Dear Editor Dr. Etienne Berthier,

We are pleased to submit a new revised version of our manuscript originally entitled: “Recent accelerated wastage of the Monte Perdido Glacier in the Spanish Pyrenees” and now entitled “Thinning of the Monte Perdido Glacier in the Spanish Pyrenees since 1981”.

- In response to your last message and following your recommendation we have sent the manuscript to a professional editing service, to ensure the quality of the grammar and minimize the possibility of appearing typographical errors. This revised version of our manuscript has been reviewed by the English Manager Service (www.sciencemanager.com), who has edited our manuscripts for the past 15 years. Therefore, we really hope that the paper is acceptable after passing this professional checking. In addition, we have tried to be consistent in the use of the terminology and the way to present the numbers. According to your suggestion, we have used the term “thinning” to make reference to the loss of ice volume, and the wording “surface elevation change” to the process measured by comparing DEMs and Terrestrial laser Scanning data; therefore, in the captions and legends of Figures 5, 6 and 7, we use the term “Surface elevation changes (meters)”. As mentioned before, we indicated to the English Manager Service to indicate the “+” or “-” sign before the numbers.
- Regarding the use of different units, this last revised version clearly states what they provide. Along the whole manuscript, but particularly in the abstract, we systematically indicate if numbers make reference to “surface elevation change” or “glacier-wide mass balance”.
- Moreover, we have carefully checked the numbers and re-calculated the operations, to ensure that they are right. We are now confident that we have reached this purpose, as well as we have checked that the time periods are properly depicted in this new revised version.
- We have also checked carefully all the cited articles and the references in both ways, the consistency between both lists, and that they follow the journal´s style.
Once again, thanks for managing our manuscript.

Sincerely,

Juan-Ignacio López-Moreno and co-authors.

Pyrenean Institute of Ecology, CSIC.
RECENT ACCELERATED WASTAGETHINNING OF THE MONTE PERDIDO GLACIER IN THE SPANISH PYRENEES SINCE 1981

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Abstract

This paper analyzes the evolution of the Monte Perdido Glacier, the third largest glacier in the Pyrenees, from 1981 to the present. We assessed the evolution of the glacier’s surface area by analysis 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) data. We interpreted the changes in the glacier based on climate data from nearby meteorological stations. The results indicate an accelerated degradation of this glacier after 1999, with a rate of ice surface loss that was almost three times greater from 1999 to 2006 than during earlier periods. Moreover, the rate of glacier thinning was 1.85 times faster during 1999 to 2010 (the ice depth decreased by rate of surface elevation change = -8.98±1.80 m, glacier-wide mass balance = -0.727±0.14 m w.e. yr⁻¹) compared to during 1981 to 1999 (the ice depth decreased by rate of surface elevation change = -8.35±2.12 m, glacier-wide mass balance = -0.394±0.10 m w.e. yr⁻¹). This loss of glacial ice from 2011 to 2014, ice thinning continued at a lower rate from 2011 to 2014 (the glacier depth decreased by slower rate (rate of surface elevation change = -1.93±0.4 m yr⁻¹, glacier-wide mass balance = -0.58±0.36 m w.e. yr⁻¹). These data indicated that this deceleration in ice thinning compared to the previous 17 years can be attributed, at least in part, to two consecutive markedly anomalous wet winters and cool summers (2012-13 and 2013-14) resulted in a deceleration in wastage compared to previous 17 years, but were counteracted by some degree the dramatic shrinkage intense thinning that occurred during the dry and warm period of 2011-2012. Local climatic changes observed during the study period do not sufficiently explain
sufficient to explain the acceleration in ice thinning of this glacier, because precipitation and air temperature did not exhibit statistically significant trends during the studied period. Rather, the accelerated degradation of this glacier in recent years can be explained by a strong disequilibrium between the glacier and the current climate, and probably by other factors affecting the energy balance (i.e., increased albedo in spring) and feedback mechanisms (i.e., heat emitted from recent ice-free bedrocks and debris covered areas).

Keywords: Glacier shrinkage, glacier thinning, climate evolution, geodetic methods, terrestrial laser scanner (TLS), Pyrenees

1 Introduction

Most glaciers worldwide have undergone intense retreat since the culmination of the Little Ice Age (LIA), believed to have been 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 and 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 have 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 Ötztal Alps (Austria), Abermann et al. (2009) calculated the loss of glacier area was calculated to be -0.4% per year from 1969 to 1997 and -0.9% per year from 1997 to 2006. (Abermann et al., 2009). 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 was found to be approximately 10-fold greater
during the more recent period. Carturan et al. (2013b) also reported that 1990-2007 than
during 1860-1990 (Scotti et al., 2014), while the rate of ice mass loss in the long-term
monitored Careser Glacier (Italian Alps) during the period 1981-2006 (~1.3 meter of
water equivalent per year; hereafter m w.e. yr⁻¹) was about twice that for the period of
1933 to 1959 (~0.7 m w.e. yr⁻¹) (Carturan et al., 2013b). 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 (Fischer et
al., 2015), which clearly exceeds the values presented by Huss et al. (2010) for the same
region over the 20th century (close to ~0.25 m w.e. yr⁻¹). In the Sierra Nevada of
southern Spain, the Veleta Glacier, which formed during the LIA, evolved into a rock
glacier during the mid-20th century and has suffered marked degradation during the last
two decades (Gómez-Ortiz et al., 2014).

The glaciers in the Pyrenees host some of, which are among the southernmost glaciers
in Europe, (Grunewald and Scheithauer, 2010), have also undergone significant
retreat (Grunewald and Scheithauer, 2010). In 2005, these glaciers had a total area of
495 hectares (González-Trueba et al., 2008) and in 2008 they), but this had a total area
of decreased to 321 hectares by 2008 (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 and 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 Ossoue Glacier (French Pyrenees).

Most studies agree that global warming is responsible for the observed glacier shrinkage and the recent acceleration of this shrinkage, and glacier thinning. The air temperature increase has been particularly strong 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 area ratios (AARs) of glaciers, such that most glaciers are not in equilibrium with current climate (Mernild et al., 2013) and many of them cannot survive persist for much longer (Pelto, 2010). In the case of the Pyrenees, the annual air temperature has increased by a minimum of 0.9°C since the end culmination of the LIA (Dessens and Büchner, 1998; Feulliet and Mercier, 2012). More recently, Deaux et al. (2014) reported an increase of 0.2°C decade\(^{-1}\) for the period between 1951 and 2010. This air temperature increase explains the ~255 m increase in the elevation of the ELA of the glaciers of the Maladeta Massif since the end culmination of the LIA, 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, it is not always easy to establish a direct relation between annual fluctuations of climate and the changes in the area and mass of a particular glacier. This
is difficult because only glaciers of small size respond rapidly to changes in annual snowfall and snow/ice melt, whereas mid-sized and large glaciers respond much more slowly (Marshall, 2014). Moreover, very small glaciers may develop and evolve for reasons unrelated to the regional long-term, monthly or seasonal climatic evolution, such as, for example, avalanches, wind drifting and new rock exposure. In the case of shrinking glaciers, the latter can be a key driver of glacier thinning (Chueca et al. and Julián, 2004; Serrano et al., 2011; Carturan et al., 2013c). 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 the area of glaciated surfaces or glacier surface areas or lengths. These parameters respond to climate fluctuations, although this relationship to climate is also affected by geometric adjustment factors (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 between changes in glacier characteristics and climatic changes in climate (Chueca et al., 2007; Cogley, 2009; Fischer et al., 2015). In the Pyrenees, there are only a few estimates of ice volume loss have been published (Del Río et al., 2014; Sanjosé et al., 2014; Marti et al., 2015), although abundant research has examined recent changes in 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 the glaciological method have been performed on the Maladeta Glacier (Spanish Pyrenees) and on the Ossoue Glacier (French Pyrenees), and these indicated the findings indicating a mean glacier thinning of -14 m during the last 20 years.
the Maladeta Glacier, and -22 m off for 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 off 1981 and 1999 in the Maladeta Massif (Chueca et al., 2008) and the Monte Perdido Glacier (Julián and Chueca, 2007), and reported losses reporting rates of loss (glacier-wide mass balance) of -0.36 m w.e. yr\(^{-1}\) and of -0.39 m w.e. yr\(^{-1}\), respectively.

This paper focuses on 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 surface elevation changes by comparing DEMs derived from topographic maps off 1981 and 1999 (Julian and Chueca, 2007), a new DEM obtained in 2010 from Airborne LIDAR, and four successive Terrestrial Laser Scanning (TLS) surveys that were performed during the autumns of 2011, 2012, 2013, and 2014. We examined these data in connection with data on precipitation, snow depth, and air temperature since 1983 from the closest meteorological station. Identifying changes during recent years in this region is particularly important because in the 21st century snowfall accumulation has been higher and the air temperatures slightly cooler than in the last decades of the 20\(^{th}\) century. This shift is associated with a persistently positive North Atlantic Oscillation index during the beginning of the 21st century (Vicente-Serrano et al., 2010; Buisan et al., 2015). Thus, the most The recent response of the remnant ice bodies to this 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 ($42^\circ 40'50''N, 0^\circ 02'15''E$) is located in the Ordesa and Monte Perdido National Park (OMPNP) in the Central Spanish Pyrenees (Figure 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 subsequent studies examined the status and extent and made descriptions of the status of the ice masses and moraine 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 locations of moraines to deduce the dynamics and extent of LIA glaciers (Nicolás, 1981 and 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 the 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) (Figure 1). The map of Schrader (1874) distinguishes the Cilindro-
Marboré Glacier, with three small ice tongues that joined at 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, but disappeared after the 1970s (Nicolas Nicolás, 1986; García-Ruiz et al., 2014). The two remaining glacier bodies, which are currently unconnected, are referred to this paper 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 present at the end of the LIA had already disappeared. The upper and lower ice bodies have mean elevations of 3110 m 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 above the glacier and its marked steepness (≈40°).

There has not been a direct observation made 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., 2.7 km from the glacier) 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°C to 0.65°C every 100 m, the annual 0°C isotherm should be roughly at 2950 to 3150 m a.s.l. The climate in this region can be defined as high-mountain Mediterranean. Precipitation as snow can fall on the glacier at any time of
year, but most snow accumulation is from November to May, and most ablation is from June to September.

3 Data and methods

3.1. Comparison of DEMs

Digital elevation models (DEM) from different dates can be used to calculate surface elevation 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 three DEMs to estimate the surface elevation 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 had a cell size of 2x2 m, and they were used in the context of a geographic information system (GIS), working under the 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 1:25000). This map was published in 1997 and its cartographic restitution was based on a photogrammetric 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 1:25000). It was published in 2006 and its cartographic restitution was based on a photogrammetric flight in September 1999. The 2010 DEM was obtained from an airborne LIDAR flight (MDT05-LIDAR)
made by the IGN in September of 2010 in the context of the National Plan for Aerial Orthophotography (NPAO).

The Root Mean Squared Error (RMSE) for elevation accuracy calculated by the IGN for their digital cartographic products at 1:25000 scale is ± 1.5 m and ± 0.2 m for their LIDAR derived DEMs. To verify these accuracies, we made a comparison of 2010-1999, 2010-1981 and 1999-1981 pairs of DEMs in areas of ice-free terrain situated near the studied glaciers. The results showed good agreement with the accuracy indicated by the IGN in almost all areas, although larger vertical errors were identified in several sectors with very steep terrain (slopes > 65º in most cases) located in the Monte Perdido glacial cirque (sharp-edged crests and abrupt cliffs linked to the geological and structural disposition of the area). In those sectors, differences between the DEMs reached 10-15 m. As both the Upper and Lower Monte Perdido glaciers are placed well outside those areas and have smoother topographical surfaces, it was assumed that the altimetric data provided by the IGN has an appropriate consistency over the glaciated terrain.

The combined vertical RMSE for DEM differences was < 2.5 m for 1999 minus 1981 and < 2.0 m for 2010 minus 1999. In the latter case it must be noted that different geodetic methods (photogrammetrical and airborne LIDAR) were used in the comparison and that this fact could alter the accuracy of the surface elevation changes (Rolstad et al., 2009). In any case, both these errors were considered precise enough for the purposes of the present work as the ice-surface elevation changes obtained in our analysis were generally much higher than these errors. The estimation of ice volume changes was performed in ArcGIS comparing, by cut and fill procedures, 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 1:30000, black and white; 1999: *Gobierno de Aragón* Flight, September 1999, scale of 1:20000, color). There were no high quality flights for 2010, so 2006 aerial photographs were used (PNOA2006 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 was used to calculate the uncertainty of glacierized and glaciated areas and their temporal changes. This uncertainty was calculated using the *buffer* tool in ArcGIS. This tool allowed quantifying the area of the polygon generated with the maximum horizontal error around the perimeter of the glacier. 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 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 in particular the instability of the device and errors from georeferencing the point of clouds of points (Reshetyuk, 2006). We used an almost frontal view of the glacier (same as similar to the view used for the photos shown in Figure 4) 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.

Eleven reflective targets of known shape and dimensions (cylinders of 10x10 cm for those targets located closer than 200 meters, and squares of 50x50 cm for longer distances) were placed at the reference points on rocks at a distance situated 200 to 500 m 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 set of target coordinates was ±0.05 m in planimetry and ±0.10 m in altimetry. A total of 65 reference points around the ice bodies (identifiable sections of rocks and cliffs) were used to assess measurement accuracy. Ninety percent of the reference points had an error lower of less than 0.40 m. Such Thus 40 cm of error was considered taken as the uncertainty (error bars) to when calculating the calculated ice depth thinning and mass loss rates. The conversion of mean ice surface elevation change to annual mass budget rate was done performed by applying a mean density of 900 kg m⁻³ (Chueca et al., 2007; Marti et al., 2015). The assumption use of this value
neglects assumes the existence absence of firn, with which has a lower density. This assumption was mostly true valid at the end of the study period, but probably unlikely some firn was present during the early eighties. This assumption is not completely true and firn areas existed (i.e., according to 1980s (Figure 3A), suggests the presence of firn). Unfortunately, the lack of additional information forced us to adopt this generalization that, which may slightly overestimate have led to a slight overestimation of the mass loss rate for 1981–1999.

3.2 Climatic data

The Spanish Meteorological Office Agency (AEMET) provided climatic data from the Góriz manual weather station, located at 2250 m a.s.l. on the southern slope of the Monte Perdido Massif. The absence of 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), suggest that the station accurately records recorded 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 lack of detailed meteorological or mass balance data over the glacier made it necessary to define the accumulation and the ablation seasons in a subjective manner based on our experience. We are aware that May and October are transitional months between accumulation and ablation conditions depending on specific annual conditions.
However, we set these periods because June and November are the months when ablation and accumulation respectively become generally evident over the surface of the glacier. The statistical significance of the linear climate trends was assessed by using the non-parametric correlation coefficient of Mann-Kendall’s tau-b (Kendall and Gibbons, 1990). Results obtained for Góriz were contrasted with those from three other observatories (see Figure 1) with precipitation (Pineta, Aragnouet and Canfranc), and air temperature (Mediano, Aragnouet and Canfranc) data for the period 1983-2013, and also for 1955-2013. The non-parametric Mann-Whitney U test (Fay and Proschan, 2010) was used to detect statistically significant differences in the medians of precipitation and air temperature when the periods 1983-1999 and 2000-2010 were compared.

4. Results

4.1. Climatic evolution and variability from 1983 to 2014

Figure 2 illustrates the high interannual variability of climate at Góriz station since 1983. The average maximum air temperatures at Góriz during the snow accumulation and ablation seasons showed no significant trends, with tau-b values close to 0 (Figs 2a and 2b). The range between the highest and lowest average seasonal anomalies during the study period exceeded 3°C and 4°C during the accumulation and ablation periods, respectively, for maximum and minimum air temperatures. The average minimum air temperatures exhibited very weak increases in both seasons, but these were not statistically significant (p<0.05). The interannual air temperature range was larger for the accumulation period (~5°C) than for the ablation period (~2.5°C). Table 1 shows that the evolution of air temperature at Góriz is in line with that
observed at the three other meteorological stations (Mediano, Aragnouet and Canfranc). They do not exhibit statistically significant trends were observed for maximum or minimum air temperature during the period 1983-2013. On period, When maximum and minimum air temperature data were considered on a monthly basis, the four analyzed observatories only exhibited statistically significant increases only in May and June, and statistically significant decreases of maximum and minimum temperature only in November and December. The Mann-Whitney test did not reveal statistically significant differences in the medians of the series for the accumulation and ablation seasons at any observatory when the periods 1983-1999 and 2000-2010 were compared.

Precipitation at Góriz during the accumulation period also exhibited strong interannual variability, with a range of approximately 600 mm to 1500 mm (Fig. 2c). The trend line showed a slight increase, but this was not statistically significant. Similarly, maximum snow accumulation during April varied from less than 50 cm to 250 cm, and there was no evident trend during the study period (Fig. 2f). Monthly trend analysis (Table 1) only found a significant increase in precipitation at Góriz only during May, and near zero tau-b coefficients for the most of the other months. Very similar results were obtained for the other three analyzed stations (Pineta, Aragnouet and Canfranc), with no statistically significant trends for the accumulation and ablation periods. Only significant increases in precipitation were observed at Aragnouet showed a statistically significant increase only in May, and at Pineta only in March. No statistically significant differences in the median of precipitation during the accumulation and ablation seasons of the 1983-1999 and 2000-2010 periods were found at any of the analyzed meteorological stations.
In addition, Figure 3 shows the interannual evolution of air temperature and precipitation series for a longer time slice period (1955-2013). The data illustrate that the climate observed during the main study period (1983-2013) is not necessarily representative of the longer climate series. Thus, the 1955-2013 period exhibited statistically significant ($p<0.05$) warming during the ablation period, and the accumulation exhibited positive tau-b values but did not reach statistical significance. Precipitation during the accumulation period did not exhibit statistically significant trends during the period 1955-2013 in any of the three analyzed observatories.

Figure 2 also shows that 2011-2014, the last three years period for which we have TLS measurements of annual glacier evolution, showed extremely variable conditions. Thus, mid-September 2011 to mid-September 2012 was one of the warmest recorded years (especially during the ablation period, which was in the 96th and 74th percentiles for maximum and minimum air temperature, respectively) and with a rather dry accumulation period (27th percentile). The period of 2012 to 2013 had an accumulation period that was more humid than average (59th percentile) and the coolest recorded summer (1st and 18th percentiles for maximum and minimum air temperatures respectively), and the accumulation period of 2013 to 2014 was very wet (78th percentile) and slightly cooler than average respectively, with air temperatures around or below the average (22th and 48th percentiles for maximum and minimum temperature, respectively) during the ablation period.

4.2 Glacier evolution from 1981 to 2010
Figure 4 shows two photographs of the Monte Perdido Glacier taken in late summer of 1981 and 2011. A simple visual assessment shows the fast degree of degradation of the glacier during this 30 year period. In 1981, the upper and lower glaciers were no longer united (they became disconnected between 1973 and 1978), and they exhibited a convex surface and a significant ice depth with noticeable seracs hanging from the edges of the cliffs. Both ice bodies were heavily crevassed, with evidence of ice motion over the whole glacier. The photograph from 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 the two ice bodies. Moreover, there are rocky outcrops in the middle of the lower glacier and areas that are partially covered by debris deposits presumably originating from several crevasses and rock falls in the upper glacier.

Table 2 shows the surface area of the ice in 1981, 1999, and 2006. From 1981 to 1999 the glacier lost losses were $-4.50 \pm 0.1950 \pm 1.27$ ha ($-1.550 \pm 0.0652$ ha in the upper glacier and $-3.00 \pm 0.1300 \pm 1.21$ ha in the lower glacier), corresponding to an overall rate of $-0.25 \pm 0.0407$ ha yr$^{-1}$. From 1999 to 2006, the glacier losses were $-5.40 \pm 0.2440 \pm 1.20$ ha ($-2.00 \pm 0.0946$ ha in the upper glacier and $-3.40 \pm 0.1540 \pm 1.16$ ha in the lower glacier), corresponding to an overall rate of $-0.77 \pm 0.2317$ 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 vs. 1999 vs. 1999 to 2010) also indicates an acceleration of glacier wastage/thinning over time (Figure 5). During the 1981-1999 period, the ice thickness decreased by an average...
of-thinning was \(-6.20\pm2.12\) m in the upper glacier and \(-8.79\pm2.12\) m in the lower glacier (-8.35\pm2.12 m overall); thus, the mean rates of glacier thinning were \(-0.34\pm0.11\) m yr\(^{-1}\) and \(-0.48\pm0.11\) m yr\(^{-1}\) (-0.46\pm0.11 m yr\(^{-1}\) overall, or \(-0.394\pm0.110\) m w.e. yr\(^{-1}\)) as a glacier-wide mass balance, respectively. Moreover, the changes in glacier thickness had spatial heterogeneity-elevation surface were not spatially homogeneous. No sector of either glacier showed increased thickness, but some small areas of the lower glacier remained rather stationary. showed only minor thinning, with declines in thickness of less than 5 m. The largest losses of glacier thickness were in the lower elevations and western regions of the upper and lower glaciers, with decreases that exceeded 25 m and 35 m, respectively. During the 1999-2010 period, the thinning was \(-7.95\pm1.8\) m in the upper glacier and \(-9.13\pm1.8\) m in the lower glacier (-8.98\pm1.80 m overall); corresponding to rates of \(-0.72\pm0.16\) m yr\(^{-1}\) and \(-0.84\pm0.16\) m yr\(^{-1}\) (-0.82\pm0.16 m yr\(^{-1}\) overall, or \(-0.72\pm0.14\) m w.e. yr\(^{-1}\)) respectively. The spatial pattern of thinning resembled the pattern from 1981-1999, but areas of noticeable glacier losses were also observed further eastward. The smallest decreases are found in the higher elevation parts of the lower glacier and the proximal area of the upper glacier, probably due to more effective shading of these areas, and the greatest decreases were observed in the distal lower reaches and central-eastern parts of both ice bodies.

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

Figure 6 shows the differences in glacier depth-surface elevation between consecutive annual scans (September 2011-12, September 2012-13, and September 2013-14) and the total change from 2011 to 2014. Figure 7 shows the frequency distribution of ice depth-change in surface elevation 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 glacier thinning, with an average decrease of -2.4±0.440 m (-2.08±0.440 m in the upper glacier and -2.12±0.440 m in the lower glacier). Ice thinning affected almost the entire glacier (the accumulation area ratio, AAR, was = 3.5%), and was particularly intense in the western sectors of the upper and lower glaciers, where losses were more than -4±0.4 m-thinning exceeded four meters. The few scattered points indicating depth increases in the middle of the lower glacier are likely to derive from rising of the ice surface due to 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 showed increased ice thickness-surface elevation. Most of these increases did not exceed 1.5±0.4 m meters, and most were in the highest elevation areas of both ice bodies. Nonetheless, during this year, large areas remained stable (AAR was = 54%) and some areas even exhibited noticeable ice loss-thinning (more than -1.5±0.4 m in the upper and lower glaciers). Despite the excellent conditions for glacier development from 2012 to 2013, the average increase of glacier thickness-surface elevation was only +0.342±0.440 m (+0.322±0.440 m in the upper glacier and +0.352±0.440 m in the lower glacier). 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 exhibited moderate increases in thickness-surface elevation (AAR was 41%, sometimes exceeding 3 m-three meters), although there were still areas with that showed significant ice loss, with an average depth decrease-thinning...
of $-0.07\pm0.440$ m in the upper glacier and $-0.07\pm0.440$ 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/thinning** of $-1.93\pm0.440$ m ($-0.58\pm0.36$ m w.e. yr$^{-1}$ as **glacier-wide mass balance**), with some regions experiencing losses greater than $6\pm0.4$ m**thinning** that exceeded six meters. Only the areas of the eastern part of the lower glacier that were at high elevations (around the bergschrund) exhibited some **surface elevation gain** during this period (accumulation area ratio, AAR, for the three years was 16%), and this was typically less than $+2\pm0.4$ m. Interestingly, the areas with greatest**highest** and lowest**lowest** **ice loss/thinning** during 1981-2010 were similar to those with the greatest**highest** and lowest**lowest** **ice loss/thinning** 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 has been occurring since the culmination of the LIA and has clearly accelerated since 2000. More specifically, the annual loss of area of the Monte Perdido Glacier was near three times greater from during 1999 to 2006 compared to the 1981-1999 period, and the glacier thinning from 1999 to 2010 was almost double that observed from 1981 to 1999. Acceleration in glacier **shrinkage/thinning** has also been reported for the
Ossoue Glacier (French Pyrenees), where the mass balance during the period 2001-2013 (−1.45 m w.e. yr\(^{-1}\)) was almost 50% greater compared to the period that during 1983-2014 (−1 m w.e. yr\(^{-1}\)) (Marti et al., 2015). Climatic analyses suggest that the recent acceleration in the wastage thinning of the Monte Perdido Glacier cannot be only explained solely by an intensification of climate warming or by a decline in snow accumulation. Climate data (1983-2014) of a nearby meteorological station, and three other Pyrenean meteorological stations, suggest that during most of the year air temperature has not exhibited statistically significant trends. The Mann-Whitney test did not reveal statistically significant differences in air temperature when the period 1983-1999 was compared to 1999-2010. Precipitation in the four analyzed stations during the accumulation period and maximum annual snow depth at Göriz were also stationary or slightly increased. Previous studies of the Pyrenees and surrounding areas showed that air temperature has increased 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). Such changes have been also similar trends were detected in the three air temperature series analyzed for this study during covering the period 1955-2013 period. At the same time, there was a regional significant decline in snow accumulation from mid-March to late-April/early-May from 1950 to 2000 in the Pyrenees (López-Moreno, 2005). These trends during this period of decreasing precipitation and milder air temperatures during winter and early spring can be 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 that a shift towards more negative NAO has affected the recent evolution of air temperature and precipitation over the Pyrenees.
not include the effects of the cold and wet period of the 1960s to 1970s, no temporal

trends of either variable are found near Monte Perdido since the 1980s, when the study

time period starts in the 1980s and the effect of the cold and wet period of the 1960s to 1970s

is removed. Vicente-Serrano et al. (2010) found that the increased occurrence of very

wet winters during the 2000s was associated with frequent strong negative NAO

winters. In agreement, Buisan et al. (2015) indicated reported 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. In a most recent study, Buisan et al. (under

review) has reported observed stationary behavior or slight increases in snow water

equivalent for the period 1985-2015 in the central Spanish Pyrenees. The findings of

Macias et al. (2014) support the view that southern Europe and some other regions of

the world have undergone clear moderations of the warming trends that were

reported recorded 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 air temperature and a dry period compared to the period

since the end of the LIA (Büngten et al., 2008; Deaux et al., 2014; Marti et al., 2015).

More research is needed to fully assess the implications of the air temperature increase

detected in May and June in at the four analyzed meteorological stations. This

could lead to less snow accumulation at the end of the accumulation

season and a longer ablation period, and an early rise of albedo that may be

affecting the mass and energy balance of the glacier (Qu et al., 2014). Another

hypothesis factor that should be considered in future research is to consider the effect of

increasing increases in the slope of the glaciers glacier due to higher thickness

loss greater thinning in the distal part lower reaches. Increasing slopes are slope is
expected to affect snow accumulation on the glacier and might constitute another feedback mechanism to explain the underlying the recent evolution of the glacier.

The glacier-wide mass balance rates presented in this study for the different periods 1980-1999 and 1999-2010 (-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 those 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 glaciers in the Swiss Alps (Fischer et al., 2015), or for the best preserved glaciers in some areas of the Italian Alps (Carturan et al., 2013a, 2013b), but are lower than those of the fastest retreating glaciers in the Alps (Carturan et al., 2013b) or that reported for the Ossoue Glacier (French Pyrenees, -1.45 m w.e. yr⁻¹ for the 1983-2014). The smaller rates of mass loss on the Spanish side of the Pyrenees than on the French side may be explained by the location of the remnant ice bodies on the Southern side of the range, confined to the most elevated and the least exposed locations in their respective cirques (López-Moreno et al., 2006). In contrast, the Ossoue glacier has maintained a considerable glacier tongue with an eastward 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 for a dramatic reduction in the accumulation area ratio (AAR), and most of this glacier is below the current ELA (at 3050 m a.s.l. during the three-year period 2011-2014, Figure 6D). This leads to a clear imbalance that is very likely to be exacerbated by negative feedbacks. Because of this imbalance, the glacier cannot recover ice losses during periods with favorable conditions (high accumulation and/or little ablation in the frame of the 1983-
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), compared to a period with unfavourable conditions for the glaciers, did not allow recovery of the glacier to recover the losses from a negative year (2011/12). Thus the glacier thinning during this three-year period was -1.93±0.4 m (-0.58±0.36 m w.e. yr⁻¹), roughly approximately one-fourth of the loss from during 1981 to 1999, and from during 1999 to 2010. The accumulation area ratio AAR for the 2011-2014 period was 16-%, and during a warm and dry year the loss of ice thickness thinning affects almost the whole glacier (AAR<4%) = 3.5%), indicating that there is the lack of a persistent accumulation zone. Pelto (2010) observed that this is a symptom of a glacier that cannot survive. There can be years with mass gain, but there is mass loss occurs in most years and the retained snowpack of positive years is lost in bad years; then in fact negative years, such that there is no cumulative accumulation. Thus, the behavior observed for the Monte Perdido glacier during the study period is very likely explained by very negative mass balance in some years that may as can be identified in Figure 2. Thus, years with very high air temperatures occurred after 2000 (were very high in 2003, 2005 and 2012), and in 2005 and 2012 they were also characterized the latter two years the high air temperatures were accompanied by low winter precipitation. The feedback from decreased albedo and increasing glacier slope of the glaciers may also be playing a key role in the recent acceleration of the glacier wastage. Obviously, this indicates thinning. Together, these findings indicate 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 in the westernmost part of the lower glacier (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 feedback associated with 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 and increasing the emissivity of long-wave radiation. The highly consistent spatial pattern of ice thinning in the last 30 years suggests that the westernmost part of this glacier will disappear first; the easternmost part will survive longer as a small residual ice mass because of greater snow accumulation during positive years and a lower rate of degradation. When the glacier 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 its mass balance 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.

Acknowledgements

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indicadores de procesos de cambio global” (MAGRAMA 844/2013). The authors are grateful for the support provided by the “Dirección General de Conservación del Medio Natural (Government of Aragón)” and to the staff of the Ordesa and Monte Perdido National Park during our field campaigns.
References


Gómez de Llarena, J.: Algunos datos sobre el glaciar actual del Monte Perdido (Pirineos). Boletín de la Real Sociedad Española de Historia Natural 36, 327-343, 1936.


Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F.,
Haeberli, W., Denzinger, F., Ahlstrøm, A.P., Anderson, B., Bajracharya, S., Baroni,
C., Braun, L.N., Caceres, B.E., Casassa, G., Cobos, G., Davila, L.R., Delgado
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A., Hagen, J.O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V.V.,
Portocarrero, C.A., Prinz, R., Sangewar, C.V., Severskiy, I., Sigurdsson, O., Soruco, A.,
Usubaliev, R., Vincent, C.: Historically unprecedented global glacier decline in the
Figure captions

**Figure 1.** Monte Perdido study area and extent of ice cover at the end culmination of the Little Ice Age (according to the map of Schrader [1874]) and in 2008. Red squares mark the scanning positions, numbered points indicate the positions of the fixed targets used for georeferencing and merging the different clouds of points. Red circles in the right panel inform of the location of the analyzed meteorological stations.

**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 Góriz meteorological station (1983 to 2014). Boxplots at the right of each panel show the interannual variability during the last 3 years of the study period (2011/12, 2012/13, and 2013/14) when terrestrial laser scanning measurements were available. Box: 25th and 75th percentiles, bars: 10th and 90th percentiles, dots: 5th and 95th percentiles, black line: median, red line: average.

**Figure 3.** Interannual fluctuations of minimum and maximum air temperatures during the accumulation and ablation periods and precipitation during the accumulation period at the stations of Aragnouet, Canfranc, Mediano (only air temperature) and Pineta (only precipitation) during the period 1955-2013. Numbers give the Tau-b values of the trends. Asterisks indicate statistically significant trends ($p<0.05$).

**Figure 4.** Photographs of the Monte Perdido Glacier during the late summer in 1981 and 2011.
Figure 5. Changes in glacier Surface elevation change in the upper and lower Monte Perdido Glacier from 1981 to 1999 and from 1999 to 2010 based on comparison of DEMs.

Figure 6. Changes in glacier Surface elevation change in the upper and lower Monte Perdido Glacier based on terrestrial laser scanning from September of 2011 to 2012 (Fig. 5A), 2012 to 2013 (Fig. 5B), 2013 to 2014 (Fig. 5C), and 2011 to 2014 (Fig. 5D).

Figure 7. Changes in glacier Surface elevation changes over the whole glacier, lower glacier, and upper glacier for the same 4 time periods examined in Figure 5. Box: 25th and 75th percentiles, black line: median, red line: average, bars: 10th and 90th percentiles, dots: 5th and 95th percentiles.
Table 1. Tau-b values of the trends for the period 1983-2013 for air temperature and precipitation in the analyzed stations. Asterisks indicate statistically significant trends ($p<0.05$). Bold numbers are statistically significant differences in the medians of the period 1982-1999 and 1999-2010 according to the Mann-Whitney test.

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<th>Mediano</th>
<th>Pineta</th>
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Table 2. Surface area (ha), loss change of surface area (ha), and annual rate of surface area loss (ha yr\(^{-1}\)) of the Monte Perdido Glacier.

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Figure 1.
Figure 2.
Figure 3.

Aragnouet: 0.21
Mediano: 0.35*
Canfranc: 0.14

Aragnouet: 0.27*
Mediano: 0.39*
Canfranc: 0.20*

Aragnouet: 0.15
Mediano: 0.13
Canfranc: 0.14

Aragnouet: 0.32*
Mediano: 0.19
Canfranc: 0.28*

Aragnouet: -0.07
Mediano: 0.12
Canfranc: 0.14

Aragnouet: 0.07
Mediano: 0.12
Canfranc: 0.14

Aragnouet
Mediano
Canfranc
Pineta
Figure 4.
Figure 5.
Figure 6.
Figure 7.