**Zaragoza 12/02/2016**

Dear editor,

It is our pleasure to submit a deeply revised version of the paper, now entitled: "RECENT ACCELERATED WASTAGE OF THE MONTE PERDIDO GLACIER IN THE SPANISH PYRENEES", by J.I. López-Moreno and others.

We want sincerely to thank to all of you by the high quality of your edits and your comments. We have followed all the comments raised by the reviewers that they were mostly stylistic, or asking for some small clarification. It also includes some small change in Figure 1 and 3. Below, you can find a point by point answer to each question received by reviewers, as well as the "tracked changes" version of the manuscript.

Of course, we will be happy to continue discussing and adding any improvement that you can consider still necessary.

Looking forward to hear your kind reply,

Ignacio López and co-authors

**REVIEWER 1**

López-Moreno et al, (2016) provide a detailed volume change/mass balance record for Peridido Glacier. The record uses typical geodetic methods, supplemented in recent years by TLS measurements. The results are compared to local climate data. Given the low probability that this glacier can survive beyond the next few decades, this paper is an important observational times series and snapshot. I encourage the authors to continue the TLS observations.

**Answer:** Thanks a lot for your time reviewing again the manuscript and your positive comments. We really want to maintain the monitoring of this glacier, and we are already looking for a permanent funding to ensure the continuity of our research

- 2-14: The mass loss cited for 2011-2014 is not close to equilibrium or that much of a change from the previous period. -0.58±0.36 m w.e. yr-1; Possible reword

**Answer:** The sentence has been reworded as follows: "This loss of glacial ice has continued at a lower rate from 2011 to 2014 (the glacier depth decreased by 1.93±0.4 m, -0.58±0.36 m w.e. $yr^{-1}$)",

- These data 15 indicated that 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 the dramatic shrinkage that occurred during the dry and warm period of 2011-2012.

**Answer:** Thanks, we have changed the sentence accordingly.

2-20: Reword: Local climatic changes observed during the study period seems do not sufficiently explain the acceleration in wastage rate of this glacier, because precipitation and air temperature did not exhibit statistically significant trends during the studied period.

**Answer:** Thanks, we have changed the sentence accordingly.

- 4-4: Reword: transitioned from an ice based glacier during the mid-20th century and became a rock glacier.

**Answer:** Reviewer 3 also suggested changing this sentence and we have followed his recommendation (very similar to yours, thanks)

- 4-7: remove “are”

**Answer:** Done, thanks

-4-14: reference

**Answer:** We have used the following reference: Grunewald, K., Scheithauer, J.: Europe's southernmost glaciers: response and adaptation to climate change. Journal of Glaciology, 56 (195), 129-142, 2010.

- 4-25: accumulation area ratios

**Answer:** Changed

-5-18: avalanches, wind drifting and new rock exposures. In the case of shrinking glaciers the latter can be key.

**Answer:** we have changed the sentence taking into account your comments: “Moreover, very small glaciers may develop and evolve for reasons unrelated to the regional long-term, monthly or seasonal climatic evolution, such as avalanches, wind drifting and new rock exposures. In the case of shrinking glaciers the latter can be key (Chueca et al. 2004; Serrano et al., 2011; Carturan et al., 2013c).”

9-5: Without providing any evidence the short lived foehn events should not be referenced.

**Answer:** We have removed the reference to potential effect of föhn events.

10-17: “punctually values “? Does the mean consistent values?

**Answer:** We changed the sentence following the recommendation of reviewer 3.

12-10: It would be useful to have an image from the TLS scan position.

**Answer:** We have stated in the revised version of the manuscript that the view from the scan position is the same than the photos shown in Figure 4.

12-13: Were the targets placed on ice or rock or what combination of these, how large are they?

**Answer:** We specify now: “11 reflective targets of known shape and dimension (cylinders of 10x10 cm for those located closer than 200 meters, and squares of 50x50 cm for longer distances) were placed at the reference points on rocks at a distance from the scan station of 10 to 500 m”.

- 13-18: Reword: May and October are transitional months between accumulation and ablation conditions depending on specific annual conditions.

**Answer:** Changed, many thanks.

14-18: Reword… is in line with observations at three other meteorological stations

**Answer:** Changed, it was also suggested by Reviewer 3.

- 15-16: The trend may not be significant but it appears from Figure 3 that the mean temperature when viewing the combination of stations all changed notably from the 1950-1983 period to the 1983-2014 period. If this can be easily reported and has occurred it would be worth noting.

**Answer:** We stated this in the following sentence, that it has been modified following the recommendation of reviewer 3: “Figure 3 shows the interannual evolution of temperature and precipitation series for a longer time slice (1955-2013). They illustrate that climate observed during the main studied period (1983-2013) is not necessarily representative of the longer climate series. Thus, the 1955-2013 period exhibits a statistically significant ($p<0.05$) warming during the ablation period, and the accumulation exhibited positive tau-b values but did not reach statistical significance.”

- 16-24: such areas increase ablation through greater retention of solar energy.

**Answer:** Probably, this is the main cause, but we are not in conditions to affirm this point as we have not yet enough data to fully understand the mass and energy balance of the glacier. We hope to have more data in the next years in this regard.

18-22: The AAR of only 54 also suggests the conditions were not that good.

**Answer:** We indicate in the revised manuscript: "Nonetheless, during this year, large areas remained stable (AAR was 54%) and some areas even exhibited noticeable ice losses (more than 1.5-2±0.4 m in the upper and lower glaciers)."

- 19-8: remove the negative sign from in front of 1.93.

**Answer:** removed

- 20-5: Since you have indicated limited snowfall change, you cannot say…"sharp decline of snow accumulation"

**Answer:** We have slightly modified this sentence as follows: "Climatic analyses suggest that the recent acceleration in the wastage of the Monte Perdido Glacier cannot be only explained by an intensification of climate warming or by a decline of snow accumulation".

-20-14: This does not agree with earlier statement of lack of significant trend. "Such changes have been also detected in the three temperature series analyzed for this study during the period 1995-2013"

**Answer:** There was a mistake in the period, the period is 1955-2013, it has been changed in the revised manuscript.

-22-5: Reword, but much lower than most retreating glaciers in the Alps (Carturan et al., 2013b), such as Ossoue Glacier.

**Answer:** We have changed it accordingly to reviewer 3, who suggested a deeper rewording of the sentence

23-22: will survive longer

- **Answer:** Changed.

**REVIEWER 3**

This manuscript is an extensive revision of an earlier submission, and I am asked to assess whether the revision responds adequately to comments by previous reviewers. The short answer is Yes, in that requests for broader treatment of local and regional climatic forcing have resulted in the incorporation of data from more weather stations and additional detail about the North Atlantic Oscillation. Moreover the detailed comments of the earlier reviewers, M. Pelto and L. Carturan, have also been attended to carefully.

My own view, like that of Dr. Pelto, is that this is a potentially and actually valuable study of a small glacier using field and remote-sensing methods. The work is documented in detail and has been carried out in accordance with prevailing norms. The annual balances obtained by terrestrial laser scanning are well described and information about this relatively new method is welcome. The mass-balance measurements themselves are intrinsically valuable. The authors conclude that more rapid mass loss in the 2000s, in spite of the climatic forcing remaining essentially constant, is due to the glacier being so far from equilibrium that occasional years of mass gain do not suffice to slow the loss rate. To put this another way, the climate has left the glacier so far behind that it is no longer capable of "catching up". Appropriately tentative suggestions are made to account for the acceleration of loss, including significant late-winter warming, increasing glacier slope and increasing coverage by thin debris. These would all be suitable subjects for further investigation.

Notwithstanding this favourable assessment, there is still scope for considerable improvement in clarity, stylistic correctness and removal of typos, but if the authors can satisfy the editor about the changes suggested below I would not anticipate a need for yet another review.

**Answer:** Authors sincerely thank the positive comments and the deep review that the reviewer has done on some technical questions and for a lot of stylistic comments. Some parts of the text were heavily modified after the first revision, and the reviewer has edited all this text in a very kind and explanative way.

**Substantive Comments**

- P2 L6, L9 The relation between the 1999 topographic map and the year 2000 that is mentioned at L9 should be clarified.

**Answer:** It has been clarified and now it is stated “after 1999”

-L17 Rewording needed to clarify the emphasis. “still” and “overall” should both be deleted, and “were” should be “was”, but I do not understand why the mass-balance clause begins with “but” when it seems to agree with the main deceleration clause.

**Answer:** The sentence has been modified and simplified as follows: “These data indicated that two consecutive markedly anomalous wet winters and cool summers (2012-13 and 2013-14) represented a deceleration in wastage compared to previous years, with a mass balance near zero”.

-L23-24 I would suggest “by the strong disequilibrium”, and change “climatic conditions” to “climate”.

**Answer:** The sentence has been changed accordingly: **“**The accelerated degradation of this glacier in recent years can be explained by the strong disequilibrium between the glacier and the current climate and probably other…”

-L8-9 Do you know that the LIA “ended” in the mid 19th century? Unless you have firm data, e.g. from lichenometry, I would say “believed to have been in …”. And strictly the LIA culminated rather than ended then.

**Answer:** Thanks, now the sentence states: “Most glaciers worldwide have undergone intense retreat since the culmination of the Little Ice Age (LIA) believed to have been in the mid 19$^{th}$ century, as indicated by measurements of ice surface area and volume”.

- P4 L25 “accumulation area ratios”. An “accumulation ablation ratio” could only be the ratio of the accumulation area to the ablation area, which would range inconveniently between 0 and infinity (as would be nearly true of the Antarctic Ice Sheet).

**Answer:** Changed to “accumulation area ratios”.

- P7 L4 Delete “short”. (You do not yet know that it is over, the two years of slight mass gain being insufficient to establish the point.).

**Answer:** We have removed “short”

-L10 The longitude and latitude of the glacier would be useful information here.

**Answer:** We agree, and we have added this information

-P9 L1 “a.s.l., 2.7 km from the glacier)”.

**Answer:** Changed as indicated

-(As at P13 L10.) L19 I do not understand “unified working under”, but a separate sentence should probably be given to the selection of the datum ED50. At P12 L14 there should be an explanation of how 2 the DGPS positions referred to ETRS89 were reconciled with the rest of the work done in ED50.

**Answer:** Reviewer was right that the text suggested that one of the datum, was converted into the other, when really the two analyses were done using a different datum. This does not affect at all to the presented results as we do not compare directly the data 1981-2010 with the one collected from 2011 to 2014. To clarify this, we have slightly modified the text as follows: “All three DEMs have and cell size of 2x2 $m^2$, and they were used in the context of a geographic information system (GIS), working under the European Datum ED50 (UTM projection, zone 30).

-P10 L6 Replace “late summer of 2010” with the exact date if it is known.

**Answer:** We have indicated now that it was in September of 2010, this is all information provided by IGN.

- P11 L14 More information is needed. It is not obvious how to calculate uncertainty in area given only an uncertainty in position.

**Answer:** We have added this information in the manuscript “The maximum horizontal error was used to calculate the uncertainty of glacierized 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”. We have checked and repeated again the procedure to calculate them and we realized that there were some mistakes in the numbers, in particular to calculate the error of areal changes in two different periods, when the individual errors for each date must be summed. This has been corrected

-L19-20 This sentence is incoherent and does not give enough information. Replace it with a proper explanation of how you calculated the uncertainties in the rates of elevation and mass change.

**Answer:** We have modified the sentence as follows: "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 than 40 cm. Such 40 cm of error was considered as the uncertainty (added as error bars) to the calculated ice depth and mass loss rates." We hope now is easier to be understood.

-P13 L2-3 This is an odd way of saying what needs to be said. Perhaps "overestimate the mass loss rate for 1981–1999."

**Answer:** We agree that your suggestion makes the sentence much easier to be understood. "Unfortunately, the lack of additional information forced us to take this generalization that may slightly overestimate the mass loss rate for 1981–1999".

- L13-14 What about October?

**Answer:** Few lines later we explain that October and May can be considered as transitional months.

-17 L17-18 "The greatest thinning was at …". Consider rationalizing the terminology; we have had "depth loss", "thickness decay" and now "loss of thickness". "Thinning" would be clearer than all of these.

**Answer:** Despite we use still some different terminology to avoid repetitiveness, this revised version uses "thinning" very often.

- P18 L1. The mixture of signed and unsigned losses and gains makes this section especially hard to follow.

**Answer:** Now all losses and gains are signed to avoid confusion. In this last version we only not use signs when the numbers immediately follow a word that informs of the sign (i.e. a decrease of…)

-P19 L4 Clean up the garbled "0.070.08".

**Answer:** Done

-L10 Nine readers out of 10 will not know that "rimaye" is the French for "bergschrund", which is the almost universal technical term.

**Answer**: Thanks, we have changed "rimaye" by "bergschrund",

-P21 L19-22 "is that increasing slope of the glaciers, due to greater thinning at lower elevations, affects snow accumulation and constitutes another …". But how does the slope "affect" accumulation? Are the lower elevations experiencing greater ablation, in which case the hypothesis is not about accumulation? Or is more snow avalanching off the glacier? Incidentally, there is nothing wrong with "distal" and "proximal", but they are more common in geomorphology, and most glaciologists have to pause to work out which is which. (At least, I do.)

**Answer:** We added this paragraph as a suggestion of one of the reviewers. We think that it is true that the slope of the glacier has increased, and it may affect to snow accumulation. However, we have not yet any evidence on how may affect and this is why we propose this just as a hypothesis to corroborate in the future. We have been thinking some alternative to "distal" and we do not find an accurate terminology to refer ths part of the glacier ("terminus"? "glacier snout"?) any suggestion will be very welcome. Thanks.

-P22 L24 Delete "average"; you mean "total". Change "decrease of glacier depth" to "thinning".

**Answer:** We have modified the sentence as follows: "Thus the glacier thinning during this three years period was 1.93±0.4 m, roughly one-fourth of the loss from 1981 to 2000, and from 2000 to 2010."

- L25 The text keeps switching between m of thickness change and m w.e. of mass change. The earlier numbers in this paragraph are all mass changes, and now the reader suddenly has to change back to thinking in units of length. In other parts of the text, both units are presented, which makes for difficult reading in a different way (too much indigestible information). Along with consistent use of minus signs, I think that presenting changes in just one unit would improve the manuscript greatly. The obvious choice would be m of thickness change, given that the density is only assumed (as in most other geodetic studies).

**Answer:** We presented the changes in both units because it was required by one of the reviewers. I can wait he editor´s decision to proceed in a definitive direction. My opinion is that presenting both units (even when mass change is estimated with some rough assumptions) may benefit the comparison with available literature that presents both units. In that part of the discussion we have added the mass change to the glacier thinning data.

**-**P23 L1 As far as I can tell from section 3.1, no measurements were made in 2000, so I do not know what this sentence is about.

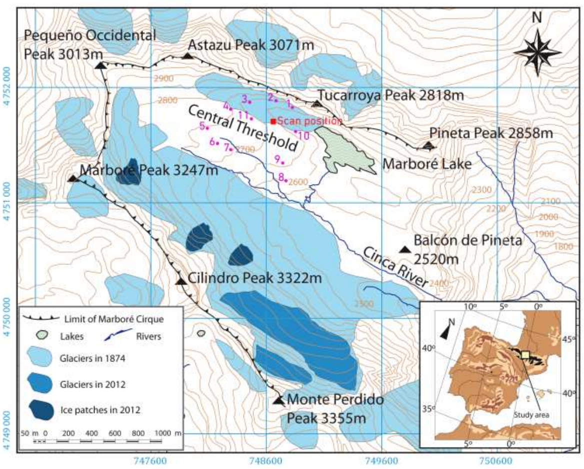
**Answer:** our mistake. It has been changed by "1999"

- L10-12 Delete "As mentioned before, also", and change "must" to the more cautious "may also". Your conjectures are persuasive, but you have no actual evidence.

**Answer:** Thanks, we have changes as follows: "The feedbacks from decreased albedo and increasing slope of the glaciers may also be playing a key role in the recent acceleration of the glacier wastage."

Figure 1 The UTM zone of panel a should be mentioned in the caption. The eastings in Figure 5 are ~492 km greater than those of Figure 1, and this must be explained (and corrected if it is an 3 error). (The scale of a UTM projection is true at eastings of ~320 km and ~680 km, so the zone chosen for Figure 5 is slightly "worse" than that of Figure 1. But the error is negligible.)

**Answer:** Thanks for detecting this mismatch. The study area is just in the change of UTM band. We have unified the coordinates of both figures, by modifying the ones in figure 1.



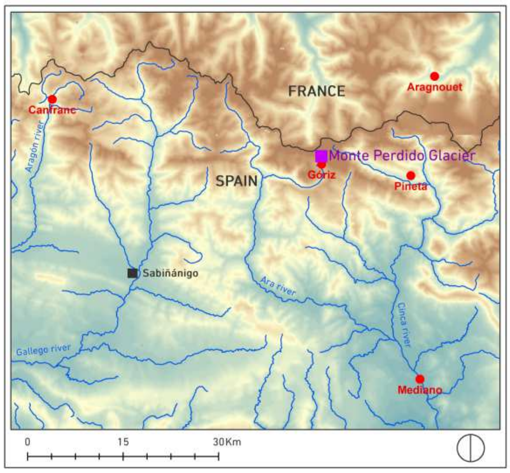




Table 1 Give Table 1 its correct number, and change “inform of” to “are”. Table 2 The errors that end with a decimal point need a following decimal digit. The caption should explain the integers that appear in the third row. By propagation of the errors in area the errors in area change should be much larger than those given. For example for 1986 to 1999 the upper-glacier error in area change should be ±0.36, not ±0.06. This illustrates why a more complete description and justification of the error analysis needs to be provided. (See P11 L14 and P12 L19-20 above.) This table should be expanded to give all of the thickness changes (or mass changes if you prefer) as well as all the area changes. After all, you yourself assert (correctly) that mass change measurements “give better information” than measurements of area or length change (P6 L2). This would allow some space to be saved in the text on P17, and perhaps even on P18-19.

**Answer:** This table was wrong because page orientation should have been “landscape” instead of “portrait” and numbers were distorted. A better description of error estimation has been provided and we hope it will be now easy to be understood for readers. In our opinion we prefer to maintain this table devoted to provide data only for surface changes, as there are 3 other figures informing of ice depth changes. Years of information on ice depth changes are different to those with surface information and we think it may result in a confusing table. Of course, we are completely open to reconsider this point.

**Stylistic Comments**

**Answer:** All stylistic comments have been closely followed. Authors really thank the big effort for improving the readability of the manuscript

Figure 2. Spelling of “accumulation” should be corrected in panels a, c and e. Figure 3 “at the stations”. Change “inform of” to “give”. Italicize p in “p

**Answer:** Figure 2 has been corrected, and the caption of Figure 3 accordingly modified.

# RECENT ACCELERATED WASTAGE OF THE MONTE PERDIDO GLACIER IN THE SPANISH PYRENEES

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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 nearby meteorological stations. The results indicate an accelerated degradation of this glacier after 20001999, with a rate of ice surface loss that was almost three -times greater from 2000 to 2006 than for earlier periods, and 1.85 times faster rate of glacier volume loss from 1999 to 2010 (the ice depth decreased by 8.98±1.80 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±0.10 m w.e. $yr^{-1}$). This loss of glacial ice has continued at a lower rate from 2011 to 2014 (the glacier depth decreased by 1.93±0.4 m, -0.58±0.36 m w.e. $yr^{-1}$). These data indicated that 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 the dramatic shrinkage that occurred during the dry and warm period of 2011-2012These data indicated that two consecutive markedly anomalous wet winters and cool summers (2012-13 and 2013-14) represented a deceleration in wastage compared to previous years, but still the overall with the mass balance were near zeroo, 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. :. Local climatic changes observed during the study period seems do not sufficiently explain the acceleration in wastage rate of this glacier, because precipitation and air temperature did not exhibit statistically

significant trends during the studied period.~~Local climatic changes observed during the study period seems not be enough to explain the acceleration in wastage rate of this glacier, because precipitation and air temperature has not exhibited generalized statistically significant trends during the studied period.~~ The accelerated degradation of this glacier in recent years can be explained by~~-~~ the strong disequilibrium~~the lack of equilibrium~~ between the glacier and the current ~~climatic conditions~~climate and probably other factors affecting the energy balance (i.e. increased albedo in spring) and feedback mechanisms (i.e. emitted heat from recent ice free bedrocks and debris covered areas).

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

## 1 Introduction

Most glaciers worldwide have undergone intense retreat since the ~~end~~ cumination of the Little Ice Age (LIA) believed to have been in ~~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 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 -0.4% per year from 1969 to 1997 and -0.9% per year 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 reported that the rate of ice mass loss in the long-term monitored Careser Glacier (Italian Alps) during the period 1981-2006 (−1.3 m w.e. $yr^{-1}$) was about twice that for the period of 1933 to 1959 (-0.7 m w.e. $yr^{-1}$). 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 exceeds 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~~,~~ during the LIA, evolved into a rock glacier during the mid-20th century and has suffered marked degradation ~~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 Pyrenees host some of the southern~~-~~most glaciers of Europe ~~are~~, and they have also undergone significant retreat (Grunewald and Scheithauer, 2010). In 2005, these glaciers had an area of 495 hectares (González-Trueba et al., 2008) and in 2008 they had a total area of 321 hectares (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 $20^{th}$ century and the beginning of the $21^{st}$ 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. The temperature increase has been particularly strong since the 1970s~~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~~ area ratios ~~(AARs)~~ of glaciers, so that most glaciers are not in equilibrium with current ~~climatic conditions~~climate (Mernild et al., 2013) and many of them cannot survive for much longer (Pelto, 2010). In the case of the Pyrenees, the annual air temperature has increased by a minimum of 0.9ºC since the end of the LIA (Dessens and Bücher, 1998; Feulliet and Mercier, 2012). More recently, Deaux et al., (2014) reported an increase of 0.2ºC decade$^{-1}$ for the period between 1951 and 2010. This explains the ~255 m increase in the elevation of the ELA ~~in~~ of the glaciers of the Maladeta Massif since the end 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~~ on 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 area and mass of a particular glacier. This is is difficult because only glaciers of small size respond rapidly to changes in annual snowfall and snow/ice melt, whereas mid and large glaciers respond much more slowly

**Con formato:** Sin Resaltar

(Marshall, 2014). 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 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 the regional long-term, monthly or seasonal climatic evolution, such as avalanches, wind drifting and new rock exposures. In the case of shrinking glaciers the latter can be keyand snow accumulation due to wind (Chueca et al. 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 lengths. These parameters respond to climate fluctuations, although this relationship is also affected 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 between glacier changes and climatic changes (Chueca et al., 2007; Cogley, 2009; Fischer et al., 2015). In the Pyrenees, there are very few estimations of ice volume loss (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 the glaciological method were only performed in on the Maladeta Glacier (Spanish Pyrenees) and on the Ossoue Glacier (French Pyrenees), and these indicated the mean glacier depth lossthinning was -14 m during the last 20 years oin the Maladeta Glacier, and -22 m oin 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 of 1981 and 1999 in the Maladeta Massif (Chueca et al., 2008) and the Monte Perdido Glacier (Julián and Chueca, 2007), and reported losses of -0.36 m w.e. $yr^{-1}$ and of -0.39 m w.e. $yr^{-1}$, respectively.

This paper focuses oin 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 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 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 in the last decades of the 20th, associated to a persistently positive North associated to persistent positive conditions of the North Atlantic Oscillation index in the beginning of the 21st century (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 (42°40′50″N 0°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 $km^2$).

Código de campo cambiado

Con formato: Inglés (Estados Unidos)

Researchers have studied glaciers in the Marboré Cirque since the mid $19^{th}$ century (Schrader, 1874), and many ~~next~~ subsequent studies examined the extent and made descriptions of the status of the 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 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 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, but

~~dissapeared~~disappeared after the 1970s (Nicolas, 1986; García-Ruiz et al., 2014). The two remaining glacier bodies, which are currently unconnected, are referred ~~in~~ 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 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 (≈40º).

There has not been a direct ~~estimation~~ observation 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 5.03ºC, although this station is on the south-facing slope of the Monte Perdido Massif. Assuming a lapse rate of 0.55ºC to 0.65ºC every 100 m, the annual 0ºC isotherm should be roughly at 2950 to 3150 m a.s.l. ~~, although it might be slightly lower because the glacier is north-facing, and the annual temperature in Góriz might be enhanced by the occurrence of föehn events.~~

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.

## 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 three~~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 2x2~~4~~ m~~$^2$~~, and they were used in the context of a geographic information system (GIS), ~~and~~ working ~~unified working~~ under ~~a single unique geodetic datum (~~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 ~~late summer~~September of 2010 in the context of the National Plan for Aerial Orthophotography (NPAO).

The Root Mean Squared Error (RMSE) for ~~vertical~~ 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 ~~the validity of~~ these accuracies we made a comparison of 2010-1999, 2010-1981 and 1999-1981 pairs of DEMs in areas of ice-free terrain placed ~~in the vicinity of~~near the studied glaciers. The results showed good agreement with the accuracy indicated by the IGN in almost all areas although larger vertical errors~~higher vertical altimetry~~ errors were identified in several sectors of very steep terrain (with slope values usually > 65º) 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 ~~punctually values in the range of~~ 10-15 m. As both Upper and Lower Monte Perdido glaciers are placed well outside those areas and have smoother topographical surfaces ~~of a smoother nature~~ it might be assumed that the altimetric data provided by the IGN has an appropriate consistency over glaciated terrain.

The combined vertical RMSE ~~for the 1981-1999 DEMs~~ for DEM differences was < 2.5 m for 1999 minus 1981 and < 2.0 m for 2010 minus 1999~~was < 2.5 m and < 2.0 m for the 1999-2010 comparison~~. 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 elevation changes ~~alter the combined data accuracy~~ (Rolstad and others, 2009). In any case, both these errors were considered~~both combined vertical RMSE were considered~~ precise enough for our purposes as the ice-depth changes obtained in our analysis were generally much higher than these values. 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 ~~value~~ was used to calculate the uncertainty of glacierized areas ~~to calculate error bars to estimated glaciated areas~~ and their temporal changes. This uncertainty was calculated using the *buffer* tool in ArcGIS. This tool allowed ~~to quantify~~quantifying~~, that calculated~~ 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~~ width~~ of 0.0188º, a laser beam divergence of 0.0468º, 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 an almost frontal view of the glacier ~~–~~(same as 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. ~~Thus,~~ 11 reflective targets of known shape and dimension (cylinders of 10x10 cm for those located closer than 200 meters, and squares of 50x50 cm for longer distances)~~are~~ were placed at the reference points on rocks 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 ~~for~~ the set of target coordinates was ±0.05 m ~~the global target coordinate was 0.05 m~~ in planimetry and 0.10 m in altimetry. A total of 65 reference points around~~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 an ~~elevation difference~~error lower than 0.40 ~~c~~m~~, and there was no apparent relationship between scanning distance and observed error~~. Such 40 cm of ~~deviations~~ error was considered as the uncertainty (~~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 $m^{-3}$ (Chueca et al., 2007; Marti et al., 2015). The assumption of this value neglects the existence of ~~a~~ firn, with a lower density. This is mostly true at the end of the study period, but probably in the early eighties this assumption is not completely true and firn areas existed (i.e. according to Figure 3A). Unfortunately, the lack of additional information forced us to adopt~~take~~ this generalization that may slightly ~~underestimate the acceleration in ice loss rates during the last years (i.e. after 1999) compared to the 1981-1999 period.~~ overestimate the mass loss rate for 1981–1999.

### 3.2 Climatic data

The Spanish Meteorological Office (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. ~~Given no~~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), 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 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.~~that May and October are transitional months between accumulation and ablation. conditions depending of the especific~~specific ~~annual conditions.~~ However, we set these periods because June and November are the months when ablation and accumulation respectively become generally evidentbecause is June and November when ablation and accumulation is generally evident over the surface of the glacier. 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). Results obtained for Góriz were contrasted with those from three in Góriz were contrasted with three other observatories (see Figure 1) with precipitation (Pineta, Aragnouet and Canfranc), and temperature (Mediano, Aragnouet and Canfranc) data for the period 1983 and 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 temperature when the periods 1983-1999 and 2000-2010 are compared.

## 4. Results

### 4.1. Climatic evolution and variability from 1983 to 2014

Figure 2 illustrates the high interannual variability of climate atin Góriz station since 1983. The average maximum air temperatures atin Góriz during the snow accumulation and ablation seasons had 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 3ºC and 4ºC during the accumulation and ablation periods, respectively for maximum and minimum temperatures. The average minimum air temperatures had 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 (~5ºC) than for the ablation period (~2.5ºC). Table 1 shows that the evolution of temperature atin Góriz is line with thate observed atin the three other meteorological stations (Mediano, Aragnouet and Canfranc). They do not exhibit~~, with no~~ statistically significant trends for maximum or minimum temperature~~, for neither accumulation nor ablation periods~~ during the period 1983-2013. ~~At~~ On a monthly basis, the four analysed observatories only ~~detected~~ exhibited a statistically significant increases in May and June; and ~~a~~ statistically significant decreases of maximum and minimum temperature in November and December ~~for both, maximum and minimum temperature~~. The Mann-Whitney test did not reveal~~ed~~ statistically significant differences in the medians of the series for the accumulation and ablation seasons ~~in~~ at any observatory when the periods 1983-1999 and 2000-2010 were compared.

Precipitation at~~in~~ Góriz during the accumulation period also exhibited strong interannual variability, with a range of ~ 600 mm to 1500 mm (Fig. 2e). The trend line had 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 of precipitation ~~in~~ at Góriz during May, and near zero tau-b coefficients for the most of the months. Very similar results are found for the other three analyzed stations (Pineta, Aragnouet and Canfranc) with no statistically significant trends for the accumulation and ablation periods. Only Aragnouet showed a statistically significant increase in May, and Pineta 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 ~~in~~ were found at any of the analyzed meteorological stations.

In addition, Figure 3 shows the interannual evolution of temperature and precipitation series for a longer time slice (1955-2013). They illustrate that climate observed during the main studied period (1983-2013) is not necessarily representative of the longer climate series. Thus, the 1955-2~~3~~013 period exhibits a statistically significant ($p$<0.05) warming during the ablation period, and the accumulation exhibited positive tau-b values but ~~but~~ did not reach statistical significance~~not reaching statistically significance~~. Precipitation during the accumulation period did not exhibit statistically significant trends during the period 1955-2013 in any of the three analyzed observatories.

Con formato: Fuente: Cursiva

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, 96th and 74th percentiles for maximum and minimum 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 18$^{th}$ percentiles for maximum and minimum temperatures respectively), and the accumulation period of 2013 to 2014 was very wet (78$^{th}$ percentile) and slightly cooler than ~~around~~ average respectively, with air temperatures around or below the average (22th and 48th percentiles for maximum and minimum temperature respectively) during the ablation months.

**4.2 Glacier evolution from 1981 to 2010**

Figure 4 shows two photographs of the glacier taken in late summer of 1981 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 between~~from~~ 1973 and~~to~~ 1978), and they exhibited a convex 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 2 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 2006, the glacier losses~~t~~ 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 (Figure 5). 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 glacier ~~thickness decay~~thinning 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 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 ~~loss of ice thickness~~thinning 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~~thinning resembled the pattern from 1981-1999, but areas of noticeable glacier losses are also found 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 most effective shading of these areas, 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 6 shows the differences in glacier depth 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 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 glacier depth~~glacier thinning, with an average decrease of 2.1 ±0.4 m (2.08±0.4 m in the upper glacier and 2.12±0.4 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 loses were more than 4 ±0.4 m~~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~~-~~±0.4 m~~m~~, 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 losses (more than 1.5-2~~–~~±0.4 m~~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 (AAR was 41%, 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 0.07~~0.08~~±0.4 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 -1.93±0.4 m (0.58±0.36 m w.e. $yr^{-1}$), with some regions experiencing losses greater than 6~~-~~±0.4 m~~m~~. Only the areas of the eastern part of the lower glacier that were at high elevations (around the bergschrund~~rimaye~~) exhibited some elevation gain during this period (accumulation area ratio, AAR, for the three years was 16%), and this was typically less than 2~~–~~±0.4 m~~m~~. Interestingly, the areas with greatest and lowest ice losses during 1981-2010 were similar to those with the greatest and 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~~after the culmination 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 glacier thinning~~loss of ice thickness~~ from 1999 to 2010 was double ~~the rate~~that observed observed from 1981 to 1999. Acceleration in glacier shrinkage has been also reported for~~in~~ the Ossoue Glacier (French Pyrenees), where mass balance~~ decline~~ during the period 2001-2013 (−1.45 m w.e. yr$^{-1}$)~~,~~ is 50% greater compared to the period 1983-2014 (−1 m w.e. yr$^{-1}$), (Marti et al., 2015). Climatic analyses suggest that the recent acceleration in the wastage of the Monte Perdido Glacier cannot be only explained by an intensification of climate warming or by ~~the sharp~~a decline of snow accumulation. Climate data (1983-2014) of a nearby meteorological station, and three other Pyrenean meteorological stations, suggests that during most of the year temperature has not exhibited statistically significant trends. The Mann-Whitney test did not reveal statistical differences in temperature when the period 1983-1999 ~~is~~ was compared to 1999-2010. Precipitation in the four analyzed stations during the accumulation period and maximum annual snow depth ~~in~~ at Góriz were also stationary or slightly increased. Previous studies of the Pyrenees and surrounding areas showed that air temperature has significantly warmed throughout the 20$^{th}$ 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 detected in the three temperature series analyzed for this study during the period 195~~9~~5-2013. 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~~ that a shift towards more negative NAO has affected the recent evolution ~~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 either variable are found near Monte Perdido since the 1980s~~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~~ during 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. In a most recent ~~research~~study, Buisan et al. (under review) has reported stationary behavior or slight increases in ~~the available series of~~ snow water equivalent ~~series available~~ for the period 1985-2015 in the central Spanish Pyrenees. 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 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). More research is needed to fully assess the implications of the temperature increase detected in May and June in the four analyzed meteorological stations. This change 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 ~~hypotesis~~hypothesis that should be considered in future research is to consider the effect of increasing slope of the glaciers, due to higher thickness loss in the distal parts. Increasing slopes are expected to affect snow accumulation on the glaciers and might constitute another feedback mechanism to explain the recent evolution of the glacier.

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 (Carturan et al., 2013 a); but lower than those of the fastest retreating~~much lower to the most retreating~~ glaciers in the Alps (Carturan et al., 2013b) or ~~the one~~that reported ~~in~~ for the Ossoue Glacier (French Pyrenees, -1.45 m w.e. yr$^{-1}$ for the 1983-2014). The smaller rates ~~in~~ on the Spanish side of the Pyrenees ~~compared to the~~ than on the French side~~later~~ may be explained by the location of the remnant ice bodies o~~i~~n Southern side of the range, confined to~~in~~ the most elevated and the least exposed locations ~~and the best topographic locations (higher snow accumulation and radiation shilding)~~ in their respective cirques (López-Moreno et al., 2006). ~~Oppositely~~In contrast, the Ossue glacier ~~still~~ has maintained a considerable

**Con formato:** Superíndice

glacier tongue on an eastward slope~~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~~ for a dramatic reduction in the accumulation area ratio (AAR), and most of this glacier is ~~currently~~ 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 1983-2014 period). 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 losses from a negative year (2011/12). Thus the ~~average decrease of~~ glacier thinning~~depth~~ during this three years period was 1.93±0.4 m (0.58±0.36 m w.e. yr$^{-1}$), roughly one-fourth of the loss from 1981 to ~~2000~~1999, and from ~~2000~~ 1999 to 2010. The accumulation area ratio for the 2011-2014 period was 16 %, and during a warm and dry year the loss of ice thickness ~~almost~~ affects almost the whole glacier (AAR<4%) ~~affects indicate~~indicating that there is not 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 loss in most years and ~~there can be years with accumulation, but if the many do not and~~ the retained snowpack of good years is lost in bad years, then in fact there is no cumulative accumulation~~in fact no accumulation persists~~. Thus, the behavior observed for the Monte Perdido glacier during the studied period is very likely explained by very negative mass balance years that may be identified in Figure 2. Thus, years with very high temperatures occurred after 2000 (2003, 2005 and 2012), and in

**Con formato:** Sin Superíndice / Subíndice

2005 and 2012 they were also characterized by low winter precipitation. ~~As mentioned before, also t~~The feedbacks from decreased albedo and increasing slope of the glaciers ~~must~~ may also be playing a key role in the recent acceleration of the glacier wastage. 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 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 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 losses in the last 30 years suggests that the western~~-~~most part of this glacier will disappear first; the eastern~~-~~most 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 ~~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.

**Acknowledgements**

This study was funded by two research grants: "CGL2014-52599-P, *Estudio del manto de nieve en la montaña española, y su respuesta a la variabilidad y cambio climatico*" (Ministry of Economy and Competitivity), and "*El glaciar de Monte Perdido: estudio de su dinámica actual y procesos criosféricos asociados como indicadores de procesos de cambio global*" (MAGRAMA 844/2013). The authors are grateful for~~Authors thank~~ 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.

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## Figure captions

**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. Red square marks the scanning positions, numbered points indicate the position of the fixed targets used for georeferencing and merging the different clouds of points.

**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 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 ~~in~~ at the stations of Aragnouet, Canfranc, Mediano (only temperature) and Pineta (only precipitation) during the period 1955-2013. Numbers ~~inform of~~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 of 1981 and 2011.

**Figure 5.** Changes in glacier elevation 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 elevation 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 elevation 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~~2~~.** Tau-b values of the trends for the period 1983-2013 for temperature and precipitation in the analyzed stations. Asterisks indicate statistically significant trends ($p<0.05$). Bold numbers ~~inform of~~are statistically significant differences in the medians of the period 1982-1999 and 1999-2010 according to the Mann-Whitney test.

| | Aragnouet | | | Canfranc | | | Mediano | | Pineta | Góriz | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Tmx | Tmn | Precip | Tmx | Tmn | Precip | Tmx | Tmn | Precip | Tmx | Tmn | Precip |
| **January** | 0.08 | 0.02 | 0.04 | -0.03 | -0.13 | 0.03 | 0.06 | 0.04 | 0.06 | 0.07 | 0.11 | 0.02 |
| **February** | 0.04 | 0.06 | 0.02 | 0.05 | -0.01 | -0.08 | 0.03 | -0.03 | **0.39*** | 0.04 | 0.02 | 0.00 |
| **March** | 0.11 | 0.11 | 0.14 | 0.03 | -0.03 | 0.26 | -0.02 | 0.03 | 0.31 | 0.02 | 0.06 | 0.20 |
| **April** | **0.28*** | 0.25 | 0.08 | 0.24 | 0.19 | -0.15 | 0.02 | 0.12 | 0.02 | 0.15 | 0.21 | -0.17 |
| **May** | 0.23 | 0.24 | 0.31* | 0.30* | 0.18 | 0.14 | -0.01 | 0.04 | 0.12 | **0.34*** | **0.33*** | 0.27 |
| **June** | **0.28*** | **0.31*** | 0.14 | **0.35*** | **0.47*** | 0.04 | 0.09 | -0.05 | 0.10 | **0.~~316~~32*** | 0.25* | -0.05 |
| **July** | -0.12 | 0.06 | 0.13 | 0.11 | 0.15 | 0.16 | -0.07 | -0.21 | 0.15 | -0.07 | -0.05 | -0.11 |
| **August** | 0.07 | 0.13 | -0.02 | -0.02 | 0.01 | 0.03 | -0.12 | -0.25 | 0.32 | 0.10 | 0.07 | -0.02 |
| **September** | 0.05 | 0.05 | 0.02 | -0.06 | -0.23 | 0.10 | -0.18 | -0.23 | 0.10 | 0.01 | -0.02 | 0.04 |
| **October** | 0.08 | 0.19 | 0.19 | 0.06 | 0.04 | 0.14 | 0.04 | -0.14 | 0.08 | 0.01 | 0.04 | 0.11 |
| **November** | -0.06 | -0.06 | 0.18 | -0.18 | -0.23 | 0.10 | -0.08 | **-0.30*** | -0.02 | -0.11 | -0.09 | 0.00 |
| **December** | -0.15 | -0.10 | -0.03 | **-0.37*** | -0.42* | 0.08 | -0.25 | -0.23 | 0.13 | -0.27* | -0.23 | -0.06 |
| **Accumulation period** | 0.10 | 0.11 | 0.12 | 0.04 | 0.11 | 0.01 | -0.22 | -0.22 | 0.00 | 0.06 | 0.15 | 0.05 |
| **Ablation period** | 0.10 | 0.10 | | 0.17 | 0.11 | | -0.26 | -0.26 | | 0.13 | 0.12 | |

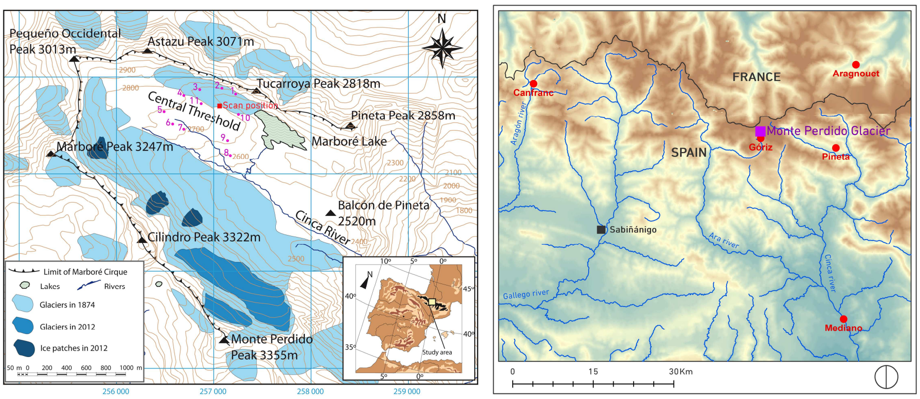
**Con formato:** Fuente: Negrita

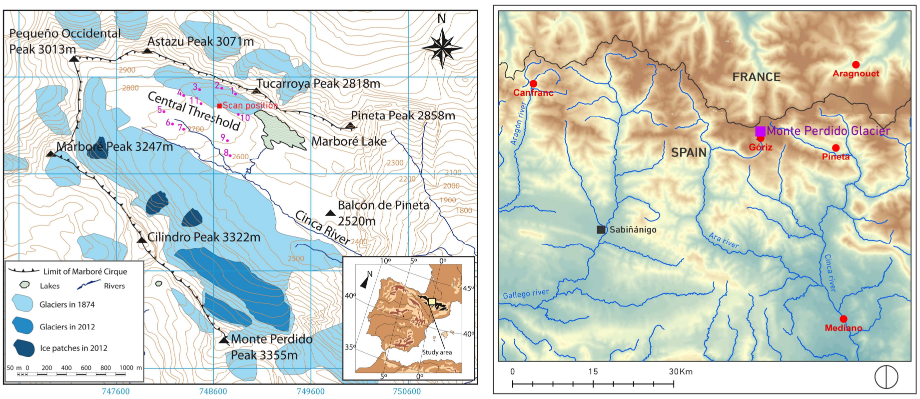
**Con formato:** Fuente: Negrita

**Con formato:** Fuente: Negrita

**Table 2.** 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) | 8.30±0.27 | 6.80±0.25 | 4.80±0.21 | 1.50±0.47 | 2.00±0.46 |
| Lower glacier (ha) | 40.10±0.59 | 37.10±0.62 | 33.70±0.54 | 3.0±1.21 | 3.40±1.16 |
| Entire glacier (ha) | 48.40±0.65 | 43.90±0.62 | 38.50±0.58 | 4.50±1.23 | 5.40±1.20 |
| Entire glacier (ha $yr^{-1}$) | | | | 0.25±0.07 | 0.77±0.17 |


Pequeño Occidental Peak 3013m
Astazu Peak 3071m
Tucarroya Peak 2818m
Central Threshold
Scan position
Pineta Peak 2858m
Marboré Lake
Marboré Peak 3247m
Balcón de Pineta 2520m
Cinca River
Cilindro Peak 3322m
Monte Perdido Peak 3355m
Limit of Marboré Cirque
Lakes
Rivers
Glaciers in 1874
Glaciers in 2012
Ice patches in 2012
Study area
FRANCE
SPAIN
Canfranc
Aragnouet
Monte Perdido Glacier
Góriz
Pineta
Sabiñánigo
Mediano
0 15 30 Km


Pequeño Occidental Peak 3013m
Astazu Peak 3071m
Tucarroya Peak 2818m
Central Threshold
Scan position
Pineta Peak 2858m
Marboré Lake
Marboré Peak 3247m
Balcón de Pineta 2520m
Cinca River
Cilindro Peak 3322m
Monte Perdido Peak 3355m
Limit of Marboré Cirque
Lakes
Rivers
Glaciers in 1874
Glaciers in 2012
Ice patches in 2012
Study area
747600
748600
749600
750600
FRANCE
SPAIN
Canfranc
Aragnouet
Monte Perdido Glacier
Góriz
Pineta
Sabiñánigo
Mediano
0 15 30 Km

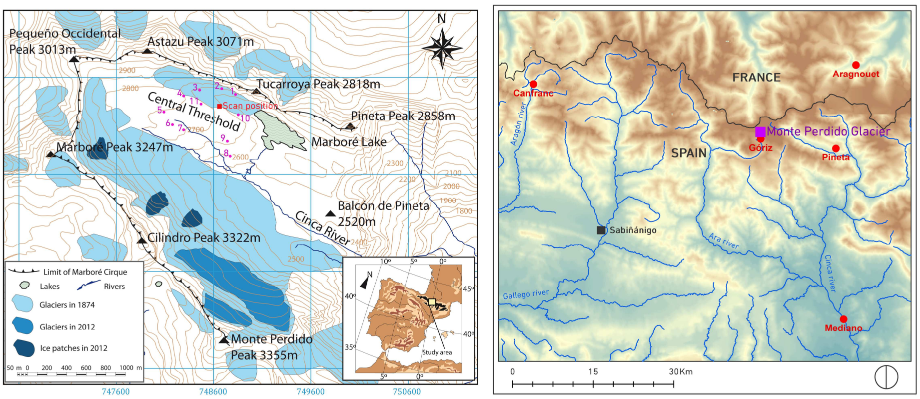
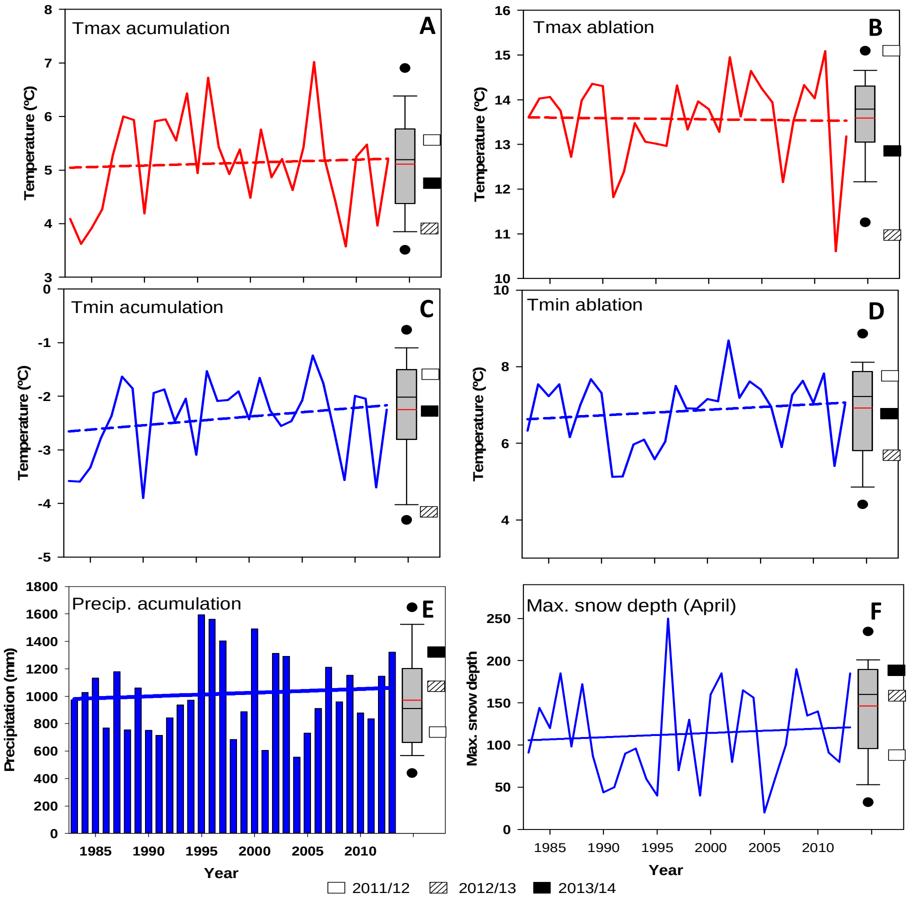

Pequeño Occidental Peak 3013m
Astazu Peak 3071m
Tucarroya Peak 2818m
Central Threshold
Scan position
Pineta Peak 2858m
Marboré Lake
Marboré Peak 3247m
Balcón de Pineta 2520m
Cinca River
Cilindro Peak 3322m
Monte Perdido Peak 3355m
Limit of Marboré Cirque
Lakes
Rivers
Glaciers in 1874
Glaciers in 2012
Ice patches in 2012
Study area
747600
748600
749600
750600
FRANCE
SPAIN
Canfranc
Aragnouet
Monte Perdido Glacier
Góriz
Pineta
Sabiñánigo
Mediano
0 15 30 Km

Figure 1.




**Con formato:** Inglés (Estados Unidos)

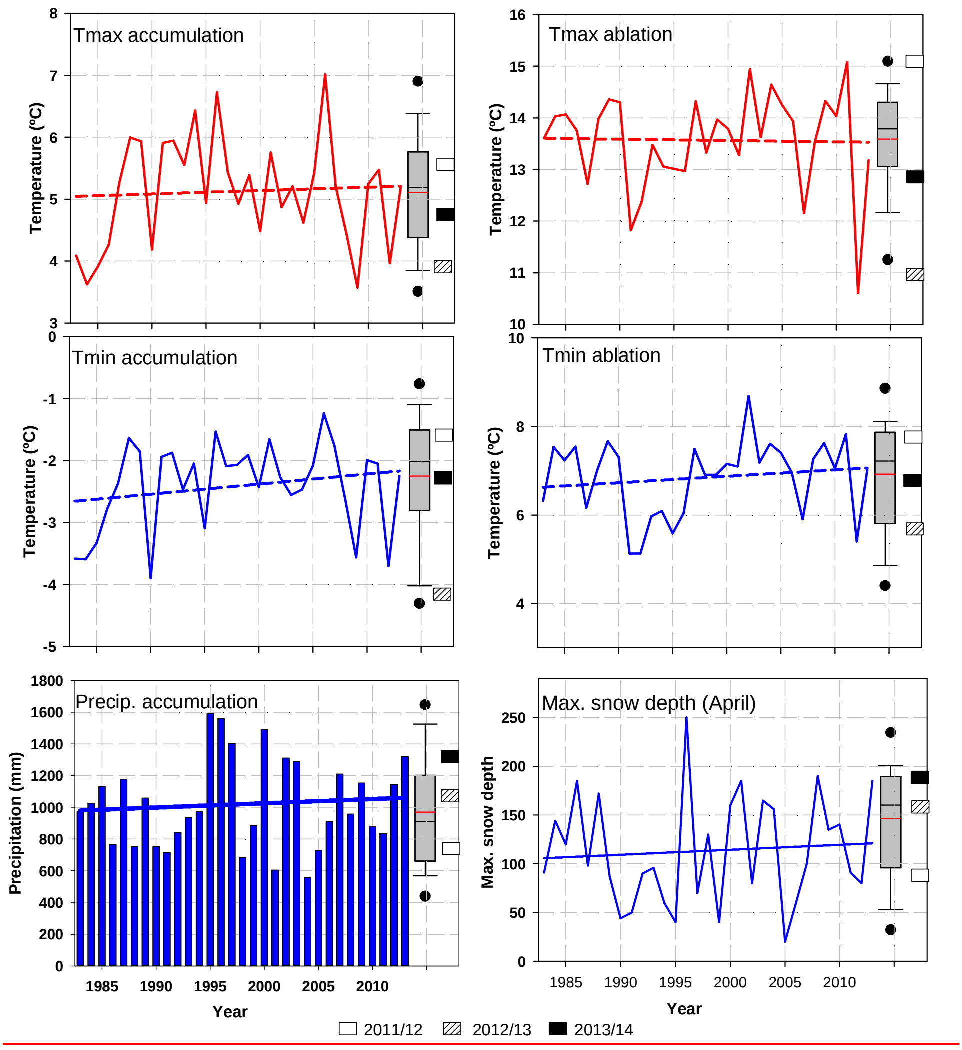

Tmax accumulation
Tmax ablation
Tmin accumulation
Tmin ablation
Precip. accumulation
Max. snow depth (April)
Temperature (ºC)
Precipitation (mm)
Max. snow depth
Year
1985
1990
1995
2000
2005
2010
2011/12
2012/13
2013/14

**Figure 2.**

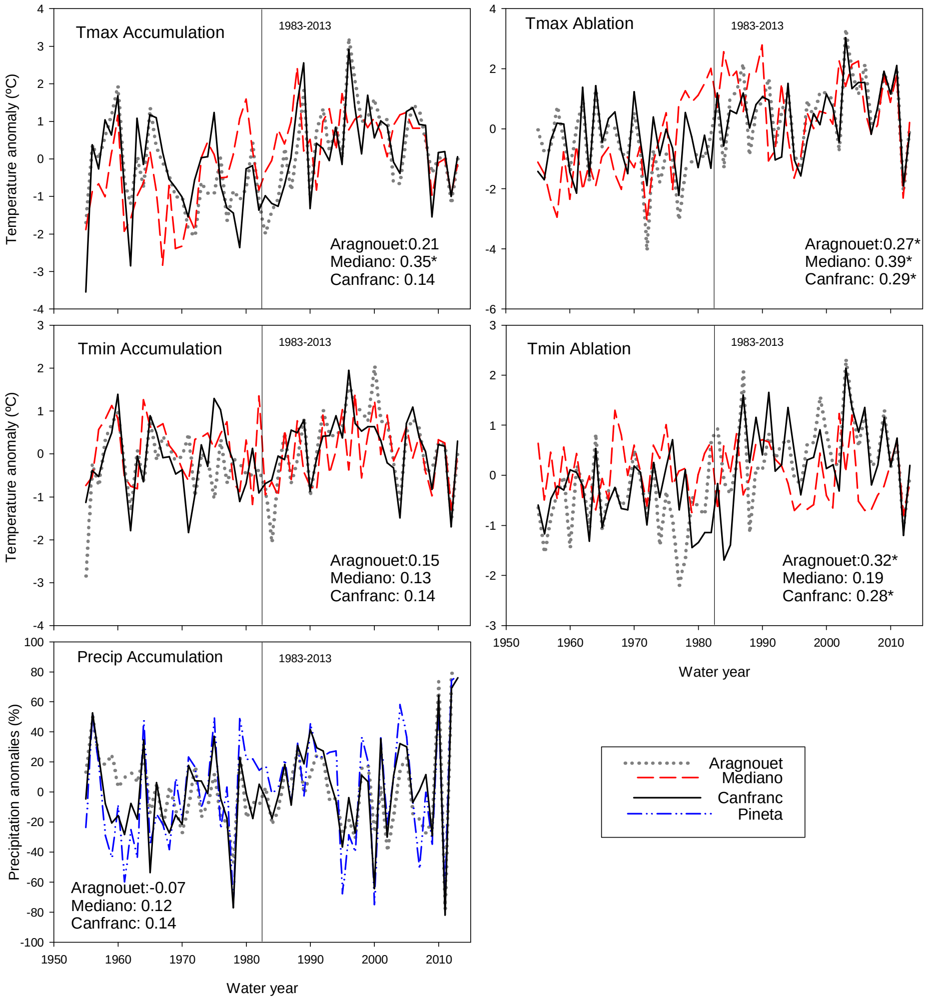

Tmax Accumulation
1983-2013
Aragnouet:0.21
Mediano: 0.35*
Canfranc: 0.14
Tmax Ablation
1983-2013
Aragnouet:0.27*
Mediano: 0.39*
Canfranc: 0.29*
Tmin Accumulation
1983-2013
Aragnouet:0.15
Mediano: 0.13
Canfranc: 0.14
Tmin Ablation
1983-2013
Aragnouet:0.32*
Mediano: 0.19
Canfranc: 0.28*
Precip Accumulation
1983-2013
Aragnouet:-0.07
Mediano: 0.12
Canfranc: 0.14
Temperature anomaly (ºC)
Temperature anomaly (ºC)
Precipitation anomalies (%)
Water year
Water year
Aragnouet
Mediano
Canfranc
Pineta

**Figure 3.**

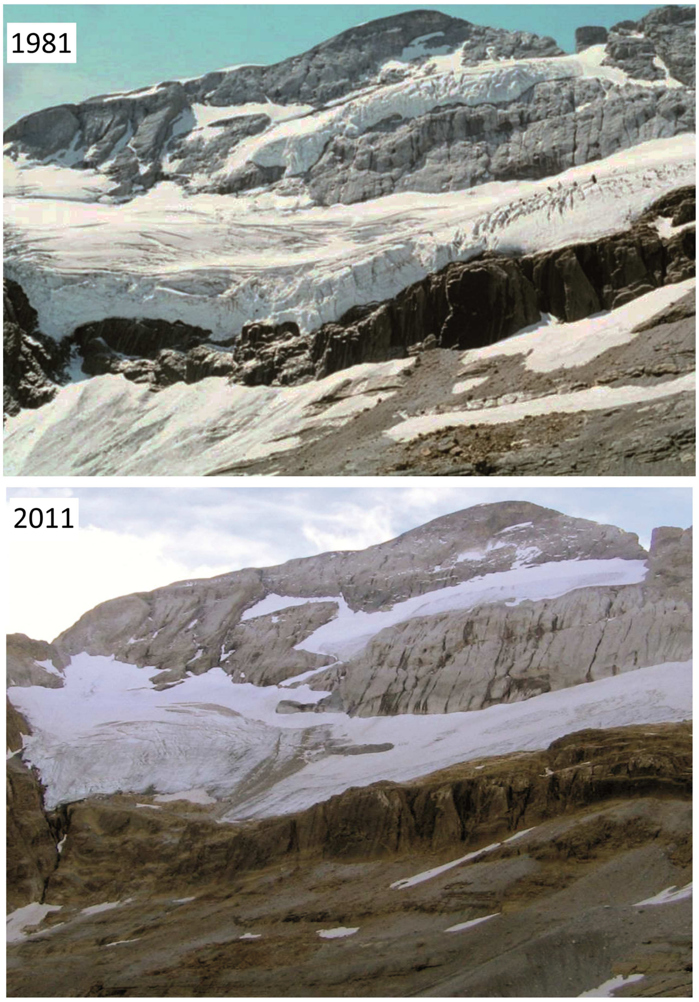
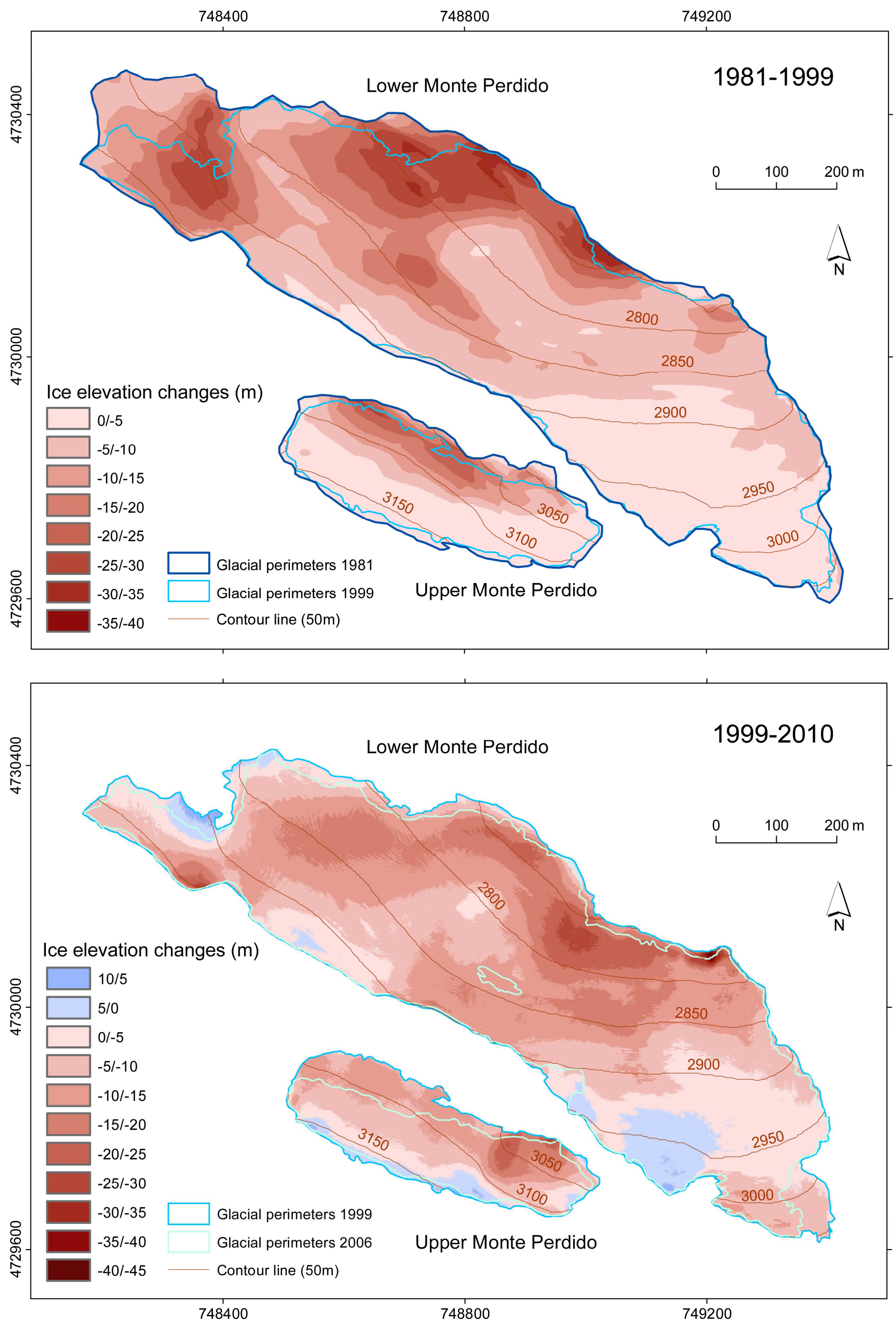



**Figure 4.**



748400
748800
749200
4730400
4730000
4729600
Lower Monte Perdido
1981-1999
0
100
200 m
N
2800
2850
2900
2950
3000
3050
3100
3150
Ice elevation changes (m)
0/-5
-5/-10
-10/-15
-15/-20
-20/-25
-25/-30
-30/-35
-35/-40
Glacial perimeters 1981
Glacial perimeters 1999
Contour line (50m)
Upper Monte Perdido
1999-2010
10/5
5/0
-40/-45
Glacial perimeters 2006


Figure 5.

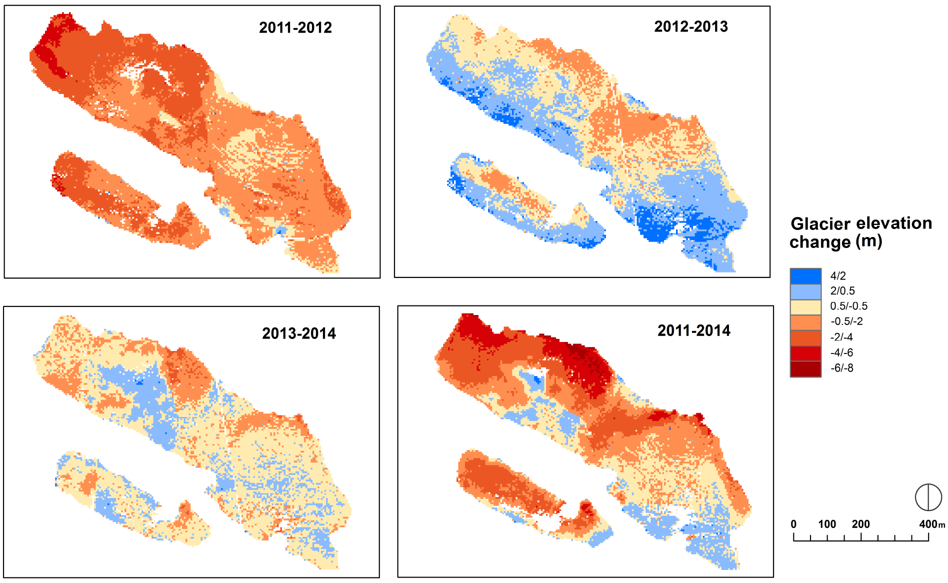

2011-2012
2012-2013
2013-2014
2011-2014
Glacier elevation change (m)
4/2
2/0.5
0.5/-0.5
-0.5/-2
-2/-4
-4/-6
-6/-8
0
100
200
400m

**Figure 6.**

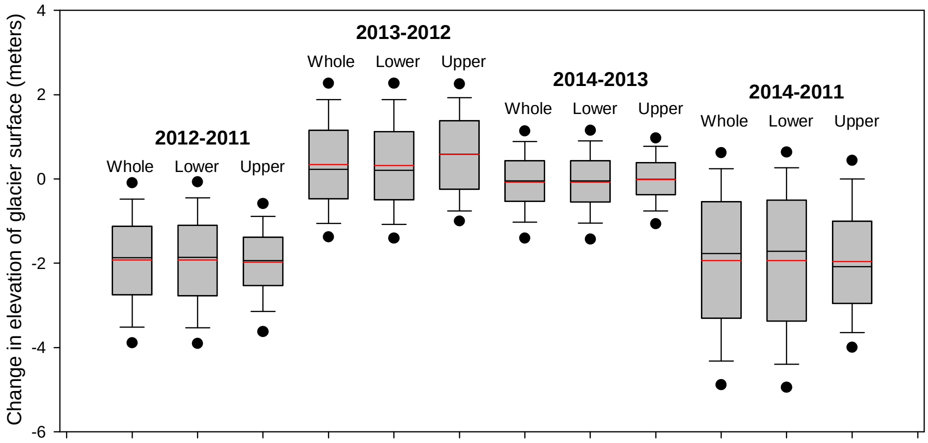

Change in elevation of glacier surface (meters)
4
2
0
-2
-4
-6
2012-2011
Whole
Lower
Upper
2013-2012
Whole
Lower
Upper
2014-2013
Whole
Lower
Upper
2014-2011
Whole
Lower
Upper

**Figure 7.**