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Long-term soil temperature dynamics in the Sierra Nevada, Spain

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ABSTRACT

Soil temperatures play a key role on the dynamics of geomorphological processes in periglacial environments. However, little is known about soil thermal dynamics in periglacial environments of semiarid mid-latitude mountains, where seasonal frost is dominant.
From September 2006 to August 2012 we have monitored soil temperatures at different depths (2, 10, 20, 50 and 100 cm) in a solifluction landform located at 3005 m.a.s.l. in the summit area of the Sierra Nevada (South Spain). Mean annual temperatures in the first meter of the soil ranged from 3.6 to 3.9 °C while the mean annual air temperature at the nearby Veleta peak was 0.08 °C. Therefore, these data point out the inexistence of widespread permafrost conditions today in this massif. Seasonal frost controls the geomorphodynamics even in the highest lands. Climate conditions have shown a large interannual variability, as it is characteristic in a high mountainous Mediterranean environment. These variations are reflected in the patterns of soil thermal dynamics. The depth and duration of the frozen layer are strongly conditioned by the thickness of the snow cover. The date of the first significant snowfalls conditioned the beginning and rhythm of freezing of the soil. Wet years resulted in a thick snow cover which insulated the ground from external climate oscillations and favored a shallow frost layer (2008–2009, 2009–2010 and 2010–2011). On the other hand, years with low precipitations promoted deeper freezing of the soil down to 60–70 cm extending until late May or early June (2006–2007, 2007–2008 and 2011–2012). When snow melted a high increase of temperatures of 10–12 °C in few weeks was recorded at all depths. At this time of the year, periglacial activity is enhanced due to higher water availability and the existence of freeze–thaw cycles. These were recorded mostly in spring and autumn in the first 50 cm depth of the soil, ranging from 9.8 days (at 2 cm) to 3.7 days (at 50 cm).
However, the inactivity of solifluction landforms suggests that the combination of present-day soil temperatures together with moisture conditions is not favorable to promote solifluction activity in the periglacial belt of the Sierra Nevada.
Future climate scenarios point to a temperature increase and precipitation decrease in the area, which would entail deeper but shorter frozen soil layers. These conditions would not be favorable for active periglacial slope processes in the Sierra Nevada.

1. Introduction

The research on soil thermal regime in periglacial environments has developed substantially over the last decades. In many periglacial regions the air temperature increase recorded since the late 70s has impacted, to a greater or lesser extent, the soil temperatures (e.g. Romanovsky et al., 2010a). In the current context of future climate uncertainty, an accurate knowledge of present-day soil thermal dynamics is essential for understanding how ecosystems in periglacial environments may react to shifting climate scenarios. Thus, the areas where permafrost is present, albeit in slightly negative values, are those most likely to be affected by soil thawing. A change of the state in soil conditions can affect the network of infrastructures, equipments and human settlements spread over permafrost areas, as well as the dynamics of geomorphological processes (Nelson et al., 2002).

Since the International Polar Year 2007–2008, research focused on soil thermal regimes in permafrost environments has been channeled through international initiatives which aim to monitor its thermal state and active layer dynamics (i.e. Global Terrestrial Network for Permafrost, Circumpolar Active Layer Monitoring). The most significant studies have been carried out in wide parts of the Arctic, where the

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thermal increase has been more pronounced in areas with cold permafrost than in those with warm permafrost (Christiansen et al., 2010; Romanovsky et al., 2010a,b). However, this trend has not been observed in Antarctica, despite the limited spatial and temporal coverage of the existing series (Vieira et al., 2010).

Regarding other periglacial environments, research has focused mainly on the monitoring of the thermal evolution of the soil in mid-latitude mountain regions with presence of permafrost (Gruber and Haeberli, 2009; Harris et al., 2009; Luetschg et al., 2004). Recently there has been an increasing interest in understanding the role of snow, altitude, aspect, lithology and vegetation on the freezing and thawing of the soil in areas of the periglacial belt in wet mid-latitude mountain ranges without continuous permafrost conditions (Gądek and Leszkiewicz, 2010; Ishikawa, 2003; Löffler et al., 2006; Takahashi, 2005; Zhang, 2005). However, little attention has been addressed to the comprehension of the factors controlling soil thermal dynamics in periglacial environments of semiarid mid-latitude mountains, as in the Mediterranean area.

In this research context, Mediterranean mountains emerge as areas of particular interest when studying the possible variations of soil temperatures, since future climate projections for the Mediterranean basin point to lower precipitations and an increase of air temperatures significantly higher than the expected for other mid-latitude environments (EEA, 2008; IPCC, 2007). This climate scenario may trigger important feedback processes in Mediterranean high mountain ecosystems: changes in the type and density of vegetation, variations of sediment production, changes of the prevailing geomorphological processes, etc. Therefore, in order to understand the potential implications in these environments, an accurate knowledge of current soil thermal regime under present-day climate conditions is needed.

Nowadays, in the highest mountains of the Iberian Peninsula there are only a few areas with marginal permafrost conditions, namely the Pyrenees (Lugon et al., 2004; Serrano et al., 2001, 2006), probably the Cantabrian Range (Ruiz Fernández, 2012) and the Sierra Nevada (Gómez Ortiz et al., 2001). The majority of the studies were conducted in areas of seasonal frozen soil, such as Serra da Estrela (Vieira et al., 2003), Guadarrama (Andrés and Palacios, 2010), Ancares (Carrera and Valcárcel, 2010) and other sites at lower elevations at the Cantabrian Range (González Trueba and Serrano, 2010; Santos-González et al., 2009).

The Sierra Nevada, in the Southeast of the Iberian Peninsula, concentrates the southernmost permafrost conditions in Europe and widespread seasonal frost conditions (Gómez Ortiz et al., 2004). The present research complements previous studies that have been carried out in the massif over the last decades focused on: (a) Monitoring of contemporary cold geomorphological processes (Gómez Ortiz et al., 2001, 2004, 2012; Oliva et al., 2009), and (b) reconstructing past environmental conditions (Oliva and Gómez Ortiz, 2012; Oliva et al., 2009, 2011).

This paper focuses on the ground thermal monitoring during a period of six years in a solifluction landform located at the headwaters of the Rio Seco cirque, in the southern slope of the Sierra Nevada. The specific objectives of this paper are:

- To analyze the thermal regime of the ground at the highest summits of the Iberian Peninsula, above 3000 m, considering the longest soil temperature record for an Iberian massif.
- To identify the role of snow in the thermal insulation of the soil in a semiarid environment characterized by a strong annual and interannual climate variability.
- To discuss the implications that ground thermal dynamics may have in contemporary and future periglacial geomorphological processes.

2. Study area

The Sierra Nevada is the highest massif of the Betic Range and of the entire Iberian Peninsula at 37°N latitude and 3°W longitude. The study area is located along the axial axis of the massif (Fig. 1), where peaks exceed 3300 m in its western fringe (Mulhacén, 3478 m; Veleta, 3398 m). The Sierra Nevada was declared a National Park in 1999 due to its natural resources, scenic and cultural–historical values (Gómez Ortiz et al., 2013a,b).

Geographically, the Sierra Nevada shows the typical characteristics of a high semiarid Mediterranean mountain environment. In the high lands climate conditions are characterized by a duality between the wet and cold season of the year (October to May) and the warmer and dryer one (June to September). The only meteorological station in the high lands (2507 m) reports a mean annual temperature of 4.4 °C and a total precipitation of 710 mm. The highest evapotranspiration rates prevail during the summer months conditioning the extremely low vegetation cover of the high valleys and the summit area (Oliva, 2009).

The lithology is characterized by the dominance of crystalline rocks, particularly micaschists. Periglacial processes are widespread above 2500 m (Gómez Ortiz, 2002), which coincides with the lower limit of the glaciated surfaces during the Last Glaciation. The deglaciation of the Sierra Nevada was a rapid process: since 14,000–15,000 year cal BP the massif remains almost ice-free (Gómez Ortiz et al., 2012), despite the reappearance of small glaciers during Holocene cold phases in the highest northern cirques (Oliva and Gómez Ortiz, 2012).

A wide range of glacial (overdeepened basins, moraines, polished bedrock, glacial stripes) and periglacial landforms (rock glaciers, solifluction lobes, nevé moraines, debris flows) are spread across the glacial cirque of Rio Seco. Soils are poorly developed inside the cirques (Cambisols, Inceptisols and Regosols; Martín García et al., 2004), whereas Histosols are developed in poorly drained areas with greater water availability. In the scarce vegetated areas of Rio Seco (1.6% of total surface), tens of solifluidal geoforms are distributed; some of them have been monitored in previous studies with the purpose of measuring solifluction displacement rates (Oliva, 2009; Oliva et al., 2009).

The solifluction lobe studied in this paper is located at 3005 m (Table 1). It has a sparse herbaceous vegetation cover on it, consisting mainly of grasses and festuca (Molero Mesa and Pérez Raya, 1987). The sediments are composed of silts and sands, with subangular gravels (up to 10 cm at the long axis) at 70–100 cm depth (Fig. 2). This layer corresponds to a Cambisol, while the upper layer is classified as a Regosol. The base of this lobe (at 90 cm depth) was radiocarbon dated at 12,973 ± 112 year cal BP. Cosmogenic datings of the polished bedrock in the cirque floor also confirmed that even during the Younger Dryas cold period the headwaters of this valley remained ice-free (Gómez Ortiz et al., 2012; Oliva, 2009). Therefore, this solifluction lobe probably developed during the Holocene.

3. Materials and methods

The thermal control of the soil was carried out by means of the installation of UTL-1 devices (Universal Temperature Loggers, GEOTEST) at depths of 2, 10, 20, 50 and 100 cm. The accuracy of the loggers is ±0.23 °C. Data were automatically recorded every 2 h from September 2006 to August 2012 (Fig. 2), with batteries being replaced annually. The 2-cm logger was damaged during the 2006–2007 campaign, with no data for this period.

The reference for air temperature for the same period corresponds to a UTL-1 installed in the summit of the Veleta peak (3398 m), located solely 1.5 km away from the soil monitoring point in Rio Seco. The logger recorded air temperatures at 2 h interval. However, it failed during three brief periods; no data is available between 1/09/2007 and 31/10/2007, 31/01/2008 and 28/02/2008 and 1/09/2011 and 30/09/2011.

Taking into account air and 2 cm depth soil temperature records, freezing degree-days were calculated for each year from November to May in order to characterize the role of snow as a thermal insulator of the ground during the cold season (Frauenfeld et al., 2007).

Due to the lack of data of the snowpack in the upper parts of the massif, precipitation records from the neighboring city of Granada (~15 km away) were used as an indirect estimation of snow fall for