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Inexistence of permafrost at the top of the Veleta peak (Sierra Nevada, Spain)

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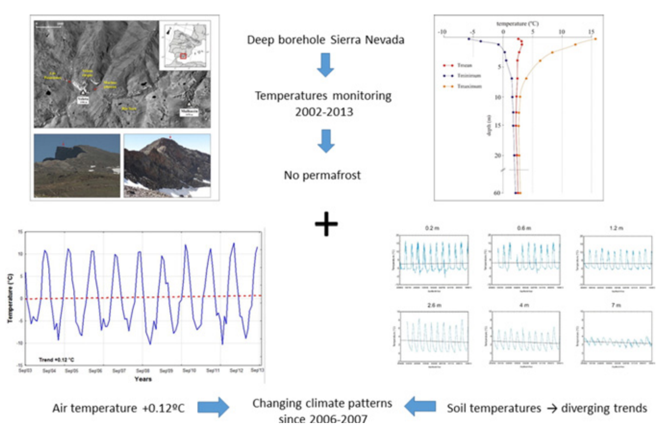
HIGHLIGHTS

- We analyse air and bedrock temperatures at the Veleta peak between 2002 and 2013.
- Temperatures down to 60 m depth showed no permafrost, with values between 2.3 and 3.2 °C
- Ground temperatures showed a large interannual variability influenced by snow cover.
- Air temperatures detect a 0.12 °C increase at the Veleta peak between 2002 and 2013.
- Different ground thermal dynamics at depth suggests changing climate patterns.

GRAPHICAL ABSTRACT



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ABSTRACT

A 114.5 m deep drilling was carried out in August 2000 in the bedrock of the Veleta peak, at 3380 m in the massif of Sierra Nevada, Southern Spain. The objective of this work is to analyse temperatures at the first 60 m depth of this drilling from September 2002 to August 2013 based on 11 UTL-1 thermal loggers located at different depths, together with air temperatures at the summit of the Veleta peak. Permanent negative temperatures have not been detected in the borehole, which shows evidence of the absence of widespread permafrost conditions nowadays in the highest lands of this massif. Bedrock temperatures oscillated between 3.2 °C at 0.6 m depth and 2 °C at 20 m below the surface. The largest temperature ranges were recorded on the most external sensors until 1.2 m depth, where values reached 22.3 °C. Seasonal temperature variations were significant until 10 m depth. The thickness of the seasonal frozen layer was highly variable (0.6–2 m) and dependent on annual climate conditions. The mean air temperature at the Veleta peak increased by 0.12 °C during the study period. Bedrock temperatures followed diverging trends: a drop of 0.3–0.4 °C down to 0.6 m depth, a decrease of up to 0.7 °C between 4 and 10 m, thermal stability at 20 m and a rise of 0.2 °C that occurred in 2009 at the deepest sensor at

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Permafrost
Seasonal frost
Climate variability

60 m. The calculation of the thermal wave damping in the subsoil of the Veleta peak has allowed for quantifying the thermal diffusivity of the rock as $(7.05 \pm 0.03)10^{-7}$ m^2/s, which means that the external climate signal arrives with an 8.5-year lag to the sensor at 60 m deep. This allows to deduce a trend change in the climate of the area, moving from warmer conditions towards a trend of cooling from 2006 to 2007.

1. Introduction

Mediterranean high-mountain ecosystems are particularly sensitive environments to climate dynamics. In these areas, slight oscillations in temperature and/or humidity can lead to significant impacts in the dynamics of natural systems, in particular in geomorphic, hydrologic and soil processes (Oliva, 2009), as well as in the distribution of flora and fauna (Pauli et al., 2012).

This study focuses on the massif of Sierra Nevada, straddling the subtropical high-pressure belt and the mid-latitude westerlies in the South of the Iberian Peninsula. The warming recorded in this massif since the last cold pulse of the Little Ice Age (LIA) at the end of the 19th century is estimated at around 0.93 °C (Oliva and Gómez-Ortiz, 2012). The impact of the post-LIA temperature rise in European alpine mountain ranges is evidenced by glacial retreat (Zumbühl et al., 2008; González-Trueba et al., 2008), alpine permafrost degradation (Harris et al., 2003; Gruber et al., 2004; Lugon et al., 2004; Zenklusen-Mutter et al., 2010), increased activity of paraglacial processes (Cossart and Fort, 2008), altitudinal rise of the periglacial belt (Veit, 1993; Veit and Höfner, 1993) or in the upward migration of plant species (Huelber et al., 2006). In Sierra Nevada, previous studies showed how the impact of rising temperatures led to the disappearance of the southernmost glacial spots in the European continent (Gómez-Ortiz et al., 2001), conditioning an elevation rise of the periglacial domain and of the late-melting snow fields (Oliva et al., 2011), and a migration in altitude of the plant species adapted to the cold (Pauli et al., 2012). The previous research carried out in Sierra Nevada focusing on fossil ice and permafrost degradation was pioneer in the context of high mountains in southern Europe, highlighting the permafrost control on geomorphodynamics in recently deglaciated alpine areas (Gómez-Ortiz et al., 2001).

At present, permafrost conditions have been only detected in the highest northern cirques of Sierra Nevada, namely in the Veleta cirque at 3150 m above sea level (Tanarro et al., 2001; Salvador-Franch et al., 2011; Gómez-Ortiz et al., 2014a). However, the frozen ground is undergoing a process of degradation as a result of the temperature increase recorded in the south of the Iberian Peninsula during the last few decades (Bladé and Castro-Díez, 2010). Permanently negative soil temperatures have not been found in other areas of Sierra Nevada, such as in the southern cirque of Rio Seco, at 3005 m (Oliva et al., 2014c), or in the summit plateau of the Cerro de los Machos, at 3327 m (Salvador-Franch et al., 2012), where the average annual temperatures in the first decimetres of the soil ranged between 1.7 °C and 3.9 °C.

Subsurface temperatures exercise decisive control over the prevailing geomorphological processes in periglacial mountain environments, particularly in permafrost areas (Haeberli et al., 2010). The monitoring of underground temperatures in deep boreholes enables to detect relative variations in past climate dynamics, as well as tracing the impact that the recent climate evolution is having on the rock thermal conditions. In this context, the project Permafrost and Climate Change in Europe (PACE) promoted the drilling of a series of deep boreholes in different areas of a north–south latitudinal transect linking Svalbard (78 °N) with Sierra Nevada (37 °N) in order to better determine the spatial distribution and thermal evolution of permafrost in Europe.

In 2000 a 114.5 m deep borehole was drilled in the highest lands of Sierra Nevada, at the Veleta peak. The objective of this work is to analyse the thermal data collected from this borehole from September 2002 to August 2013. The aims of this study are the following:

- Characterise the seasonal and annual temperature dynamics in the bedrock of the Veleta peak together with air temperatures throughout the control period.
- Discuss the local factors that may control the ground thermal regime (e.g. topography, snow cover).
- Infer the thermal evolution of the bedrock temperatures in the first 60 m depth during the control period.
- Determine if the air and soil temperature trends in the summits of the highest massif in southern Europe followed the regional and global climate patterns observed in recent years.

2. Study area

Sierra Nevada is a high massif of the semi-arid Mediterranean mountain ranges located in the SE tip of the Iberian Peninsula, between 36° 55′ and 37° 15 N latitude and 2° 56′ and 3° 38′ E longitude. The highest summits of the massif exceed 3000 m in its western part, with the Mulhacén (3478 m) and Veleta (3398 m) being its highest peaks, as well as the most elevated peaks of the Iberian Peninsula.

Current climate conditions in Sierra Nevada are characterised by a marked seasonality, between the warm and dry season from May to September and the cold and wet season from October to April. The only high-altitude observatory (2507 m) showed an average annual temperature of 4.4 °C and a precipitation of 710 mm for the observation period from 1965 to 1992.

The present landscape of Sierra Nevada is consequence of Quaternary climate fluctuations that shaped the highest sectors of this massif through glacial and periglacial morphodynamics (Oliva et al., 2014a), as in other high mountains of the Mediterranean basin (Hughes and Woodward, 2008). The maximum expansion of the ice during the Last Glaciation occurred at 30–32 ka, with a readvance around 19–20 ka before the onset of the deglaciation of the massif that was completed at 14–15 ka (Gómez-Ortiz et al., 2012). Since then, periglacial processes control the geomorphological processes in the high lands of the massif, despite a brief reappearance of small glaciers in the highest northern cirques during the Holocene, at around 2.8–2.7, 1.4–1.2 cal year BP and 510–240 cal year BP (Oliva and Gómez-Ortiz, 2012).

The Veleta peak is a rocky monolith situated in the western fringe of this massif, between the Cerro de los Machos and Las Posiciones (Fig. 1). It is included in the periglacial belt of Sierra Nevada that currently extends above 2500–2600 m, where vegetation is sparse in an open disposition. A carved series of mica schists and quartzites makes up a vertical drop of over 300 m on its northern face, in contrast to its less pronounced southern and western sides. This morphology is due to the combination of past glacial activity and of post-glacial periglacial processes. The rock fissuring and cracks existing in the northern wall of the Veleta peak (enhanced by post-glacial decompression) favour the physical weathering of the bedrock. During the Quaternary glacial periods the Veleta peak must have been a horn, standing above the heads of the different glacial valley systems. On its northern slope is the Veleta cirque, forming a bowl-shaped hollow mostly covered by scree from the destruction of the walls of the cirque. It is closed by a