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Accelerated wastage of the Monte Perdido Glacier in the Spanish Pyrenees during recent stationary climatic conditions

J. I. López-Moreno[1], J. Revuelto[1], I. Rico[2], J. Chueca-Cía[3], A. Julián[3], A. Serreta[4], E. Serrano[5], S. M. Vicente-Serrano[1], C. Azorín-Molina[1], E. Alonso-González[1], and J. M. García-Ruiz[1]

[1]Dept. Geoenvironmental Processes and Global Change, Pyrenean Institute of Ecology, CSIC, Campus de Aula Dei, P.O. Box 13.034, 50080 Zaragoza, Spain
[2]University of the Basque Country, Department of Geography, Prehistory and Archeology, Vitoria, Spain
[3]Dept. Geography, University of Zaragoza, Zaragoza, Spain
[4]Dept. Graphic Design and Engineering, University of Zaragoza, Huesca, Spain
[5]Dep. Geography, University of Valladolid, Valladolid, Spain

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Correspondence to: J. I. López-Moreno (nlopez@ipe.csic.es)

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Abstract

This paper analyzes the evolution of the Monte Perdido Glacier, the third largest glacier of the Pyrenees, from 1981 to the present. We assessed the evolution of the glacier's surface area by use of aerial photographs from 1981, 1999, and 2006, and changes in ice volume by geodetic methods with digital elevation models (DEMs) generated from topographic maps (1981 and 1999), airborne LIDAR (2010) and terrestrial laser scanning (TLS, 2011, 2012, 2013, and 2014). We interpreted the changes in the glacier based on climate data from a nearby meteorological station. The results indicate an accelerated degradation of this glacier after 2000, with a rate of ice surface loss that was almost three-times greater from 2000 to 2006 than for earlier periods, and a doubling of the rate of ice volume loss from 1999 to 2010 (the ice depth decreased 8.98 ± 1.8 m, -0.72 ± 0.14 m w.e. yr^{-1}) compared to 1981 to 1999 (the ice depth decreased 8.35 ± 2.12 m, -0.39 ± 0.1 m w.e. yr^{-1}). This loss of glacial ice has continued from 2011 to 2014 (the ice depth decreased 2.1 ± 0.4 m, -0.64 ± 0.36 m w.e. yr^{-1}). Local climatic changes during the study period cannot explain the acceleration in wastage rate of this glacier, because local precipitation and snow accumulation increased slightly, and local air temperature during the ablation period did not significantly increase. The accelerated degradation of this glacier in recent years can be explained by the lack of equilibrium between the glacier and the current climatic conditions. In particular, the average air temperature increased by at least 0.9 °C in this region since the end of the Little Ice Age (LIA) in the mid-1800s. Thus, this glacier shrinks dramatically during years with low accumulation or high air temperatures during the ablation season, but cannot recover during years with high accumulation or low air temperatures during the ablation season. The most recent TLS data support this interpretation. These data indicated that two consecutive markedly anomalous wet winters and cool summers (2012–13 and 2013–14) led to near zero mass balance conditions, with significant losses of ice in some areas. These anomalous periods could not counteract the dramatic shrinkage that occurred during the dry and warm period of 2011–2012.

1 Introduction

Most glaciers worldwide have undergone intense retreat since the end of the Little Ice Age (LIA) in the mid 19th century, as indicated by measurements of ice surface area and volume (Vincent et al., 2013; Marshall, 2014; Marzeion et al., 2014, 2015; Zemp et al., 2014). This trend has apparently accelerated in the last three decades (Serrano et al., 2011; Mernild et al., 2013; Carturan et al., 2013a; Gardent et al., 2014; López-Moreno et al., 2014). Thus, Marshall (2014) and Zemp et al. (2015) noted that loss of global glacier mass during the early 21st century exceeded that of any other decade studied. Several studies examined this phenomenon in Europe. In the French Alps, glacier shrinkage has accelerated since the 1960s, mainly in the 2000s (Gardent et al., 2014). In the Ötzal Alps (Austria), Abermann et al. (2009) calculated the loss of glacier area was 0.4 % $year^{-1}$ from 1969 to 1997 and 0.9 % yr^{-1} from 1997 to 2006. In the Central Italian Alps, Scotti et al. (2014) compared the period of 1860–1990 with 1990–2007 and reported an approximately 10-fold greater average annual decrease of glacier area during the more recent period. Carturan et al. (2013b) also studied the Italian Alps and found that the average rate of ice mass loss during the period 1980–2010 (-0.69 ± 0.12 m w.e. yr^{-1}) was about twice that for the period of 1933 to 1959. Over the same period (1980–2010), Fischer et al. (2015) calculated a very similar rate of ice mass loss for the Swiss Alps (-0.65 m w.e. yr^{-1}) that clearly exceed the values presented by Huss et al. (2010) for the 20th century (close to -0.25 m w.e. yr^{-1}). In the Sierra Nevada of southern Spain, the Veleta Glacier, which was reconstructed during the LIA, disappeared as a white glacier during the mid 20th century and became a glacier-derived rock glacier with a marked degradation during the last two decades (Gómez-Ortiz et al., 2014).

The southern-most glaciers of Europe are in the Pyrenees, and they have also undergone significant deglaciation. In 2005, these glaciers had an area of 495 ha (González-Trueba et al., 2008) and in 2008 they had an area of 321 ha (René, 2013). Since 1880, the different massifs have had variable reductions in area covered by ice, with a 59%

reduction in the Vignemale Massif and an 84% reduction in the Posets-Llardana Massif (Gellatly et al., 1995; René, 2013). A total of 111 glaciers have disappeared in the Pyrenees from 1880 to 2005, and only 31 actual glaciers (with ice motion) remain. There has been a rapid glacial recession since the 1990s, and many of these glaciers face imminent extinction. Chueca et al. (2005, 2008) reported that the rates of glacial shrinkage during the last two decades of the 20th century and the beginning of the 21st century were similar to those observed from 1860 to 1900, immediately after the end of the LIA. A similar conclusion has been reached by Marti et al. (2015) for the Ossue Glacier (French Pyrenees).

Most studies agree that global warming is responsible for the observed glacier shrinkage and the recent acceleration of this shrinkage. The temperature increase has been particularly strong since the end of the LIA, and also since the 1970s in most mountain ranges of the world (Haeberli and Beniston, 1998; Beniston et al., 2003; Nogués-Bravo et al., 2008; Gardent et al., 2014). Global warming has increased the equilibrium line altitudes (ELAs) and reduced the accumulation ablation ratios (AARs) of glaciers, so that most glaciers are not in equilibrium with current climatic conditions (Mernild et al., 2013). In the case of the Pyrenees, the air temperature has increased at least 0.9 °C since the end of the LIA (Dessens and Bücher, 1998; Feulliet and Mercier, 2012), showing an increase of 0.2 °C decade^{-1} between 1951 and 2010 (Deaux et al., 2014). This explains the ~ 255 m increase in the elevation of the ELA in the glaciers of the Maladeta Massif, which is currently close to 2950 m a.s.l. (Chueca et al., 2005). The decreased accumulation of snow, and the increase in air temperature during the ablation season are thought to be the principal causes of recent glacier decline in the southern (Spanish) side of the Pyrenees (Chueca et al., 2005).

Glaciers are very good indicators of climate change due to their high sensitivity to anomalies in precipitation and air temperature (Carrivick and Brewer, 2004; Fischer et al., 2015). However, establishing a direct relationship between annual fluctuations of climate and the changes in area and mass of a particular glacier is difficult, because only glaciers of medium or small size respond rapidly to changes in annual snowfall and snow/ice melt, whereas large glaciers respond much more slowly (Marshall, 2014). Moreover, very small glaciers may develop and evolve for reasons unrelated to long-term monthly or seasonal climatic changes, such as avalanches and snow accumulation due to wind (Chueca et al., 2004; Serrano et al., 2011). Local topography also has a considerable effect on the development of ice bodies, and can cause notable variations in the ELAs of different glaciers in the same region (Reinwarth and Escher-Vetter, 1999; Carrivick and Brewer, 2004; López-Moreno et al., 2006). Moreover, many studies of recent changes in glaciers examined the evolution of glaciated surfaces or glacier lengths, parameters that respond to climate fluctuations, although this relationship is also explained by geometric adjustments (Haeberli, 1995; Carturan et al., 2013a). Thus, direct mass-balance estimations or geodetic methods that determine changes in ice volume provide better information on the relationship of changes in glaciers with changes in climate (Chueca et al., 2007; Cogley, 2009; Fischer et al., 2015). In the Pyrenees, there are very few estimations of lost ice volumes (Del Río et al., 2014; Sanjosé et al., 2014; Marti et al., 2015), although abundant research has examined recent changes of glaciated surface areas (Chueca et al., 2005; López-Moreno et al., 2006; González-Trueba et al., 2008). Annual estimates of glacier mass fluctuations based on glaciological method were only performed in the Maladeta Glacier (Spanish Pyrenees) and the Ossoue Glacier (French Pyrenees), and these indicated the mean loss of ice thickness was 14 m during the last 20 years in the Maladeta Glacier, and 22 m in the Ossoue Glacier (Arenillas et al., 2008; René, 2013; Marti et al., 2015). Other studies in the Spanish Pyrenees compared digital elevation models (DEMs) derived from topographic maps for 1981 and 1999 in the Maladeta Massif (Chueca et al., 2008) and the Monte Perdido Glacier (Julián and Chueca, 2007), and reported losses −0.36 and −0.39 m w.e. yr^{-1}, respectively.

This paper focuses in the recent evolution of the Monte Perdido Glacier, the third largest glacier in the Pyrenees. We document changes in the glacier surface area from 1981 to 2006 and provide updated information on volumetric changes by comparing DEMs derived from topographic maps of 1980 and 1999 (Julian and Chueca, 2007), a new DEM obtained in 2010 from Airborne LIDAR, and four successive Terrestrial Laser Scanning (TLS) runs that were performed during the autumns of 2011, 2012, 2013, and 2014. We examined these data along with data on precipitation, snow depth, and air temperature from the closest meteorological station. Identification of changes during recent years in this region is particularly important because in the 21st century snowfall accumulation has been higher and the temperatures slightly cooler than the last decades of the 20th, associated to persistent positive conditions of the North Atlantic Oscillation index (Vicente-Serrano et al., 2010; Buisan et al., 2015). Thus, the most recent response of the remnant ice bodies to this short climatic anomaly is as yet unknown. Moreover, the availability of annual TLS data in recent years permits detailed examination of the relationship between changes in climate and glaciers.

2 Study area and review of the previous research on the Monte Perdido glacier

The Monte Perdido Glacier is located in the Ordesa and Monte Perdido National Park (OMPNP) in the Central Spanish Pyrenees (Fig. 1). The ice masses are north-facing, lie on structural flats beneath the main summit of the Monte Perdido Peak (3355 m), and are surrounded by vertical cliffs of 500–800 m in height (García-Ruiz and Martí-Bono, 2002). At the base of the cliffs, the Cinca River flows directly from the glacier and the surrounding slopes, and has created a longitudinal west–east basin called the Marboré Cirque (5.8 km^2).

Researchers have studied glaciers in the Marboré Cirque since the mid 19th century (Schrader, 1874), and many next studies examined the extent and other characteristics of ice masses and the features of the moraines deposited during the LIA (Gómez de Llarena, 1936; Hernández-Pacheco and Vidal Box, 1946; Boyé, 1952). More recent studies have established the location of moraines to deduce the dynamics and extent of LIA glaciers (Nicolás, 1981, 1986; Martínez de Pisón and Arenillas, 1988; García Ruiz and Martí Bono, 2002; Martín Moreno, 2004) and have analyzed environmental changes during the Holocene through study of sediments in Marboré Lake

(Oliva-Urcia et al., 2013) and by dating of Holocene morainic deposits (García-Ruiz et al., 2014).

The map of Schrader (1874), numerous old photographs, and the location of the LIA moraines (García Ruiz and Martí Bono, 2002) indicate a unique glacier at the foot of the large north-facing wall of the Monte Perdido Massif (Monte Perdido, Cilindro and Marboré peaks) (Fig. 1). The map of Schrader (1874) distinguishes the Cilindro-Marboré Glacier, with three small ice tongues that joined in the headwall, from the Monte Perdido Glacier, which was divided into three stepped ice masses connected by serac falls until the mid 20th century. The glacier that existed at the lowest elevation was fed by snow and ice avalanches from the intermediate glacier, dissapeared after the 1970s (Nicolas, 1986; García-Ruiz et al., 2014). The two remaining glacier bodies, which are currently unconnected, are currently referred as the upper and lower Monte Perdido Glaciers. The glacier beneath the Cilindro and Marboré peaks has transformed into three small and isolated ice patches (García-Ruiz et al., 2014). It is noteworthy that Hernández-Pacheco and Vidal Box (1946) previously estimated a maximum ice thickness of 52 m for the upper glacier and 73 m for the lower glacier. In 2008, 82% of the ice cover at the end of the LIA had already disappeared. The upper and lower ice bodies have mean elevations of 3110 and 2885 m (Julián and Chueca, 2007). Despite the high elevation of the upper glacier, snow accumulation is limited due to the minimal avalanche activity over the ice body and its marked steepness ($\approx 40°$).

There has not been a direct estimation of the current location of the ELA in the upper Cinca valley, but studies at the end of the 20th and beginning of the 21st century placed it at about 2800 m in the Gállego Valley, west of the OMPNP (López-Moreno, 2000), and at about 2950 m in the Maladeta Massif, east of the OMPNP (Chueca et al., 2005). The mean annual air temperature at the closest meteorological station (Góriz at 2250 m a.s.l.) is 5.03 °C, although this station is on the south-facing slope of the Monte Perdido Massif. Assuming a lapse rate of 0.55 to 0.65 °C every 100 m, the annual 0 °C isotherm should be roughly at 2950 to 3150 m a.s.l., although it might be slightly lower because the glacier is north-facing.

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The climate in this region can be defined as high-mountain Mediterranean. Precipitation as snow can fall on the glacier any time of year, but most snow accumulation is from November to May, and most ablation is from June to September. Previous research estimated the mean annual precipitation was about 2000 mm in Marboré Lake (Del Valle, 1997), with most precipitation occurring during spring and autumn.

3 Data and methods

3.1 Comparison of DEMs

DEMs from different dates can be used to calculate changes in glacier ice volume. This technique is well established for the study of glaciers in mountainous areas (Favey et al., 2002), and we have previously applied it in several studies of the Pyrenees (Chueca et al., 2004, 2007; Julián and Chueca, 2007). Thus, we used 3 DEMs to estimate the changes in ice volume in the Monte Perdido Glacier. Two DEMs (1981 and 1999) were derived from topographic maps and one (2010) was from airborne LIDAR measurements. All three DEMs have and cell size of 4 m^2, and they were used in the context of a geographic information system (GIS) and unified working under a single geodetic datum (European Datum ED50; UTM projection, zone 30).

The 1981 DEM was obtained from the cartography published by the Spanish *Instituto Geográfico Nacional* (IGN) (Sheet 146-IV, Monte Perdido; Topographic National Map Series, scale 1 : 25 000). This map was published in 1997 and its cartographic restitution was based on a photogrammetry flight in September 1981. The 1999 DEM was also derived from cartography published by the IGN (Sheet 146-IV, Monte Perdido; Topographic National Map Series MTN25, scale 1 : 25 000). It was published in 2006 and its cartographic restitution was based on a photogrammetry flight in September 1999. The 2010 DEM was obtained from an airborne LIDAR flight (MDT05-LIDAR) made by the IGN in late summer of 2010 in the context of the National Plan for Aerial Orthophotography (NPAO).

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The root mean squared error (RMSE) for vertical accuracy calculated by the IGN for their digital cartographic products at the 1 : 25 000 scale is ±1.5 m for the 1981 and 1999 DEMs, and ±0.2 m for the LIDAR-derived DEM of 2010. The combined vertical RMSE for comparison of the 1981 and 1999 DEMs is ±2.12 m, and is less than ±1.8 m for comparison of the 1999 and 2010 DEMs. Vertical RMSE values were used to estimate error bars to provided values of glacier changes in both analyzed periods. These combined vertical RMSEs were considered precise enough for our purposes, because changes in ice depth in our analyses were generally much greater than these values. The estimation of ice volume changes was performed in ArcGIS (ESRI, Inc.) by the use of the tool "cut-and-fill" for comparing pairs of glacier surface DEMs (1981–1999 and 1999–2010). The glacial perimeters associated with each DEM date were retrieved from aerial photographs (1981: *Pirineos Sur* Flight, September 1981, scale of 1 : 30 000, black and white; 1999: *Gobierno de Aragón* Flight, September 1999, scale of 1 : 20 000, color). There were no high quality flights for 2010, so 2006 aerial photographs were used (PNOA 2006 Flight, August 2006, scale of 1 : 5000, color). The 1999 and 2006 photographs were already orthorectified, but we had to correct the geometry and georeference the aerial survey of 1981 by use of the georeferencing module of ArcGIS. The reference for the control points was from the orthophotos and DEM data from 1999. The horizontal RMSE accuracy of the set of control-points ranged from 2.1 to 4.7 m, and was considered sufficiently precise for our study. The maximum horizontal error value was used to calculate error bars to estimated glaciated areas and their temporal changes. A resampling procedure using cubic convolution was used to generate the final rectified images.

The most recent estimates of the evolution of the glacier were from annual TLS surveys. LIDAR technology has developed rapidly in recent years, and terrestrial and airborne LIDAR have been used in diverse geomorphology studies, including monitoring changes in the volume of glaciers (Schwalbe et al., 2008; Carturan et al., 2013b). The device used in the present study is a long-range TLS (RIEGL LPM-321) that uses time-of-flight technology to measure the time between the emission and detection of a light pulse to produce a three-dimensional point cloud from real topography. The TLS used in this study employed light pulses at 905 nm (near-infrared), which is ideal for acquiring data from snow and ice cover (Prokop, 2008; Grünewald et al., 2010; Egli et al., 2011), a minimum angular step width of 0.0188°, a laser beam divergence of 0.0468°, and a maximum working distance of 6000 m.

When TLS is used for long distances, various sources of error must be considered, namely the instability of the device and errors from georeferencing the point of clouds (Reshetyuk, 2006). We used a frontal view of the glacier with minimal shadow zones in the glacier and a scanning distance of 1500 to 2500 m. We also used indirect registration, also called target-based registration (Revuelto et al., 2014), so that scans from different dates (September of 2011 to 2014) could be compared. Indirect registration uses fixed reference points (targets) that are located in the study area. Thus, 11 reflective targets of known shape and dimension are placed at the reference points at a distance from the scan station of 10 to 500 m. Using standard topographic methods, we obtained accurate global coordinates for the targets by use of a differential global positioning system (DGPS) with post-processing. The global coordinates were acquired in the UTM 30 coordinate system in the ETRS89 datum. The final precision for the global target coordinate was 0.05 m in planimetry and 0.1 m in altimetry. Invariant elements of the landscape surrounding the ice bodies (identifiable sections of rocks and cliffs) were used to assess measurement accuracy. Ninety percent of the reference points had elevation difference lower than 40 cm, and there was no apparent relationship between scanning distance and observed error. Such 40 cm of deviations was considered to add error bars to the calculated ice depth and mass loss rates. The conversion of mean ice elevation change to annual mass budget rates was done applying mean density of 900 kg m^{-3}, considering that the firn zone was nearly absent (Chueca et al., 2007; Marti et al., 2015).

3.2 Climatic data

The Spanish Meteorological Office (AEMET) provided climatic data from the Góriz weather station, located at 2250 m a.s.l. on the southern slope of the Monte Perdido Massif. Given no changes in instrumentation and observation practices in the meteorological station since 1983, and the proximity of the meteorological station to the glacier (2.7 km) suggests that it accurately records the climate variability over the glacier. The climatic record consists of daily data of air temperature, precipitation, and snow depth. From these data, we derived annual series of maximum and minimum air temperatures for the main periods of snow accumulation (November–May) and ablation (June–September), precipitation during the accumulation season, and maximum snow depth in April (generally the time of maximum snowpack at this meteorological station). The statistical significance of the linear climate trends was assessed by the non-parametric correlation coefficient of Mann–Kendall's tau-b (Kendall and Gibbons, 1990).

4 Results

4.1 Climatic evolution and variability from 1983 to 2014

Figure 2 illustrates the high interannual variability of climate in the study area since 1983. The maximum air temperatures during the snow accumulation and ablation seasons had no significant trends, with Mann–Kendall values close to 0 (Fig. 2a and b). The range between the highest and lowest anomalies during the study period exceeded 3 and 4 °C during the accumulation and ablation periods, respectively. The minimum air temperatures had very weak increases in both seasons, but these were only statistically significant ($p < 0.05$) during the accumulation period (Fig. 2c and d). The air temperature range was larger for the accumulation period (∼ 5 °C) than for the ablation period (∼ 2.5 °C). Precipitation during the accumulation period also exhibited strong interannual variability, with a range of ∼ 600 to 1500 mm (Fig. 2e). The trend line had

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a slight increase, but this was not statistically significant. Similarly, maximum snow accumulation during April varied from less than 50 to 250 cm, and there was no evident trend during the study period (Fig. 2f).

Figure 2 also shows that the last three years, for which we have TLS measurements of annual glacier evolution, had extremely variable conditions. Thus, mid-September 2011 to mid-September 2012 was one of the warmest recorded years (especially during the ablation period) and one of the driest recorded years (close to the 25 %). The period of 2012 to 2013 had an accumulation period that was more humid than average and the coolest recorded summer, and the accumulation period of 2013 to 2014 was very wet and mild, with air temperatures well below average during the ablation months.

4.2 Glacier evolution from 1981 to 2010

Figure 3 shows two photographs of the glacier taken in late summer of 1980 and 2011. A simple visual assessment shows the fast degradation of the glacier during this 30 year period. In 1981, the upper and lower glaciers were no longer united (they became disconnected from 1973 to 1978), and they exhibited a concave surface and a significant ice depth with noticeable seracs hanging from the edge of the cliffs. Both ice bodies were heavily crevassed, with evidence of ice motion over the whole glacier. The photograph of 2011 shows that the two ice bodies are further separated, as well as showing a dramatic reduction in ice thickness, manifested by the concave surface, the disappearance of almost all seracs, and the retreat of ice from the edges of the cliffs. Crevasses are only evident in the eastern part of the lower glacier, indicating that the motion of the glacier has slowed or stopped in most of these two ice bodies. Moreover, there are rocky outcrops in the middle of the lower glacier and areas that are partially covered by debris deposits from several crevasses or rock falls in the upper areas.

Table 1 shows the surface area of the ice in 1981, 1999, and 2006. From 1981 to 1999 the glacier lost 4.5 ± 0.19 ha (1.5 ± 0.06 ha in the upper glacier and 3.0 ± 0.13 in the lower glacier), corresponding to an overall rate of 0.25 ± 0.01 ha yr^{-1}. From 1999 to

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2006, the glacier lost 5.4 ± 0.24 ha (2.0 ± 0.09 ha in the upper glacier and 3.4 ± 0.15 ha in the lower glacier), corresponding to an overall rate of 0.77 ± 0.23 ha yr^{-1}, more than three-times the rate of the previous 18 years.

Comparison of the elevation of the glacier's surfaces derived from the DEMs (1981 to 1999 vs. 1999 to 2010) also indicates an acceleration of glacier wastage over time (Fig. 4). During the 1981–1999 period, the ice thickness decreased by an average of 6.20 ± 2.12 m in the upper glacier and 8.79 ± 2.12 m in the lower glacier (8.35 ± 2.12 m overall); thus, the mean rate of ice thickness decay was 0.34 ± 0.11 m and 0.48 ± 0.11 m yr^{-1} (0.46 ± 0.11 m yr^{-1} overall, or 0.39 ± 0.1 m w.e. yr^{-1}), respectively. Moreover, the changes in glacier thickness had spatial heterogeneity. No sectors of either glacier had increased thicknesses, but some small areas of the lower glacier remained rather stationary, with declines in thickness less than 5 m. The largest losses of ice thickness were in the lower elevations and western regions of the upper and lower glaciers, with decreases that exceeded 25 and 35 m respectively. During the 1999–2010 period, the loss of ice thickness was 7.95 ± 1.8 m in the upper glacier and 9.13 ± 1.8 m in the lower glacier (8.98 ± 1.8 m overall); corresponding to rates of 0.72 ± 0.16 m and 0.81 ± 0.16 m yr^{-1} (0.8 ± 0.16 m yr^{-1} overall, or 0.72 ± 0.14 m w.e. yr^{-1}), respectively. The spatial pattern of ice losses resembled the pattern from 1981–1999, with the smallest decreases in the eastern and higher elevation parts of the lower glacier and the proximal area of the upper glacier, and the greatest decreases in the distal and central-eastern parts of both ice bodies.

4.3 Evolution of Monte Perdido Glacier from 2011 to 2014 from TLS measurements

Figure 5 shows the differences in ice depth between consecutive annual scans (September 2011–2012, September 2012–2013, and September 2013–2014) and the total change from 2011 to 2014. Figure 6 shows the frequency distribution of ice depth change measured over the glacier for these periods.

The period of mid-September 2011 to mid-September 2012 was very dry during the accumulation period and very warm during the ablation period. These conditions led to dramatic declines of ice depth, with an average decrease of 1.94 ± 0.4 m (1.92 ± 0.4 m in the upper glacier and 1.97 ± 0.4 m in the lower glacier). Ice thinning affected almost the entire glacier, and was particularly intense in the western sectors of the upper and lower glaciers, where loses were more than 4 m. The few scattered points indicating depth increases in the middle of the lower glacier are likely to be from the motion of the existing crevasses.

Conditions were very different from 2012 to 2013, with a rather wet accumulation period and very cool ablation period. These conditions led to changes that contrasted sharply with those of the previous year, in that large areas of the glacier had increased ice thickness. Most of these increases did not exceed 1–1.5 m, and most were in the highest elevation areas of both ice bodies. Nonetheless, during this year, large areas remained stable and some areas even exhibited noticeable ice losses (more than 1.5–2 m in the upper and lower glaciers). Despite the excellent conditions for glacier development from 2012 to 2013, the average increase of glacier thickness was only 0.34 ± 0.4 m (0.32 ± 0.4 m in the upper glacier and 0.38 ± 0.4 m in the lower glaciers). Very similar conditions occurred in 2013–2014, with very wet accumulation months and below average air temperature during the ablation period. Again, there were large areas with moderate increases in thickness (sometimes exceeding 3 m), although there were still areas with significant ice loss, with an average depth decrease of 0.07 ± 0.4 m (0.08 ± 0.4 m in the upper glacier and 0.01 m in the lower glacier).

The overall result of a very negative year (2011–2012) for glacier development followed by two years (2012–2013 and 2013–2014) of anomalous positive conditions led to a net average ice loss of 2.1 ± 0.4 m (0.64 ± 0.36 m w.e. yr^{-1}), with some regions experiencing losses greater than 6 m. Only the areas of the eastern part of the lower glacier that were at high elevations (around the rimaye) exhibited some elevation gain during this period, and this was typically less than 2 m. Interestingly, the areas with greatest and lowest ice losses during 1981–2010 were similar to those with the greatest and

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lowest ice losses during 2011–2014, indicating a consistent spatial pattern of glacier shrinkage over time.

5 Discussion and conclusions

The results of this study indicate that the recent evolution of the Monte Perdido Glacier was similar to that of many other glaciers worldwide (Marshall, 2014; Vincent et al., 2013), especially those in Europe (Gardent et al., 2014; Abermann et al., 2009; Scotti et al., 2014; Marti et al., 2015) where glacier shrinkage began at the end of the LIA and has clearly accelerated after 2000. More specifically, the annual loss of area of the Monte Perdido Glacier was three-times greater from 2000 to 2006 compared to the 1981–1999 period; and the loss of ice thickness from 1999 to 2010 was double the rate observed from 1981 to 1999. Acceleration in glacier shrinkage has been also reported in the Ossoue Glacier (French Pyrenees), where mass balance decline during the period 2001–2013 ($-1.45\,\mathrm{m\,w.e.\,yr^{-1}}$), is 50% greater compared to the period 1983–2014 ($-1\,\mathrm{m\,w.e.\,yr^{-1}}$) (Marti et al., 2015). The accelerated degradation of the Monte Perdido Glacier cannot simply be explained by an intensification of climate warming or by the sharp decline of snow accumulation. Climate data (1983–2014) of a nearby meteorological station clearly refute this hypothesis, because air temperatures remained stationary during the ablation period (i.e. average maximum temperature was 13.4 and 13.6 °C for the periods 1983–1999 and 1999–2010 respectively), and precipitation and snow depth accumulation during accumulation period were also stationary or slightly increased (average precipitation was 1013 and 1028 mm; and average maximum annual snow depth in April was 104 and 131 cm for the periods 1983–1999 and 1999–2010 respectively). Previous studies of the Pyrenees and surrounding areas showed that air temperature has significantly warmed throughout the 20th century, especially after the relatively cold period from the 1960s to the mid-1970s (López-Moreno et al., 2008; El Kenawy et al., 2012; Deaux et al., 2014). At the same time, there was a regional significant decline of snow accumulation from mid-March to late-April/early-May from 1950 to

2000 in the Pyrenees (López-Moreno, 2005). These trends of decreasing precipitation and milder air temperatures during winter and early spring were related to changes in the North Atlantic Oscillation (NAO) index during this period (López-Moreno et al., 2008). Most recent studies that used updated databases (including data of the 21st century) confirmed a shift in NAO evolution toward more negative evolution that affected to the most recent evolution of temperature and precipitation over the Pyrenees. Thus, no temporal trends of both variables are found near the Monte Perdido Peak, when the study period starts in the 1980s and the effect of the cold and wet period of the 1960s to 1970s is removed. Thus, Vicente-Serrano et al. (2010) found that the increased occurrence of very wet winters after the 2000s was associated with frequent strong negative NAO winters. In agreement, Buisan et al. (2015) indicated that for the period of 1980 to 2013 the overall number of snow days in the Pyrenees remained stationary and even slightly increased in some locations. Macias et al. (2014) also support the view that southern Europe and some other regions of the world have undergone clear moderations of the warming trends that were reported at the end of the 20th century. Nonetheless, it is necessary to bear in mind that the longest climatic records or dendroclimatological reconstructions for the Pyrenees still point out the period considered in this study (1980–2014) as a very strong positive anomaly of temperature and a dry period compared to the period spanning since the end of the LIA (Büngten et al., 2008; Deaux et al., 2014; Marti et al., 2015),

The mass loss rates presented in this study for the different periods (0.39 ± 0.1 and 0.72 ± 0.14 m w.e. yr^{-1} for 1980–1999 and 1999–2010 periods respectively) are similar to the reported by Chueca et al. (2007) and Marti et al. (2015) for the Maladeta massif (0.36 m w.e. yr^{-1} for the 1981–1999 period; and 0.7 m w.e. yr^{-1} for the 1991–2013). The most recent mass balance values obtained for the Monte Perdido Glacier are more similar to those reported for the Swiss Alps (Fischer et al., 2015), or the best preserved glaciers in some areas of the Italian Alps (Caturan et al., 2013a); but much lower to the most retreating glaciers in the Alps (Carturan et al., 2013b) or the one reported in the Ossoue Glacier (French Pyrenees, −1.45 m w.e. yr^{-1} for the 1983–2014). The smaller rates in the Spanish side of the Pyrenees compared to the later may be explained by the location of the remnant ice bodies in Southern side of the range, confined in the most elevated and the best topographic locations in their respective cirques (López-Moreno et al., 2006). Oppositely, the Ossue glacier still has maintained a considerable glacier tongue in an easting slope. In this context, the only explanation for the rapid degradation of the Monte Perdido Glacier after 1999 is that the progressive warming observed since the end of the LIA was responsible of a dramatic reduction in the accumulation-ablation ratio (AAR), and most of this glacier is currently below the current ELA (at 3050 m a.s.l. during the period 2011–2014, Fig. 5d). This leads to a clear imbalance, in that significant ice losses occur during unfavorable years and even during "normal" years (with little accumulation or warm ablation seasons). Because of this imbalance, the glacier cannot recover ice losses during periods with favorable conditions (high accumulation and/or little ablation). This hypothesis is strongly supported by our detailed TLS measurements from the last four years. In particular, these TLS data showed that two consecutive anomalously positive years (2012/13 and 2013/14) did not allow recovery of the losses from a negative year (2011/12). Thus the average decrease of glacier depth during this three years period was 2.1 ± 0.4 m, roughly one-fourth of the loss from 1981 to 2000, and from 2000 to 2010. Obviously, this indicates that the future of the Monte Perdido Glacier is seriously threatened, even under stationary climatic conditions. A ground-penetrating radar (GPR) survey of the lower glacier in 2010 reported a maximum ice depth close to 30 m (unpublished report), suggesting that large areas of this glacier may even disappear within the next few years. This process may be accelerated by negative feedbacks such as the recent rise of rocky outcrops in the middle of the glacier and the thin cover of debris, both of which may accelerate glacier ablation by decreasing the albedo. The highly consistent spatial pattern of ice losses in the last 30 years suggests that the western-most part of this glacier will disappear first; the eastern-most part will survive as a small residual ice mass because of greater snow accumulation during positive years and a lower rate of degradation. When the glacier

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is restricted to this smaller area, it is likely that its rate of shrinkage will decrease, as observed for other Pyrenean glaciers (López-Moreno et al., 2006).

The future long-term monitoring of the Monte Perdido Glacier is likely to provide important information on the year-to-year response of the mass balance of this glacier to a wide variety of climatic conditions, and will allow detailed analysis of the role of positive and negative feedbacks in this much deteriorated glacier. Thus, study of this glacier may serve as a model for studies of the evolution of glaciers in other regions of the world that have similar characteristics now and in the future.

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Table 1. Surface area (ha), loss of surface area (ha), and annual rate of surface area loss ($ha\,yr^{-1}$) of the Monte Perdido Glacier.

	Surface Area			Loss of Surface Area	
	1981	1999	2006	1981–1999	1999–2006
Upper glacier (ha)	8.3 ± 0.36	6.8 ± 0.29	4.8 ± 0.21	1.5 ± 0.06	2 ± 0.09
Lower glacier (ha)	40.1 ± 1.76	37.1 ± 1.63	33.7 ± 1.48	3 ± 0.13	3.4 ± 0.15
Entire glacier (ha)	48.4 ± 2.12	43.9 ± 1.93	38.5 ± 1.69	4.5 ± 0.19	5.4 ± 0.24
Entire glacier ($ha\,yr^{-1}$)				0.25 ± 0.01	0.77 ± 0.23

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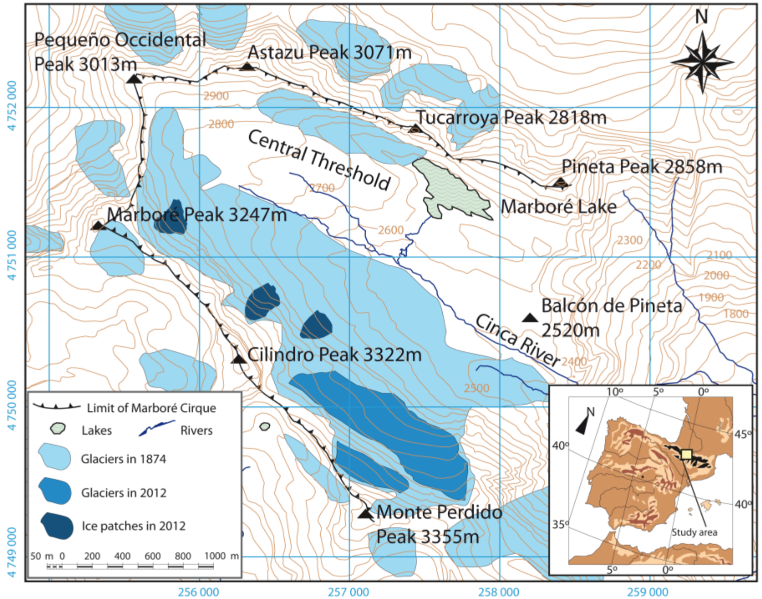

Figure 1. Monte Perdido study area and extent of ice cover at the end of the Little Ice Age (according to the map of Schrader, 1874) and in 2008.

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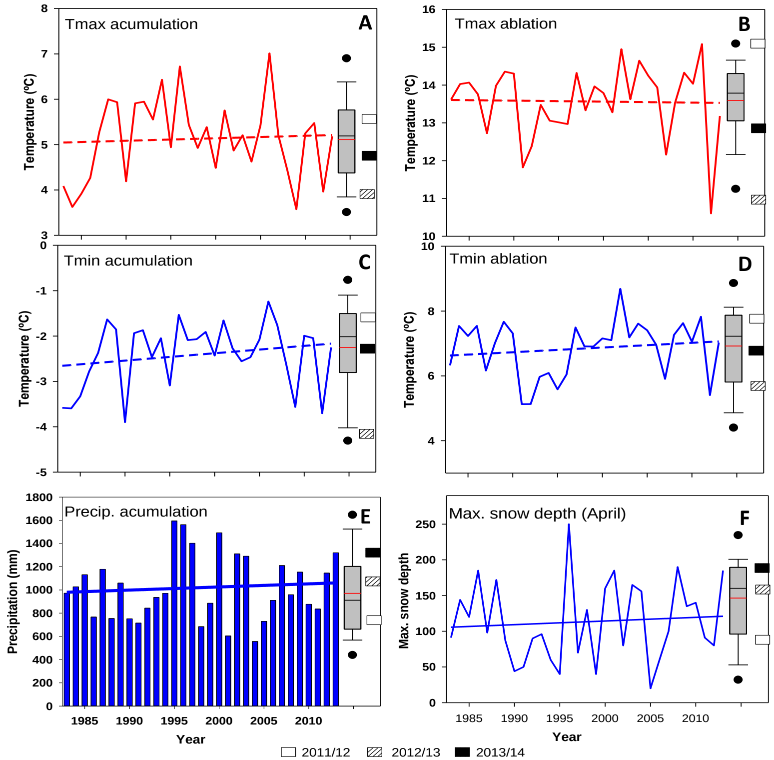

Figure 2. Interannual fluctuations and overall trends (straight lines) of minimum and maximum air temperatures during the accumulation and ablation periods, precipitation during the accumulation period, and maximum snow depth during April based on data from the Goriz meteorological station (1983 to 2014). Boxplots at the right of each panel show the interannual variability during the most recent 3 years (2011/12, 2012/13, and 2013/14) when terrestrial laser scanning measurements were available. Box: 25th percentiles and 75th percentiles, bars: 10th percentiles and 90th percentiles, dots: 5th percentiles and 95th percentiles, black line: median, red line: average.

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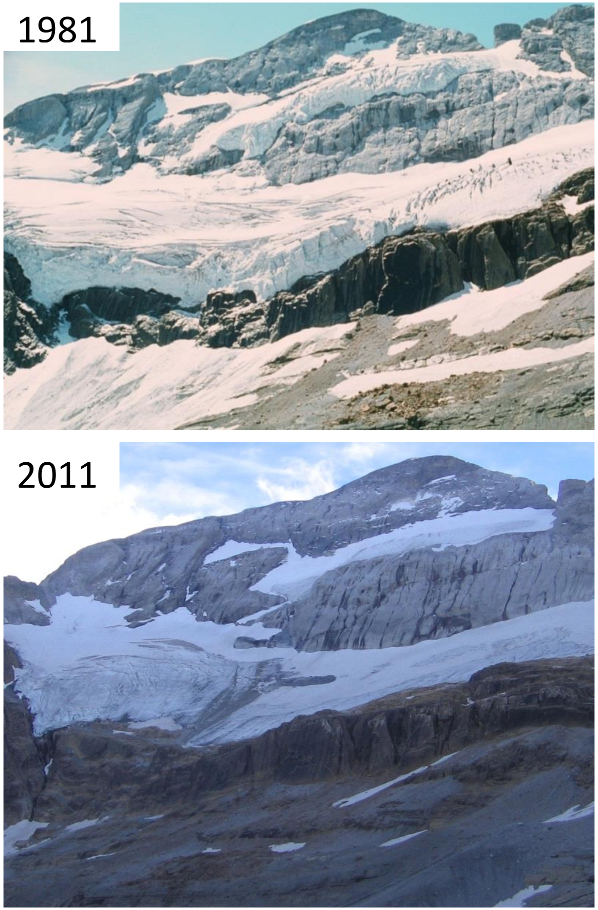

Figure 3. Photographs of the Monte Perdido Glacier during the late summer of 1980 and 2011.

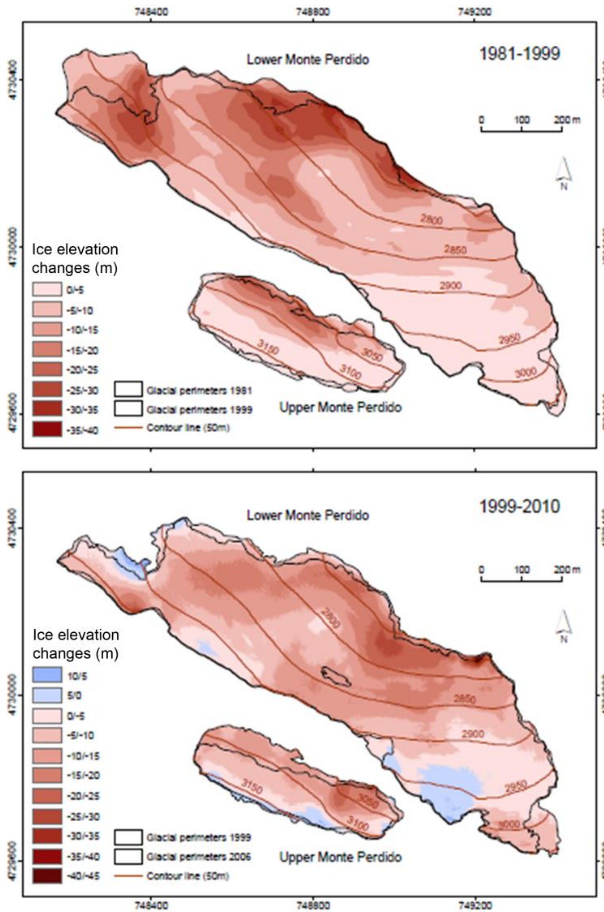

Figure 4. Changes in ice thickness in the upper and lower Monte Perdido Glacier from 1981 to 1999 and from 1999 to 2010 based on comparison of DEMs.

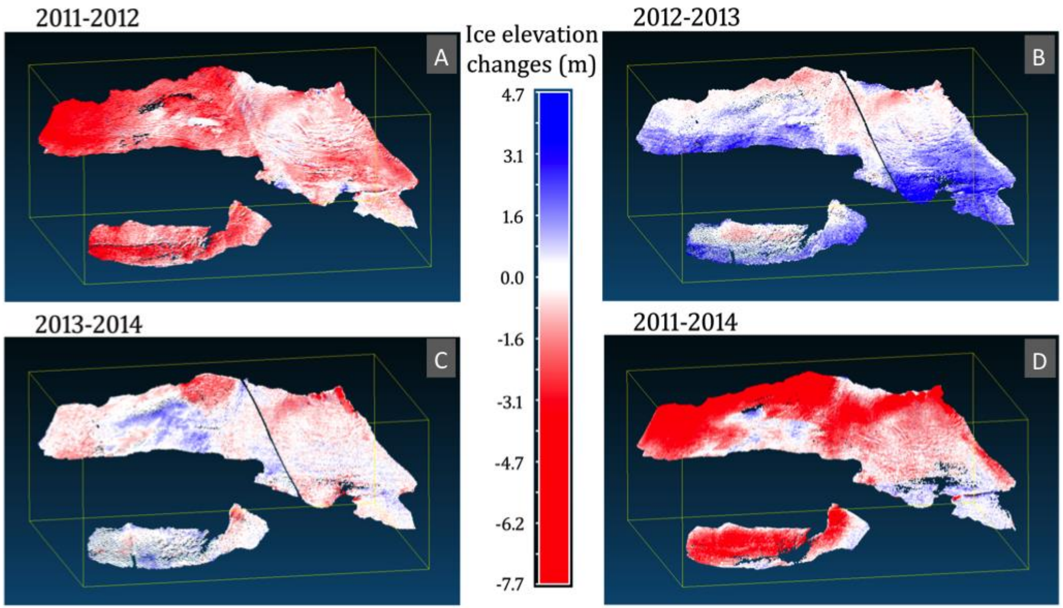

Figure 5. Changes in ice thickness based on terrestrial laser scanning from September of 2011 to 2012 **(a)**, 2012 to 2013 **(b)**, 2013 to 2014 **(c)**, and 2011 to 2014 **(d)**.

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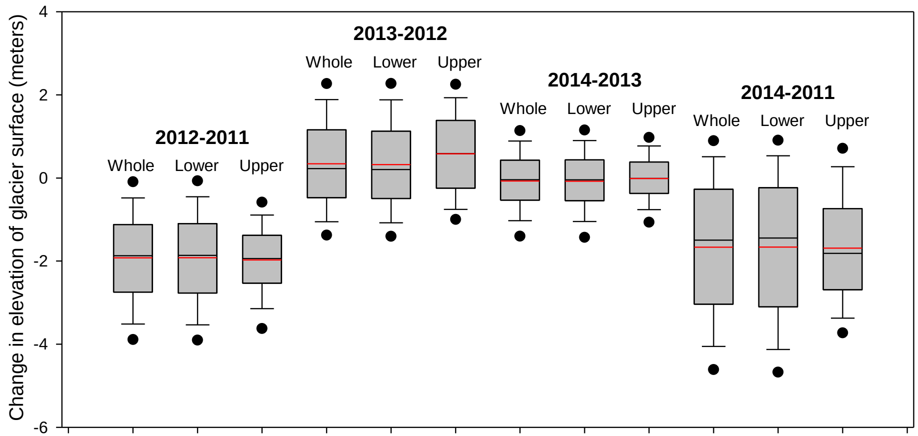

Figure 6. Changes in ice thickness over the whole glacier, lower glacier, and upper glacier for the same 4 time periods examined in Fig. 5. Box: 25th percentiles and 75th percentiles, black line: median, red line: average, bars: 10th percentiles and 90th percentiles, dots: 5th percentiles and 95th percentiles.