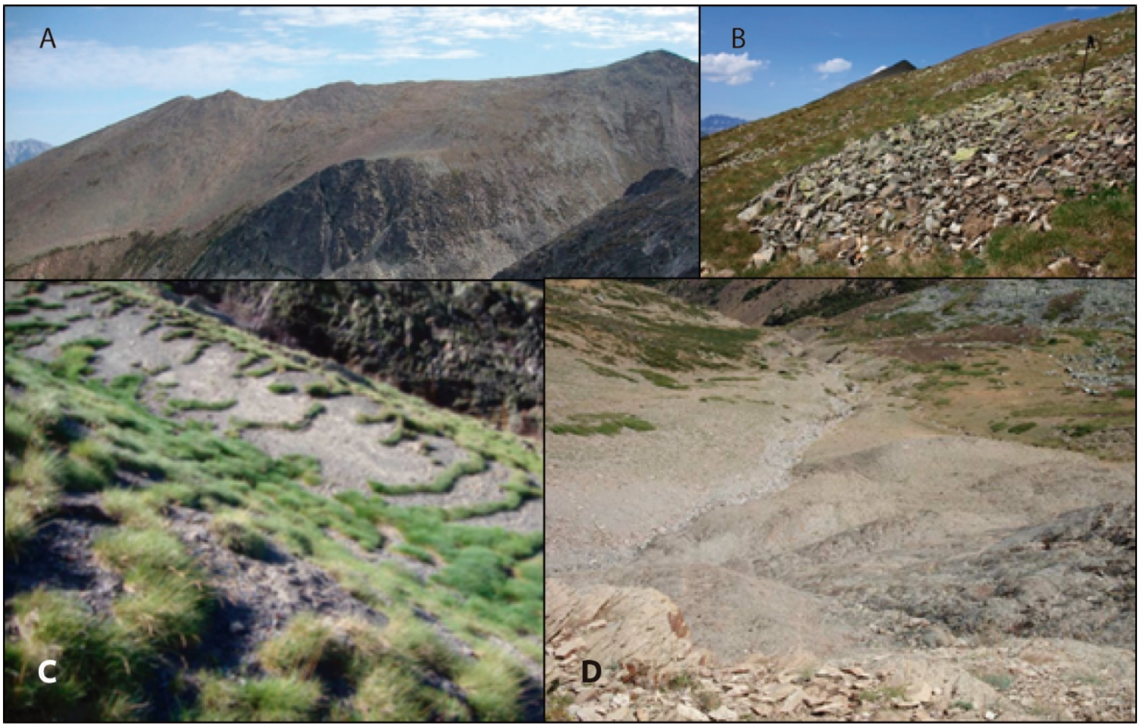


Figure 11. A) The W face of Tres Provincias peak, where the gelifluction lobes have developed. B) Stone banked solifluction lobe. The lobe front shows fresh material at its front, with not liquen-colonized clasts over fine-grained material and roots pulled downslope. C) Nival melt solifluction terraces versus right periglacial solifluction terraces. Scarce vegetation and a sufficient regolith is a must for their formation. Both terraces are formed on slate lithology. D) Snow abraded surface and snow-push moraine at a cirque around 2000 m. in FC

Landforms linked to solifluction: Fine grained, water saturated regolith is prone to solifluction, which is also conditioned by the snow cover, the ground thermal regime and the absence of vegetation (Brosche, 1978, 1994; González-Trueba, 2007). In PE solifluction processes have been measured to a range between 2.1 and y 18.8 mm yr^{-1} (Brosche, 1994). The **solifluction terraces** can be defined as decimetric steps on slopes where their front is turf-banked (usually *Festuca* gender turf), whereas the flat back is often vegetation free. Their vertical development is around 20 cm. step longitude is usually around a meter and the lateral development can attain several meters. Some terracettes are conversely related to long lasting snow patches, which inhibit the vegetation to grow and provoke solifluction on the snow melt season. These terracettes are longer and steeper than those formed by several F/Tc (Fig. 11). In PE they sit on slopes between 15º and 40º steep, on fine grained superficial formations, such as moraines, colluvium or debris talus, over 1500 m. In FC they are most ubiquitous periglacial landform over 1950 m. where the lithology allows the formation of a surface regolith with enough fine material (Fig. 11).

Ploughing boulders exist on slopes where large blocks move faster than the fine matrix, always in a context of water availability and fine grained regolith. This landform is scarce both in PE or FC, and usually it is linked to a slate or schist bedrock above 1700 m. Measured displacements are very low, between 8 y 14 mm yr^{-1} (measured with DGPS between 2008 y 2014 in Áliva area, PE by Sanjosé et al. 2016).

Fine banked lobes are metric to decametric solifluction lobes associated to a 30 – 40 cm. deep fine matrix regolith, also on shales, schist, till or sandstone. It is located on 20-25º slopes at an altitudinal range between 1500-1800 in PE and over 1900 m. in FC. The clayey regolith prevents water percolation, and once it is water saturated, especially at the end of the spring season, it starts to flow downslope. DGPS measurements in Áliva (PE.) between 2008 and 2014 show an average annual displacement lower than 2 cms. yr^{-1} (Sanjosé et al. 2016). These landforms are located at the transition between the highest portion of the mid-mountain belt and the high mountain, in a pasturage landscape just over the treeline.

Patterned ground: Circles and stripes are located in plain areas with a fine grained regolith, mainly on karstic depressions or on debris and till formation. Stripes sizes are between 2-3 m in length and circles are between 40 and 150 cm wide. They are always located above 2200 m. Active patterned ground has been found PE at 2400 m in Peña Vieja, and semi-active ones at 2100 m (Brosche, 1994; González-Trueba, 2007; Serrano and González-Trueba, 2011; Serrano et al. 2011). In FC active patterned grounds has not been found.

Frost mounds are the rarest periglacial landform in the Cantabrian Mountains. They can only be found in the debris generated by a slide of the Little Ice Age moraine on the Jou Negro relict ice-patch at 2200 meters in PE. These frost mounds have been preserved during at least the last twenty years, and they are located on a deposit where an ice core has been found beneath (González-Trueba, 2007; González-Trueba et al, 2012; Serrano et al. 2011). They have been attributed to the melt water flow on the ice patch and segregation ice growth on the supra-ice debris, therefore they are not related to atmospheric conditions.

4. Discussion

Correlation between altitude and Tg is not strong. The described annual thermal phases do not happen uniformly as a function of altitude, due to topoclimatic factors such as solar radiation, snow redistribution and the existence of buried ice bodies (Pisabarro et al. 2015). Nevertheless, nivation effect is present on the ground thermal regime at any height over 2200 m. mostly restricting the F/Tc by the zero curtain effect at the base of the snow mantle. This determines geomorphological processes in the high mountain belt of the Cantabrian Mountains. As a morphological agent, snow is responsible for the nival karst, snow accumulation landforms at the proximity of snow patches and solifluction, in PE as low as 1400 m. Solifluction sheets, long-shaped terracettes and some turf-banked solifluction lobes are a consequence of nival fusion and the subsequent water saturation of the regolith. Protalus ramparts, snow-push moraines, stone pavements and nivation hollows are conversely generated by material dragging and accumulation at the foot of snow-patches.

Below 1900 m. the number of F/Tc is much reduced, because of high temperatures and the snow mantle protection during winter; moreover, none of the thermometers registered temperatures below -2ºC. Nevertheless, in Áliva (PE, 1700 m.), solifluction on slopes is active or has been active recently. Solifluction lobes and ploughing boulders, always genetically associated to laminar solifluction (Ballantyne, 2001, Berthling et al., 2001) are found here. Solifluction lobes depend on an array of climatic, hydrologic, geologic and topographic factors (e.g. slope, land cover, soil moisture or snow cover depth and duration or soil thermal regime) (Matsuoka, 2001; Oliva et al. 2009, Oliva and Gómez-Ortíz, 2011). Often they associated to some extent with F/Tc (French, 2007), however, in Áliva the thermal record points denote an absence of them. We offer two interpretations for these landforms: either they are inherited, given their displacement is 14 mm yr^{-1} for the ploughing boulders and 5 mm yr^{-1} for the lobes, or originated by spring snowmelt in a water saturated environment. The fine material abundance in the regolith, and human-induced deforestation and overgrazing might play their role in this process.

Above 1900 m. the thermal environment is defined by a strong disparity between Tg and Ta. The F/Tc at this altitude are moderate and the FI can reach 461 in PE and 360 in FC. The ground keeps below 0ºC up to 3 months, with a month of temperatures below -2 ºC in PE. In FC the inter-annual differences are large depending on the snowfall and the atmospheric temperature regime. The existence of SFG can be associated to the existence of solifluction lobes in slopes and debris cones, ploughing boulders and turf-banked solifluction lobes.

Screes and debris cones show a distinctive pattern depending on their altitude, orientation and pervious tectonic shattering of the rock. An intense previous rock weakening enhances the thermally driven processes on the walls, such as frost or thermal shattering. Ice effectiveness increases at the highest portions of screes and debris cones.

The ground thermal data shows a highly variable snow cover in FC between 2009 and 2011 (Fig. 8) which involves in turn a high thermal regime variability, with snowmelt and runoff during winter. South oriented slopes do not have active periglacial landforms below 2100 m. West oriented slopes combine a lower solar radiation and the snow blow-out, so winter atmospheric frost is more intense, able to penetrate deeper in the regolith, and F/Tc are also more abundant. Here, terracettes, blockfields and gelifluction lobes are most extensively developed. North oriented slopes usually maintain a thick snow mantle, which protects it from thermal oscillations. Here we found mostly of the snow-patches and their associated landforms.

In general, over 2200 meters the FI is between 360-400, getting more than 430 at around 2500 m assuring the SFG because is surpassed a FI value of 360, which is considered as a SFG indicator (Fraunfeld et al. 2007). At this belt, the ground keeps four months below 0ºC, one of them below -2ºC. MAAT is here moderately cold (2ºC) with an MAAT <0ºC only over 2500 m. At N and E slopes over 2200 m. the snow mantle prevents an intense frost except in exposed areas. Nevertheless, out of protected areas frost penetration is deep, and we can find blockfields and gelifluction lobes, as per example near Peña Prieta, the highest peak in FC (Pellitero et al. 2013).

There is a large inter-annual disparity in the ground thermal regime, which reflects the different atmospheric dynamics along the year. Wet winters, as in 2009/10, entail a lower thermal stress on the ground, because snow cover protects it through the curtain-effect. Dry years, as in 2010/11, conversely generate a higher thermal stress on the ground, with more F/Tc and deeper thermal oscillations. Grounds at the peak can suffer a total snow blow-out and therefore get a deep freeze. Permafrost on the regolith can be ruled out in FC and almost certainly in PE, except in the latter case from inherited ice-patches (Jou Negro, Trasllambrión, Palanca and Forcadona) and frozen caves, which can be considered a subaerial permafrost (Gómez-Lende, 2015).

5. Conclusions

The snow cover control is the main geomorphological factor for periglacial processes in the Cantabrian Mountains because the wave of cold is blocked. This factor aided by other topoclimatic factors (aspect, radiation, slopes, convective movements, wind, and superficial deposits) are the key to characterize the ground thermal regime and a geoecological belt in a wet and temperate high mountain. In PE, limestone lithology makes easy the irradiation of cold from ice bodies beneath and the permafrost formation, but the general lack of soil and regolith inhibits the formation of solifluction landforms. In Fuentes Carrionas, the more impermeable lithologies (conglomerates, granites, sandstones and turbidites) and fine-grained superficial deposits permits the formation of periglacial features, which are widespread over 2000 meters.

Both massifs have a correlation between days <0º C and their altitude. However this correlation does not exist with days below -2ºC. The buried and surface iced bodies in PE is the cause for abnormal low temperatures in some selected locations. In others, the snow cover prevents the ground temperatures to go lower than 0ºC. Therefore, there is not altitudinal gradient of ground minimal temperatures above 1700 – 1800 m. Topoclimatic factors explain both the minimum temperature and the SFG. The maximum depth of SFG is close to 0.7 m, a magnitude order similar to the vertical active periglacial landforms over 2100 m. like frost mounds and gelifluction lobes. Such a SFG is achieved only on the mentioned ice-patches in PE and on exposed (W face and unsheltered N locations) soils over 2400 m. in FC, where the minimum temperatures are also lowest and the snow cover is not continuous or deep. The most active periglacial processes, associated to the gelifluction and frost-heave, are also generated at these locations. Between 2400 and 1900 meters the slope dynamics is ruled by the combination of freeze/thaw cycles (most common at the W aspects) and snowmelt (on E and N aspects). Below 1900 m. the ice influence on the ground is negligible. Solifluction landforms at this height have no relation with freeze/thaw cycles, but with spring snowmelt.

November and December are the months with most F/Tc, with 41% of the total annual cycles. This is due to the arrival of cold artic air without the protection of a snow mantle on the ground, so the cycles are generalized at all orientations. At this point steep temperature gradients are also present, as well as daily thermal amplitudes over 5 ºC. This is a moment for intensification of periglacial processes. This behaviour can extend into the winter and even early spring on exceptionally dry years, but gives way to the winter and spring regime, in which the snow cover imposes a thermal equilibrium around 0ºC with located values below -2ºC and a general SFG over 1900 m. in PE and 2000 m. in FC. Spring snowmelt and defrost reactivates periglacial and nival processes and affects to a shallow soil or regolith layer between 0.3 and 0.7 m. depth.

The active periglacial landforms created by the morphogenetic process in the superficial layer are distributed following topoclimatic factors, being the SFG and the F/Tc relevant indicatives of them (Fig.12). Some landforms are included clearly in the SFG altitudinal belt, but others like debris talus and cones, terracetes, fine lobes, ploughing boulders have not directly relationship with the ground temperatures (Fig.12).

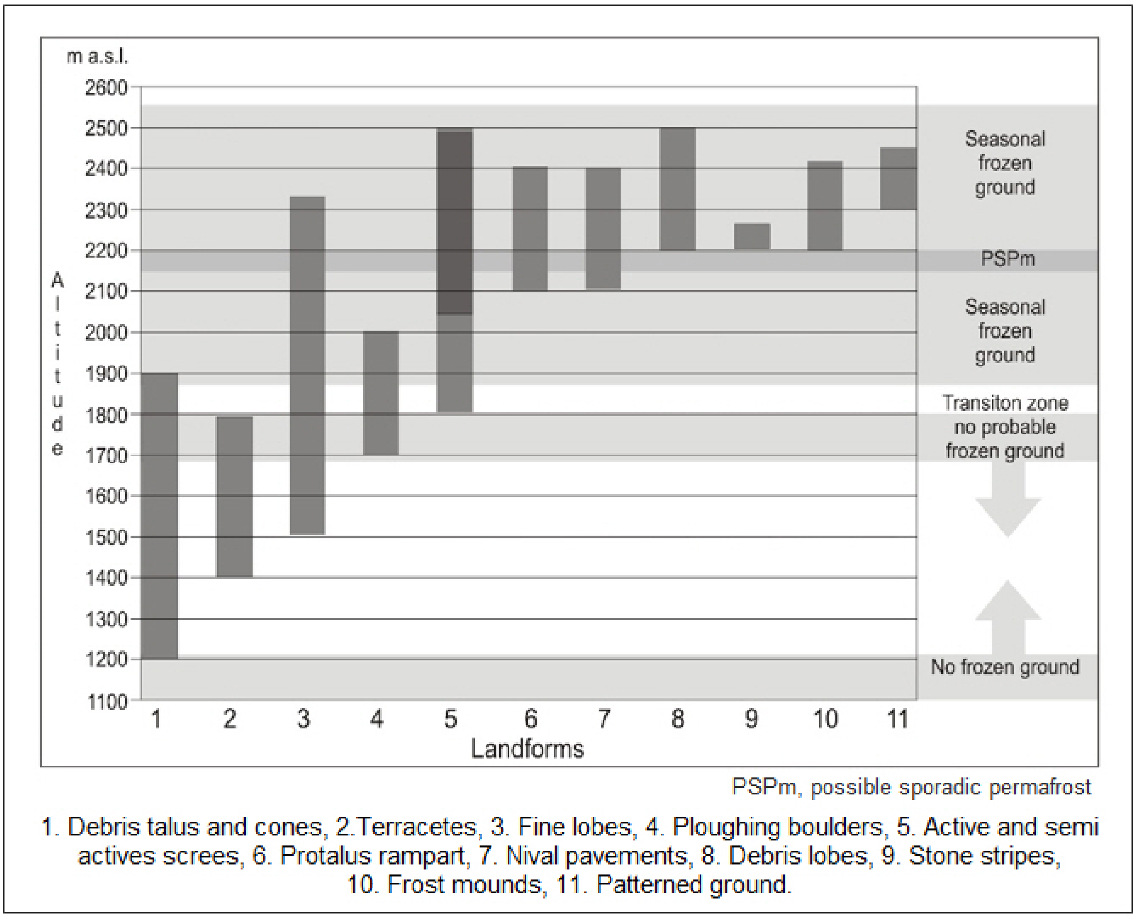


Figure 12. Altitudinal distribution of environment, ground ice, landforms and processes in the Picos de Europa.

Overall, the nival and periglacial geomorphological processes are exceptional in the Cantabrian Mountains high mountain, and they are only located in climatically favourable locations. In PE they are mostly related to relict ice masses, or inherited from the colder Little Ice Age. In FC periglacial processes are active on exposed slopes over 2000 m., whereas snow-related processes are predominant on the N and E face, where freeze/thaw cycles are limited to autumn cycles and spring snowmelt.

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