Zaragoza 18/01/2016

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 López-Moreno and others.

We want sincerely to thank to all of you by the high quality of your edits and your comments that have definitively helped us to improve a lot our original submission. In our opinion, the revised manuscript has gained a lot in clarity, in the interpretation of the results, in the presentation of the climate evolution around the glacier and in the quality of the text and the figures. The response letter is mostly based on the responses provided during the discussion process; but we have added new ideas provided by the editor (concerning to include longer periods in the analysis and more discussion on the accuracy of the used maps). 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

INTERACTIVE COMMENT ON "ACCELERATED WASTAGE OF THE MONTE PERDIDO GLACIER IN THE SPANISH

Pyrenees during recent stationary climatic conditions" by J. I. López-Moreno et al.

M. Pelto (Referee)

General comment: López-Moreno et al (2015) provide the most detailed assessment of areal, thickness, and volume changes on a Pyrenees glacier. This is a crucial moment to do so, as the glacier is losing volume so quickly. The use of DEM and TLS are an excellent combination. I only have minor comments on the glaciology. There is one significant issue the over reliance on a single weather station examined for seasonal changes in either temperature or precipitation. This single weak data set is used to identify that ablation increase is not the reason for increased volume loss. This maybe but until the data is stronger including use of SWE, precipitation and temperature records during the wet periods of spring and fall and more than a single weather station is used the conclusion is not justified. With better meteorological data for more robust analysis this will be a fine contribution.

Answer: We want to thank the supportive assessment of our work, and also the valuable comments to improve the manuscript. We understand the criticisms on using a single meteorological station, even when this is the closest to glacier, and it belongs to the main network of the Spanish Meteorological Agency. As this comment coincides with the ones of the other reviewer we have acted in two ways. First we have smoothed the mention along the whole manuscript about the "recent stationary climate", as this cannot be completely confirmed with the available data (small detected monthly changes in temperature and precipitation may introduce changes in the mass and energy balance of the glacier that they are not fully quantified even understood yet). It includes a modification in the title of the revised version that is: "Recent accelerated wastage of the Monte Perdido glacier in the Spanish Pyrenees". In our opinion it is shorter and makes reference to the result that may be completely demonstrated by our presented analysis. In addition we have used another three neighboring stations for precipitation (Canfranc, Pineta and Aragnouet) and temperature (Canfranc, Mediano and Aragnouet), and new and more robust statistical analyses to compare the 1983-1999 and 2000-2010 period. Both of them had almost complete records for the period 1980-2013 and they belong to the database of the Pyrenean Observatory of the Climate Change (OPCC), which carefully tested the quality and homogeneity of the data (Deaux et al., 2014). We can now confirm that the results from Goriz are consistent with the other three observatories, but the analyses reveals some monthly changes that needs of consideration (see comments below).

1- Abstract: 5022-15-18: Data presented is not sufficient to warrant the conclusion that local climate change cannot explain the acceleration, particularly in light of the next sentence, which notes recent changes can be explained.

Answer: As mentioned before we have smoothed our statements on this issue along the whole manuscript. Now in the abstract we state: "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."

2-5022-18-21: It is noted that the glacier shrank in recent years, but then the warming since the Mid- 1800's is used. Instead of the more recent 0.2 C per decade noted in paper.

Answer: We indicate in the abstract of the revised manuscript: "In particular, the average air temperature increased a minimum of 0.9ºC in this region since the end of the Little Ice Age (LIA) in the mid-1800s" and then in the introduction we have change the paragraph as follows: "In the case of the Pyrenees, the air temperature has increased 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". In my opinion, the reported warming rate for the 1951-2010 is not representative of the climate evolution in the region since the end of the LIA, because it starts just before the rather cold period of the 60´s and 70´s exacerbating the magnitude of the proposed rate (It is very well known that such magnitude is highly dependent on the selected studied period).

3-5024-17: And many are in disequilibrium and cannot survive (Pelto, 2010).

Answer: Added, Thanks.

4-5025-20: is the mass change in m or m w.e.?

Answer: In that sentence, we are reporting losses in ice thickness, hence they are in m; "these indicated the mean loss of ice thickness was 14m during the last 20 years".

5-5026-4: One station not sufficient, just because it is closest does not make it best either. There are other stations not far away such as Torla and Bescos. These are lower elevation but have good long records. Deaux et al (2015) examined the 1950-21010 period at a monthly scale with 66 stations and precipitation at 139. Surely some of that can be utilized. This topic is further discussed below

Answer: As we mentioned before we have used the three new temperature and precipitation stations (from the suggested database) to support the results discussed with Góriz. In the Methods section we have added "In addition, we analyzed the trends of monthly series and for the accumulation and ablation periods during the 1983-2013 period, available for three observatories (see Figure 1) with precipitation data (Pineta, Aragnouet and Canfranc), and three for temperature (Mediano, Aragnouet and Canfranc). The non-parametric Mann-Whitney U test (Fay and Proschan, 2010) was used to detect statistically significant differences in precipitation and temperature data when the periods 1983-1999 and 2000-2010 are compared.**"**

In the results section we have added a table with the results of the trend analyses and indicating which stations and months have statistically significant differences between the periods 1983-1999 and 2000-2010.

Table 1. Tau-b values of the trends for the period 1982-2013 for temperature and precipitation in the analyzed stations. Asterisks indicate statistically significant trends ($p<0.05$). Bold numbers inform of 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	.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*	0.3*	0.18	0.14	-0.01	0.04	0.12	**0.34***	**0.33***	0.28*
June	**0.28***	**0.31***	0.14	**0.35***	**0.47***	0.04	0.09	-0.05	0.10	0.31*	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	**-0.3***	-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	

And we have expanded the explanation of the evolution of climate in the region with data presented in the table. Thus we have added:" Table 1 shows that the evolution of temperature in Góriz is line with the observed in the three other meteorological stations (Mediano, Aragnouet and Canfranc) with no statistically significant trends for maximum or minimum temperature, for the accumulation and ablation periods during the period 1983-2013. At monthly basis, the four analyzed observatories only detected a statistically significant increase in May and June; and a statistically significant decrease in November and December for both, maximum and minimum temperature. The Mann-Whitney test did not reveal statistically significant differences in the medians of the series for the accumulation and ablation periods in any observatory when the periods 1983-1999 and 2000-2010 were compared." and "Monthly trend analysis (Table 1) only found a significant increase of precipitation in Góriz during May, and relatively low tau-b coefficients for the rest of the years. 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 during March. No statistically differences in the median of precipitation during the accumulation and ablation seasons of the 1983-1999 and 2000-2010 periods in any of the analyzed meteorological stations.". In addition, we have added a new Figure that shows the evolution of temperature and precipitation in neighbor stations for the period 1955-2013, what permits to frame better the climate fluctuations around the glacier in a longer time slice. Thus we comment this Figure as follows: “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 longer climate series. Thus, the 1955-3013 period exhibit a statistically significant ($p<0.05$) warming during the ablation period, and the accumulation exhibited positive tau-b values but 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”.

6- 5027-12: do not need “currently” twice in this line.

Answer: Changed

7-5028-5: The statement that most of the precipitation occurs in spring and autumn also indicates the importance of reporting temperature changes during these months specifically. Are these part of your ablation season or accumulation season?

Answer: September and April are very wet and we have not doubt to include it in the ablation and accumulation period respectively. May is also wet some years and this could be a transitional year depending on weather conditions. See more discussion about this in the next question

8-5031-17: Define the ablation and accumulation season. Given that the ablation season can expand in length using a limited frame may not be sufficient for temperature.

Answer: We think this is a bit tricky question but it should not affect seriously the presented results or main findings. The lack of meteorological data “in situ” or series of spring mass balance makes very difficult to accurately define the length of the accumulation and ablation periods that logically varies from one year to the other. May is also characterized by high precipitation. A good portion fall as snow, but some rainy events may occur at this time of the year. May should be considered as a transitional year between accumulation and ablation conditions depending of the year, but is in June when ablation over the glacier is normally evident. October is also a transitional month, and it may still continue with some ablation (depending of the year), or it begins some accumulation. But again, in a normal year is in November when accumulation clearly dominates at the elevation of the glacier. We have tested the trend analyses considering other possible combinations of months belonging to each period, and no change have been found in order to show stationary precipitation and temperature conditions during the accumulation period.

In section 3.1., we have added this explanation: “The lack of detailed meteorological or mass balance data over the glacier made necessary to define the accumulation and the ablation season in a subjective manner based on our experience. We are aware that May and October are transitional months between accumulation and ablation conditions depending of the specific annual conditions. However, we set these periods because is June and November when ablation and accumulation is generally evident over the surface of the glacier”. In the discussion we mention that observed temperature trends in May and June may lead to shorten the accumulation period, and increase the length of warm season with lower albedo.

9-5029-16: It would be useful to see the location of the scan station and the fixed points on the glacier. These could be added to current figure 5 for the reference points anyway.

Answer: They have been added to Figure 1, as they fall far away from the glacier. The reference points (reflectors) were located at a maximum distance of 400 meters, to ensure they were scanned at high resolution, ensuring a good estimation of the central point of the reflectors.

10-5032-10: Use a deviation in precipitation not “very wet”. Also note here mild winter and cool ablation season. This may indicate importance of accumulation season temperature changes.

Answer: We agree, now we specify: “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 (78th percentile) and around average, with air temperatures well average (22th and 48th percentiles for maximum and minimum temperatures respectively) during the ablation months.”

11-5032-25: Significant thinning even in the highest regions of the glacier, indicate the lack of a persistent accumulation zone, and that the glacier cannot survive (Pelto, 2010).

Answer: This comment is included in the revised manuscript

12-5034-23: If possible it would be ideal to report the AAR for the three years somewhere on this page.

Answer: We have added this information to that paragraph

13-5035-13: This statement needs to be reexamined the data presented are not sufficient to show that the acceleration in mass loss cannot be explained by recent climate change. That may be the case, but not based on this data. 5035-18 Must define ablation season and must examine the period from April-October as any expansion in length of ablation season, or shortening of accumulation season is important. Figure 2 indicates warming in the accumulation season that could be important. This could change the amount of snowpack, SWE retained. Also this data is based on one station, which is not robust, and is not shown to match regional trends. There are many stations in this range, you must utilize others to demonstrate a real trend. One key point is that a long term average not always best measure. In the plot shown 8 of last 11 years have been notably above the trend line, and only two are notably below. The average of all these years, would miss the important role that the trend of warm summers play. The one really cold summer will affect the average greatly, but as noted does not compensate on the glacier for the warm summers.

Answer: As it was mentioned before we have smoothed the statements about the stationary character of the climate and its influence on glacier evolution. Moreover, we present the results of the three other new stations included in the analyses. Results are presented in section 4.1 and basically indicate that the other 3 stations exhibit very similar temporal evolution than Góriz station. We also mention the individual months in which we found statistically significant trends. There is an agreement that any of the 4 stations show significant temporal trends for the accumulation and ablation periods but all stations have shown an increase of Tmax and Tmin during May and June. This, increase does not affect the temperature change for the accumulation period that is not significant in any station, but it is true that it may lead lo less snowfall during May, affecting to snow accumulation in the glacier, and also to an earlier decay of snow albedo on the glacier surface. This point is discussed in the revised version of the manuscript. In the discussion we have modified the 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 the sharp decline of snow accumulation. Climate data (1983-2014) of a nearby meteorological station, and three other Pyrenean meteorological stations, suggests that 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 compared to 1999-2010. Precipitation in the four analyzed stations during the accumulation period and maximum annual snow depth in Góriz were also stationary or slightly increased.". The use of the Mann Whitney test to compare the median of the two considered periods prevent the potential impact of the presence of isolated anomalous years in the long-term series, as i) it is based in the median; and ii) it also takes into account the variance of the two sub periods to determine the statistical significance of the differences.

Finally we added this paragraph in the discussion "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). "

13-5035-24: Accumulation season precipitation not the best measure since increased freezing level and rain rates can be important. Particularly true given comment in paper note above that spring and fall are the wettest periods. The maximum snow depth may argue against this, but not in SWE, depth is not a good measure. It is noted on the next page that Buisan et al (2015) had other evidence of more snow days. This needs more careful usage. They examine 38 stations all below 1500 m. The two closest to Perdido are Torla and Bescos which in their figure 12 have negative trends in snowfall. More snow days does not necessarily mean greater SWE at the end of the accumulation season and further given the decline near Perdido is a poor reference. In the western US the ratio of SWE to precipitation has declined due to more winter rain and melt events (Mote et al., 2008).

Answer: As mentioned before, we have mentioned in the revised manuscript the possibility to have an increase of precipitation as rain over the glacier that might be relevant for the mass and energy balance of the glacier especially during May, when precipitation and temperature have increased. However, given the elevation of the glacier (above 2750 m a.s.l.) much of the current precipitation in May and the majority of the precipitation during the fall season continue currently as snow. Previous studies in the Pyrenees, highlight that the most sensitive elevation to detect significant changes in the precipitation phase are found at lower elevation (around 2200 m a.s.l.; López-Moreno 2005. Arctic, Antarctic and Alpine Research). We think that it is realistic to affirm that snowfall in the surroundings of the glacier has remained stationary or even slightly increased during the studied period, and it can be inferred from the presented data. Precipitation during the period November-May has shown positive tau-b coefficients (with no statistically significance at $p<0.05$) in the four analyzed stations, as well as the annual maximum snow depth in Goriz. It is true that SWE would be a much better information than snow depth, but in spring time (when maximum depth is generally reached) snow density in the Pyrenees tends to be rather similar in both, spatially and at interannual basis (López-Moreno et al., 2013; Water Resources Management). We agree that an increase of snow days does not mean an increase in total snow amounts, but it is another useful indicator (together the stationary evolution of precipitation amounts) to think that accumulation of snow has not changed significantly over the last 30 years. Finally, a last work of Buisan et al (in review), based on a network of snow poles indicates that not only snow days, but also SWE series have not changed significantly during spring (late April-Early May) in the central Spanish Pyrenees. We are not sure if we should use this reference since at this time the paper is still in the reviewing process (submitted to Climate Research). We wait for reviewers and editor comments.

14-5037-8: Again what have been the AAR during recent years. The loss of ice thickness across the glacier indicates 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 be with accumulation, but if the many do not and the retained snowpack of good years is lost in bad years, then in fact no accumulation persists.

Answer: We have added this comment in the discussion section as follows: "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 the whole glacier (AAR<4%) affects indicate 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 accumulation, but if the many do not and the retained snowpack of good years is lost in bad years, then in fact no accumulation persists."

15-5037-28: This is dependent on initial ice thickness too, if the eastern part is not thicker than the west it may not last longer. Also given the stated lack of avalanching, a remnant may not last much longer, as this is the typical reason (Hoffman and Fountain, 2007).

Answer: The west part of the glacier is supposed to be actually the thickest (according the GPR survey, unpublished). This is now mentioned in the paragraph.

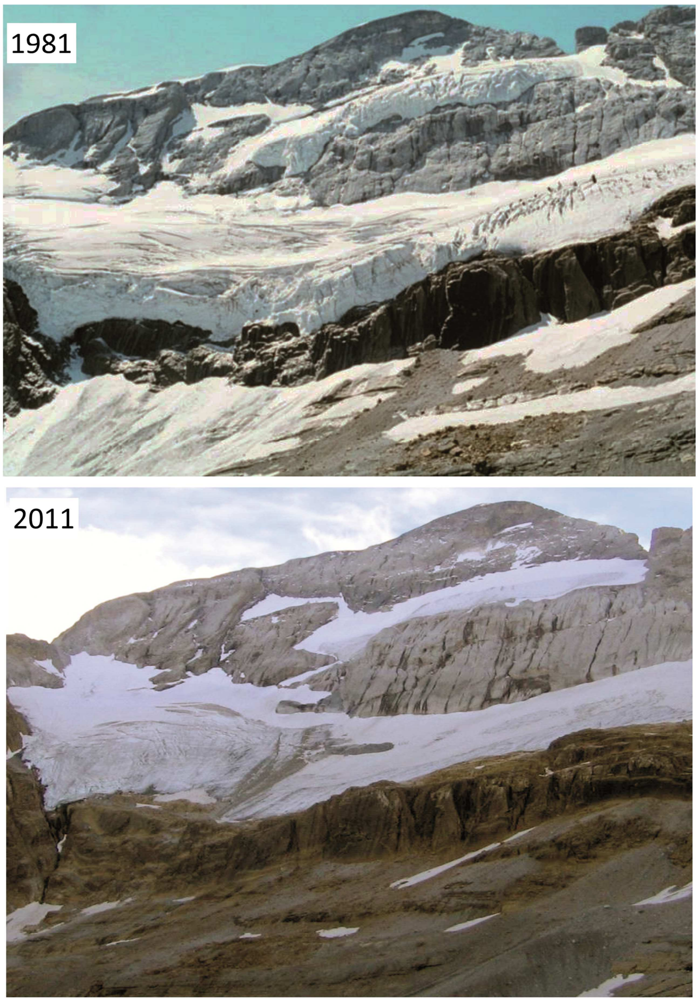
16-References: Buntgen et al (2008) not cited in text.

Answer: There was a mistake for spelling the name, the name is Büngten, it has been corrected in the revised manuscript.

17- Figure 3: Top photograph overexposed a bit, bottom photograph underexposed, both

could be adjusted to better view glacier surface.

Answer: The picture of 1981 is rather old and the quality is not the best, but still is very informative of the dramatic change in the glacier during the last decades. Following your recommendation, we have adjusted the exposition and we think we have improved the visualization.



*We have corrected all the references indicated by the reviewer. Many thanks.

REVIEWER 2

Interactive comment on "Accelerated wastage of the Monte Perdido Glacier in the Spanish Pyrenees during recent stationary climatic conditions" by J. I. López-Moreno et al.

Luca Carturan (Referee)

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General comments

In their paper, López-Moreno et al. provide an assessment of the area and thickness change rates of Monte Perdido Glacier in the last three decades. In particular, they quantify the accelerated wastage of the glacier at the beginning of the 21st Century, compared to the last two decades of the 20th Century. Moreover, they compare the observed behaviour of the glacier with the time series of meteorological variables recorded by a weather station close to the glacier. The main result of the paper is potentially interesting, because the Authors affirm that the observed behaviour of the glacier cannot be explained by the climatic conditions recorded at the weather station, implicitly claiming for a current non-linear response of the glacier. In particular, they say that during years with 'favourable' climatic conditions the glacier is no more able to recover ice losses occurred during 'unfavourable' years. In my opinion, the statements of the Authors are not adequately supported by the data and analyses used in this paper. I mainly refer to i) the use of only one weather station, which cannot be considered sufficient for detecting possible irregularities and inhomogeneities in the series, and ii) to the focus in the period from 1983 to 2014, neglecting previous decades (years from 1950 to 1980). As detailed in the specific comments, it is not clear if the current 'favourable' years are comparable to the 1960s and 1970s, when the glaciers in that area were close to balanced-budget conditions. In the case that the current 'favourable' years were warmer than the 1960s and 1970s, why they should bring to mass gain and recover on the glacier? Moreover, the Authors should hypothesize possible reasons for this (speculated) peculiar behaviour of the glacier, as for example positive feedbacks during glacier shrinking. The local increase in the debris cover and the appearance of a small rock outcrop look insufficient for explaining the observed accelerated wastage.

In addition to these issues, I note that the paper is often unclear and imprecise. The Authors do not use the right terminology and in several cases they are too general and descriptive, whereas they should be more specific and quantitative (e.g. when they report the meteorological anomalies). Sometimes it is difficult to understand which variables they refer to (e.g. absolute minimum and maximum temperature, or seasonal average of daily minimum and maximum temperature?). The assessment of DTMs accuracy could be improved based on recent published research. The non linear response of the glacier could be pointed out by the application of a mass balance model.

I suggest a major revision of the paper, and I also strongly recommend a complete review of the paper by an English native speaker.

Answer: Authors really thanks the degree of detail of the review that has helped to improve the presentation of the main ideas of our research. As it is explained in detail in the answer to reviewer 1, we have added more stations and new analyses and more quantitative numbers to present the recent climate evolution and climatic anomalies in the region, and relate them with the observed changes in glacier wastage. In addition we realize that the statement of the "accelerated glacier wastage under stationary climatic conditions" was too strong and difficult to be supported with the available data that do not permit perform detailed energy and mass balance. In this way we have changed the simplified the title of the manuscript to: RECENT ACCELERATED WASTAGE OF THE MONTE PERDIDO GLACIER IN THE SPANISH PYRENEES, and smoothed some sentences regarding the climate-wastage relationships. What we obviously maintain is that the glacier has clearly accelerated the degradation and there are clear indicators (as reviewer 1 mentions) that the situation of the glacier is critical. Moreover, we have included more discussion suggested by both reviewers related with possible negative feedbacks affecting the mass and energy balance of the glacier. We thank some suggestions to clarify some sentences and the detection of some mistakes. The paper was already edited by a professional English editing service. We have worked with them tens of times in the last decade with very satisfactory results. Prior to the publication of the discussion paper, the editor also provided in a first round very useful suggestions to improve the accuracy of some of the used terminology. Nonetheless, we have checked again the manuscript and included all the useful suggestions indicated by reviewers.

Specific comments

1-P. 5022, L. 3-7: Why not using also the 2010 LiDAR and the ALS DTMs of 2011-2014 to characterize the area loss after the last aerial photo of 2006?

Answer: we did not use this information, because the accuracy of aerial photographs and LIDAR was different; and because there are areas of polished bedrock that could be mixed with the glacier surface attending to the hillshade. The existence of some topographic shadows in the edges of the glacier from the TLS view also prevented to use them. As, it can be noted in the manuscript the information provided about areal changes is used to support the main ideas of the manuscript and to frame the most recent evolution, but it is not the main body of our results. For this reason, we think is valid to work with the presented data based only in available ortophotos

2-P. 5022, L 11: please replace ‘doubling’ with the exact percent increase.

Answer: Done is 1.85 times faster rate of ice volume loss.

3-P. 5022, L 12: ...has decreased ‘by’ (also in the following).ç

Answer: Done, thanks.

4-P. 5022, L 14: it appears that the volume loss rate has slightly decreased in the latest years; please add few words for highlighting or commenting that.

Answer: we have commented this: “This loss of glacial ice has continued from 2011 to 2014 (the ice depth decreased by 2.1±0.4 m, -0.64±0.36 m w.e. yr-1) despite of rather wet and cool conditions, in comparison with the 1983-20125 period, in two out of the three years.”

5-P. 5022, L 19: in my opinion the lack of equilibrium between the glacier and the current climatic conditions is not a sufficient explanation for the accelerated degradation. The authors should better explain what they mean, which factors they refer to (e.g. decreased albedo, elevation decrease, or other feedbacks)

Answer: We have modified the sentence as follows: “The accelerated degradation of this glacier in recent years can be explained by the lack of equilibrium between the glacier and the current climatic conditions 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)”.

6-P. 5022, L 25: the two years 2012-13 and 2013-14 are actually years of decelerated or null wastage, compared to the average conditions of the previous years.

Answer: We have combined this idea with the structure of the original sentence 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, but still the overall mass balance were near zero, with significant losses of ice in some areas.”

7-P. 5023, L 15-17: please, mention that Carturan et al. (2013b) reported that increase for the long-term monitored Careser Glacier. Also check for mean values reported in that work

Answer: we state in the revised version ". 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 (-0.7m w.e. yr^{-1}).

8-P. 5023, L 19: clearly exceeds (please check also elsewhere).

Answer: Changed

9-P. 5023, L 25: according to Grunewald and Scheithauer (2010) the southern-most glaciers of Europe are not in the Pyrenees. Please reformulate and also rephrase because it sounds like the glaciers underwent deglaciation. Grunewald, K., & Scheithauer, J. (2010). Europe's southernmost glaciers: response and adaptation to climate change. Journal of Glaciology, 56(195), 129-142.

Answer: We have slightly modified the sentence: "The Pyrenees host some of the southern-most glaciers of Europe, and they have also undergone significant retreat."

10-P. 5023, L 26: these glaciers had a 'total' area.

Answer: Changed

11-P. 5024, L 15: the AAR is not the 'accumulation ablation ratio'. Please report the correct terminology (e.g. Cogley et al., 2011). Cogley, J.G., R. Hock, L.A. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson and M. Zemp, 2011, Glossary of Glacier Mass Balance and Related Terms, IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris.

Answer: Yes, we are aware that AAR means "accumulation area ratio", it was a mistake that has been corrected. Thanks for providing information on this publication.

12-P. 5024, L 17: the annual air temperature or seasonal air temperature?; P. 5024, L 19: in six decades it makes an increase of 1.2°C, which is larger than the 0.9°C total increase since the end of the LIA. Please clarify.

Answer: The revised manuscript states: "In the case of the Pyrenees, the annual air temperature has increased 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." As, we explained to reviewer 1, this dissagreement is because each study uses different stations and also the warming rate is very dependent on the selected study period. Thus, the 1950-2010 starts with one of the coldest periods of the 20th century, followed by the very warm late eighties and nineties, and the warm 2000-2010 period. Thus, the warming rate for this period is very sharp.

13-P. 5024, L 27, to P5025, L. 1: I agree that annual areal (or length) changes cannot be directly related to annual climatic fluctuations, but annual changes in mass actually are directly related to annual climatic fluctuations. That's one of the main reasons why the annual mass balance of glaciers is measured. Please clarify and rephrase.

Answer: We think that the phrase is not wrong nor unclear, it simply informs that often is not easy to directly relate glacier mass changes with climate due to the inertia of glaciers of medium and large size, and the problems to relate changes in mass or geometry with climatic series (due to other local factors as topography, avalanches, etc). Of course, we do not want to mean that is not possible to relate climate and changes in the characteristics of the glaciers (area, length, mass, etc).

14-P5025, L. 3: please specify what you mean with 'climatic' changes. Maybe temperature changes? Avalanche and wind-borne snow accumulation actually depends on climate.

Answer: We have changed "climatic changes" by "climatic evolution". Yes, regional frequency and magnitude of avalanches depends on climate, but we think that its effects on the mass balance of specific glaciers depend on local topographic characteristics. We think that that sentence reflects properly that idea.

15-P5025, L. 4: consider adding Carturan et al., (2013) Carturan L., G.A. Baldassi, A. Bondesan, S. Calligaro, A. Carton, F. Cazorzi, G. Dalla Fontana, R. Francese, A. Guarnieri, N. Milan, D. Moro, P. Tarolli. 2013. Current behavior and dynamics of the lowermost Italian glacier (Montasio Occidentale, Julian Alps). *Geografiska Annaler: Series A, Physical Geography*, 95(1), 79-96.

Answer: Thanks for the suggestion. It was added as Carturan et al. (2013b). Nice paper.

16-P5025, L. 7-10: please rephrase this period for clarity, in my opinion it is not clear enough

Answer: we have rephrased as follows: "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)."

17-P5025, L. 12: the relationship between glacier changes and climatic changes

18-P5025, L. 14: there are very few estimations of ice volume loss

19-P5025, L. 19: and these indicated that the total loss of ice

20-P5025, L. 23: topographic maps of 1981 and 1999.... and reported losses of -0.36 (please correct also in the following)

21-P5026, L. 2: (TLS) surveys

22-P5026, L. 3: these data in connection with data on precipitation

23-P5026, L. 6: cooler than in the last decades

24-P5026, L. 7: it is unclear if the positive NAO is associated to climatic conditions of the 21st century (better to say the beginning of the 21st century) or last decades of 20th century

Answer (17-24): All the suggested changes have been done

25-P5026, L. 9: it is unclear in which years/period happened the climatic anomaly

Answer: we think that this sentence is properly linked with the previous one. Thus, to insist that we are talking of the beginning of the 21st century results very repetitive.

26-P5026, L. 21: and many following (I'm not sure what you mean) studies; -P5026, L. 21-22: other characteristics. Which characteristics?

Answer: We changed by: "... and many next studies examined the extent and made descriptions of the status of the of ice masses and the features of the moraines deposited during the...."

27-P5027, L. 6: in which period?; -P5027, L. 8: which was composed of three; -P5027, L. 9-11: unclear description. It is not clear when the glacier spread into separate ice masses, which was the relationship among these ice masses, and which one disappeared after the 1970s (the lower, I guess, or the intermediate?)

Answer: By the mid of the 20th century. The sentence says: "The glacier that existed at the lowest elevation was fed by snow and ice avalanches from the intermediate glacier, dissapeared after the 1970s" We think is clear we are doing reference to the lower glacier.

28-P5027, L. 19-20: I do not understand. Why 'minimal' avalanche activity? From Figure 3 I can argue that the avalanche activity is very effective in redistributing snow, on both ice bodies. Moreover, the current glacier looks steeper than it was in 1981, and therefore it could be more prone to snow removal by avalanches, at least in some parts.

Answer: In the sentence we say that snow accumulation in the upper glacier is limited. One reason is because there is very small accumulation area above the upper glacier, and it does not receive avalanche channels. Moreover, as the reviewer states, this is currently a rather steep glacier (around 40º) and it limits the snow accumulation by gravity. The sentence has been modified as follows: "Despite the high elevation of the upper glacier, snow accumulation is limited due to the minimal avalanche activity above the glacier over the ice body and its marked steepness (≈40º)."

29-P5027, L. 26-29: please argument (also reporting references) the reasoning about colder (warmer) temperature in the north-(south-) facing slopes. The location of the weather station should be visible in the geographical setting map (Figure 1) .

Answer: We have modified the paragraph as follows: "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 location of Góriz and the other meteorological stations are now visible in a new pannel of Figure 1.

30-P5028, L. 3-5: The methods used for estimations are not mentioned.

Answer: We have removed the precipitation estimation for Marbore lake, since Del Valle did not mentioned the period and the methodology used to obtain such number.

31-P5028, L. 20: photogrammetric flight (also in the following);

Answer: Changed

32-P5029, L. 3-5: how these accuracies were calculated? Are these single-pixel (or single-point) estimates? Please see the work of Rolstad et al., (2009) for considerations about area-averaged error propagation. Rolstad, C., Haug, T., and Denby, B.: Spatially integrated geodetic glacier mass balance and its uncertainty based on geostatistical analysis: application to the western Svartisen ice cap, Norway, J. Glaciol., 55, 666–680, 2009.

Answer: Thanks for your comments. It has been very difficult to us obtain detailed information on technical specifications of the IGN products. Finally, we think we have noticeably improved the explanations in this regard. Taking into consideration this question we have modified the paragraph as follows: "The Root Mean Squared Error (RMSE) for vertical 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 (single-point estimates). 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 the studied glaciers. The results showed agreement with the accuracy indicated by the IGN in almost all areas although 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 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 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 combined data accuracy (Rolstad and others, 2009). In any case, 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)".

33-P5029, L. 14: a DTM with a cell size of 2x2 m is a high-quality DTM. Did you evaluate the opportunity of using the hillshade of that DTM (and of the ALS DTMs of the following years) to outline the perimeter of the glacier?

Answer: This is an interesting suggestion that we tried to apply. Unfortunately there is a new sector of bare rocks composed by a very smooth polished surface that is very difficult to be discriminated from the surface covered by ice and, hence, we cannot delineate an accurate edge of the glacier.

34-P5029, L. 24 to P5030, L. 26: I suggest adding the TLS scanning positions and the target positions in one of the figures. The error estimates can be improved using training areas, rather than single points, in stable terrain outside the glacier. See for example Carturan et al., (2013) and Rolstad et al., (2009).

Answer: We have tried to apply this technique (was new for us), and we did not obtain significant improvement regarding using fixed targets. I think that as we are scanning at very long distance is better to scan reflective targets at shorter distances to define very accurately the position of the scan with respect to the acquired clouds of points. We use eleven targets (now marked in Figure 1) covering much different angles from the scanning position, we consider this is an appropriate way to georreference the scans and make them comparable between different dates.

35-P5030, L.25: this assumption seems to be not supported by Figure 3. The exact date of the 1981 (or 1980?) is not reported, but you mention that it is a ‘late-summer’ photo at P5032, L. 13. The 1980 glacier is largely covered by snow and maybe firn, and that period was preceded by several years with balanced-budget conditions, or even positive budgets (e.g. Marti et al., 2015). Moreover, the ice density is used for converting thickness change to annual mass budget rates also in the period from 2011 to 2014, when large variations in the extent of the accumulation area have been observed. Please, refer to the work of Huss, 2013 for indications. Huss, M. (2013). Density assumptions for converting geodetic glacier volume change to mass change. *The Cryosphere*, *7*(3), 877-887.

Answer: We agree with the comment of the reviewer but we fail to have information to make a better approach for estimating densities. However, the assumption we took only may underestimate the acceleration of the loss of ice over the glacier, as the density must be lower during the first compared period (1981-2009). The revised manuscript includes this clarification: “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 the lack of additional information forced us to take is 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.”

36-P5031, L. 2-13: information about the type of instrumentation is missing. Is the weather station manual or automatic? The lack of changes in instrumentation during the observation period does not guarantee the absence of inhomogeneities, malfunctioning or instrumental drifts. In my opinion this is a very important point for detecting meteorological anomalies and corresponding accelerated reactions of the glaciers. I suggest i) to better describe the weather station, adding also its location in Figure 1, ii) to check the homogeneity of the series comparing Góriz with (homogeneous) meteorological data series from neighbouring weather stations, iii) to extend the meteorological series backward, at least in the 1960s and 1970s. The latest point is crucial for detecting trends and changes in temperature and precipitation, which are responsible for the observed changes in geometry of the Monte Perdido Glacier, from the early 1980s to its current state. Accurate meteorological data series are also essential for calculating current temperature and precipitation anomalies and trends, and for detecting possible non-linear behaviour of the analysed ice bodies. Moreover, I cannot understand which variables are analysed and why. Do the authors deal with absolute seasonal maximum and minimum temperatures, or maybe with average seasonal values? 'Total' precipitation during the accumulation season? The raw precipitation data are corrected for gauge undercatch? how?

Answer: Following the recommendations of both reviewers we have strongly modified this section by adding new stations of temperature and precipitation, and also adding new analyses (using Mann-Whitney test to compare 1983-199 and 2000-2010 periods). In addition we present the interannual variability and trends of the temperature and precipitation in the three new stations for the period 1955-2013. We are very aware of the importance of homogeneity issues, and indeed it has been one of the main research lines of our research team in the last years (i.e. works of Vicente-Serrano, El Kenawy and myself for creating climatic databases in the Pyrenees, the whole Spain and the Andes). However, we realize about the difficulty to proceed with homogeneity testing of a relatively short series (1983-present) in a high mountain environment and quite far of potential reference stations (or reference series). However, due to the proximity to the glacier, I think that this data must be presented and used as a reference of the climate evolution in the neighborhood of the glacier. The new used stations (Canfranc, Mediano, Aragnouet and Pineta) have been carefully checked in terms of quality and homogeneity by the Pyrenean Observatory of Climate Change (OPCC, Deaux et al., 2014). As it is answered in detail to reviewer 1, the results obtained in Góriz (and presented in the original submmision) are fully consistent with the new added stations. All of them shows a generalized lack of climatic trends after 1983, being an exception of warmer temperatures in May and June, that may have important consequences in the energy and mass balance of the glacier, but they are currently difficult to be quantified (see answer to reviewer 1). However, it exits a significant warming during the ablation period when the time slice 1955-2013 is analyzed. The revised manuscript states clearly that we are working with average seasonal temperatures instead of absolute maximum or minimum temperatures. We did not apply undercatch correction to precipitation, because it is a manual station so we do not have the right information on wind speed during the precipitation events, and also because we do not have a proper transference function to do such corrections. Since, we are not aiming to get absolute values of accumulated precipitation, but to have an idea of the interannual variability; we do not think that this is a major problem.

37-P5031, L. 13: please use the right symbol or avoid mentioning 'tau-b'

Answer: Changed.

38-P5031, L. 22-23: what do you mean with air temperature range? I can see mean daily temperature ranges of about 6-7°C both in the accumulation and ablation periods from Figure 2.

Answer: We wanted mean interannual range, now this is clarified.

39-P5031, L. 25: why not indicating the exact extremes of total precipitation in the accumulation period? The same consideration is valid also for the other analysed variables.

Answer: We prefer not indicating the exact extremes because it does not provide any key information but force us to give exact numbers for highest and lowest values of Tmax, Tmin during the accumulation and ablation periods, which in our opinion enlarges unncesarily the text, and difficults the reading.

40-P5032, L. 5-8: why mid-September to mid-September? Previously it was stated that analyses have been carried out considering the two periods Nov-May and Jun-Sep. Close to the 25% of what?

Answer: It is because is normally the time of the year when ablation has almost finished in the area, whilst there is a big chance of not having received the first snowfalls in the season. They are not normally heavy and generally ephimeral snow cover, but difficults the field work, and introduce uncertainty in the estimation of ice depth changes. It is normally the most usual time of the year for glaciological surveys in the Pyrenees.

41-P5032, L. 8-11: from Figure 2 I can see that the 2012'13 total precipitation during the accumulation period was only slightly above the long-term mean (why not providing the exact annual % anomalies?). Then it is reported that the 2013-'14 accumulation period was very wet (please quantify the anomaly) and mild, but the air temperature has been close to the mean. Concerning the ablation months, they were described as 'well below average', while from Figure 2 a negative anomaly can been seen only for the Tmax, of less than. 0.5°C below the long-term mean. I strongly suggest checking the accuracy and homogeneity of meteorological data. I did a quick check of gridded reanalyses at http://data.giss.nasa.gov/, plotting the temperature anomaly of the ablation season 2013 vs. the 1983-2014 mean (http://data.giss.nasa.gov/cgi-bin/gistemp/nmaps.cgi?sat=4&sst=6&type=anoms&mean_gen=0506&year1=2013&year2=2013&base1=1983&base2=2014&radius=250&pol=rob). The resulting map shows almost no anomalies in the study area, which is very different from the -3°C anomaly plotted in Figure 2b. I did another check at this link: http://climexp.knmi.nl/start.cgi?id=someone@somewhere, where homogeneous meteorological series can be downloaded and analysed. Among the closest series to the study area, I have plotted the seasonal anomalies of Zaragoza/Aeropuerto (homogenized time series) from 1950 to 2015 (http://climexp.knmi.nl/plotseries.cgi?id=someone@somewhere&TYPE=t&WMO=8160&STATION=ZARAGOZA/AEROPUERTO&NAME=GHCN_v3_mean_temperature&KIND=season). The mean summer temperature of 2013 and 2014 were very similar, close to the mean of the last 2 decades and about 2°C higher than the mean temperature in the period from 1950 to 1980, i.e. 2°C higher than required for balanced-budget or slightly positive mass balances in the neighboring glaciers that were analyzed in previous studies (e.g. Marti et al., 2015, and references cited therein).

Answer: Thank you for the recommendation, we now indicate the percentiles that represent the values in order to make an appropriate assessment of magnitude of the anomalies, and author is right that 2014 ablation minimum temperatures was rather close to the average of the period 1983-2014. This now more clearly stated in the paper. However, I think we can state that they were "cool" ablation periods compared to the studies period, as the results are: "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 temperatures respectively), and the accumulation period of 2013 to 2014 was very wet (78th percentile) and around average, with air temperatures well average (22th and 48th percentiles for maximum and minimum temperatures respectively) during the ablation months." Probably, if we would have available longer series, such anomalies would not be as marked as for the studied period, but we want highlight is that the loss of ice is much faster after 1999, compared to the period 1983-1999, and that apparently climatic data cannot explain such changes. Indeed, the Mann Whitney test does not find any significant difference between the 1983-1999 and 2000-2010 periods.

42-P5032, L. 13: 1980 or 1981? Can you report the exact dates?

Answer: 1981, it has been corrected along the whole manuscript.

43-P5032, L. 16: please check if 'concave' is what you intend. Maybe convex?

Answer: It is convex. Thanks for detecting the error.

44-P5032, L. 20: the reduction in ice thickness is much more evident in the lower margin of the two ice bodies, whereas it is smaller in the upper edge, especially in the lower portion of the glacier. This behavior has important implications for their future survival (e.g., Pelto, 2010). Pelto, M. S. (2010). Forecasting temperate alpine glacier survival from accumulation zone observations. *The Cryosphere*, *4*(1), 67-75.

Answer: Pelto was the other reviewer of the manuscript and he has provided useful comments on this regard that have been added to the revised manuscript.

45-P5033, L. 3: I suggest adding the area loss in percent, and a description of where it happened (which parts of the glacier), highlighting the different behavior of the two ice bodies.

Answer: Thanks. This has been also suggested by the other reviewer and added to the new text. Also we have followed your recommendations on the figures and this is now seen more easily.

46-P5033, L. 12: it seems that also some areas of the upper glacier have been stationary. Briefly describe where these areas are and why they thinned at a lower rate (e.g. higher snow accumulation, more effective shading?). P5033, L. 18-21: The pattern slightly changed, because the higher elevation losses occurred in the western part during the period from 1981 to 1999, and in the eastern part from 1999 to 2010. I suggest also mentioning the small areas with thickening in the period from 1999 to 2010.

Answer: we think that these stationary areas are mainly due to more effective shading, but with available data is not possible to be confirmed. We agree with the slight change in the wastage patterns. Thus the paragraph is now: "The spatial pattern of ice losses 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".

47-P5033, L. 24: these are not only changes in ice depth, but also in snow and firn thickness. Please refer to general changes in thickness of the glacier/s (here and in the rest of the paper).

Answer: We agree and we have changed it in the paper

48-P5034, L. 13-15: this is the normal behaviour of glaciers close to equilibrium, with the accumulation area gaining mass and the ablation area loosing mass.

Answer: Yes we agree and this is why we state that the balance of the glacier is near zero.

49-P5034, L. 18: based on the data series, the conditions of 2013-'14 were not so similar to the previous year, with significantly higher accumulation in winter and higher temperature in summer. Is the annual mass balance of the Monte Perdido Glaciers more controlled by summer ablation or by winter accumulation? Why?

Answer: We would really like to be able to answer this question. Last spring thanks to new funding we have started to scan the glacier in early May, and we installed ablation stakes to have a “seasonal” mass balance of the glacier and hence to be able to answer this question. Our hypothesis is that ablation dominates accumulation, but we will need several years of data collection to confirm or reject this idea. Hence, we prefer avoid introducing this discussion in the manuscript.

50-P5034, L. 23-25: please check the calculations and terminology. How the cumulative average thickness change can be -2.1 m, if the annual values (I guess, in the entire glacier area) are -1.94, +0.34 and -0.07 m for 2012, 2013 and 2014, respectively? It should be -1.67 m, if I have well understood what the meaning. In addition take care of consistency using always the same number of decimals, and consider my indications at comment P5030, L.25 for density assumptions.

Answer: thanks a lot for this observation, because there was an small error in the calculation that affected to the ice losses of 2011 that affected also to the overall glacier loss (that is -1.93m). It has been carefully checked and corrected along the whole manuscript.

51-P5035, L. 2: what could be the explanation for this spatial consistency?

Answer: We think that the reason is that accumulation or ablation patterns over the glacier have been maintained in time. However, as it is not possible to check right now which of the elements dominates, we think is better not introducing this discussion and just report this fact.

52-P5035, L.14-23: as discussed above, the meteorological data presented in this paper and information on data collection and processing cannot be considered as a sufficient evidence of the discussed behaviour of the meteorological variables and glaciers analysed. Moreover, I doubt that some of them are representative of the true conditions on the glaciers. For example, the total precipitation from November to May (why excluding October?) cannot be representative of the total snow accumulation on the glacier, because an increasing fraction of precipitation is expected to fall as rain, in place of snow, due to warmer temperature. In addition, why the maximum snow height in a single month at a weather station located several hundreds of metres below the glaciers should be considered useful? Furthermore, mean seasonal or decadal values of air temperature alone cannot provide a comprehensive description of the climatic conditions during the ablation season, which also depends on cloud cover and, most importantly, on snow falls over the glaciers and related changes in the surface albedo. Finally, in Figure 2 it is clear that years with extremely high temperature occurred after 2000 (2003, 2005 and 2012), and in 2005 and 2012 they were also characterised by low winter precipitation. As detected by TLS surveys, these years have led to very negative mass balance and huge ice losses, which were not compensated in more favourable years like 2013 and 2014. In my opinion these could be valid explanations for the behaviour observed on the Monte Perdido Glacier, considering also the feedbacks from decreased albedo and increasing slope of the glaciers, due to higher thickness loss in the distal parts. Increasing slopes are expected to affect the avalanche activity and in my opinion can decrease the snow accumulation on the glaciers, or in significant portions of them. Could it be a possible explanation for the shift of the areas with higher thickness loss rates from the western to the eastern part of the glaciers, as can be observed in Figure 4 for the two sub-periods 1981-1999 and 1999-2010?

Answer: The treatment of the meteorological data, the criteria to select accumulation and melting periods the limitation of using one single snow depth data has been also discussed in the response to reviewer 1. We think that the new stations and analyses (monthly trends and Mann-Whitney analysis) give more robustness to the study and confirms the validity of the first results derived from working only with Góriz station. We also explained that October was not introduced in the accumulation nor ablation period as it is a very transitional month and it changes a lot from one year and other. However, looking the monthly trends of section 4.1, its inclusion should not affect the presented trends. Indeed we did trials of including and excluding months to the accumulation and melting periods and most relevant results (lack of statistical significant trends). We have also added a new reference in which is stated that the recent trend in snow accumulation found in Góriz is consistent with SWE data observed in other locations of the central Pyrenees (Buisan et al., in review): "...In a most recent research, Buisan et al. (in 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". The increasing temperature of May and June could lead to decreased albedo earlier in the season, as well as the apparition of rocky outcrops and debris cover. It is now stated stressed in the revised manuscript and I think this point open new lines of research for the immediate future. We agree and indeed is the idea we wanted to send with the hypothesis of the effect of isolated years in the long-term mass balance of the glacier, and we have added it similarly you explain to the discussion, same as the theory that increasing steepness of the glacier may explain changes in the accumulation patterns. Thanks a lot for such comments.

Below there are some of the most important new paragraphs added to the discussion of the revised paper: "...However, 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)."... "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 the whole glacier (AAR<4%) affects indicate 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 accumulation, but if the many do not and the retained snowpack of good years is lost in bad years, then 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 2005 and 2012 they were also characterized by low winter precipitation. As mentioned before, also the feedbacks from decreased albedo and increasing slope of the glaciers might be playing a key role in the recent acceleration of the glacier wastage"... "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".

53- P 5037, L. 3: please clarify what you mean with 'best topographic locations' (high snow accumulation? high shielding? both?)

Answer: We think both. Added to the discussion.

54-P 5037, L. 10-11: unclear, why normal years should have little accumulation or warm ablation season?

Answer: We agree that the sentence was confusing and we have removed the second part.

55-P 5037, L. 9-13: the reasoning is difficult to follow. What is called 'periods with favourable conditions' in the 21st century are likely much warmer than periods with balanced-budget or slightly positive conditions in 1960s and 1970s, as mentioned at P5035, L. 25, and reported by several studies cited in this work. So I cannot understand why the current warmer conditions should lead to mass gains in the same glacier, without mentioning possible negative feedbacks.

Answer: We agree and we have modified the sentence as follows: "In this context, the only explanation for the rapid degradation of the Monte Perdido Glacier after 1999 is that the progressive warming observed since the end of the LIA was responsible of a dramatic reduction in the accumulation area ratio (AAR), and most of this glacier is currently below the current ELA (at 3050 m a.s.l. during the period 2011-2014, Figure 5D). 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)."

56-P 5037, L. 15: anomalously positive compared to a period with unfavourable conditions for the glaciers

Answer: We agree and we have modified the sentence accordingly.

57-P 5037, L. 25: it is unclear how the rock outcrops can decrease the albedo

Answer: We agree the sentence was unclear. The outcroprs increase the long-wave emissivity, and a thin debris cover may affect the albedo), and we have modified the paragraph :" 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"

58-P 5037, L. 26: why the western part is losing thickness faster?

Answer: Probably because it receives higher radiation and accumulates less snow during accumulation period. We hope to be able to answer this question soon.

Comments on the figures:

59-Figure 1: I suggest adding a label to the current Monte Perdido Glacier and the location of the meteorological station/s and TLS scanning positions.

Answer: Figure 1 has been modified following the recommendations of both reviewers

60-Figure 2: I suggest removing the boxplots and also the small rectangles at the right of the charts. If the last year is 2014, then the X axis labels are shifted by one year. Consider also the opportunity of adding gridlines to facilitate the comparison among the different years.

Answer: we think the small triangles are useful to identify in a visual way the location of the most recent years within the observed variability since 1983. For this reason, we prefer maintain them. Years are in "water years" starting in October to be consistent with the accumulation periods. We think this is clear with the reference to the seasons 2011/12; 2012/13 and 2013/14.

61-Figure 3: 1980 or 1981?

Answer: 1981.

62-Figure 4: the outlines from different years have the same colours and cannot be distinguished.

Answer: We have modified the figure accordingly

63-Figure 5: in my opinion 2D spatial representations like those in Figure 4 are more effective than the 3D representations reported in Figure 5. Moreover, there is a rather wide range of thickness change around zero which is represented by white, whereas it could be interesting to see the switch from negative to positive thickness changes, as reported in Figure 4. I also suggest, if feasible, to outline the accumulation area of each year and to use a classified colour scale, as in Figure 4, rather than a stretched one.

Answer: We have modified the figure accordingly and converted into a 2D figure. We finally do not outline accumulation zones, because in some years there are small areas near 0 that gives a lot of small marked areas and hinder an appropriate view of the figure.

REVISED PAPER TRACKED CHANGES

RECENT ACCELERATED WASTAGE OF THE MONTE PERDIDO GLACIER IN THE SPANISH PYRENEES ~~DURING RECENT STATIONARY CLIMATIC CONDITIONS~~

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Abstract

This paper analyzes the evolution of the Monte Perdido Glacier, the third largest glacier of the Pyrenees, from 1981 to the present. We assessed the evolution of the glacier's surface area by use of aerial photographs from 1981, 1999, and 2006, and changes in ice volume by geodetic methods with digital elevation models (DEMs) generated from topographic maps (1981 and 1999), airborne LIDAR (2010) and terrestrial laser scanning (TLS, 2011, 2012, 2013, and 2014). We interpreted the changes in the glacier based on climate data from a nearby meteorological stations. The results indicate an accelerated degradation of this glacier after 2000, with a rate of ice surface loss that was almost three-times greater from 2000 to 2006 than for earlier periods, and a doubling 43% higherof the1.85 times faster rate of glacierice volume loss from 1999 to 2010 (the ice depth decreased by 8.98±1.8 m, -0.72±0.14 m w.e. yr^{-1}) compared to 1981 to 1999 (the ice depth decreased 8.35±2.12 m, -0.39±0.1 m w.e. yr^{-1}). This loss of glacial ice has continued from 2011 to 2014 (the ice glacier depth decreased by 1.932.1±0.4 m, -0.5864±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) represented a deceleration in wastage compared to previous years, but still the overall mass balance were near zero, 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. despite of rather wet and cool conditions, in comparison with the 1983-20125 period, in two out of the three considered years.. Local climatic changes observed during the study period seems not be enough cannot 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 periodlocal

precipitation and snow accumulation increased slightly, and local air temperature during the ablation period did not significantly increase. The accelerated degradation of this glacier in recent years can be explained by the lack of equilibrium between the glacier and the current climatic conditions and probably other factors affecting the energy balance (i.e. increased albedo in spring) and feedback mechanisms (i.e. emitted advected heat offrom recent ice free bedrocks and debris covered areas). In particular, the average air temperature increased by at a minimum least of 0.9ºC in this region since the end of the Little Ice Age (LIA) in the mid-1800s. Thus, this glacier shrinks dramatically during years with low accumulation or high air temperatures during the ablation season, but cannot recover during years with high accumulation or low air temperatures during the ablation season. The most recent TLS data support this interpretation. the two years 2012-13 and 2013-14 are actually years of decelerated or null wastage, compared to the average conditions of the previous years. 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, but still led to near zero the overall mass balance were near zeroconditions, 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.

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

1 Introduction

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Most glaciers worldwide have undergone intense retreat since the end of the Little Ice Age (LIA) in the mid 19th century, as indicated by measurements of ice surface area and volume (Vincent et al., 2013; Marshall 2014; Marzeion et al., 2014 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 Ötzal 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 ~~reported~~ that the rate of ice mass loss in the long-term monitored Careser Glacier~~studied the Italian Alps and found that the average rate of ice mass loss~~ (Italian Alps) during the period 1981~~0~~-200610 ~~10~~ (−0.1~~.~~3~~69~~ ~~± 0.12~~ m w.e. yr^{-1}) was about twice that for the period of 1933 to 1959 (-0.7~~XX ± XX~~ 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, 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).

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The Pyrenees host some of the southern-most glaciers of Europe are~~ in the Pyrenees~~, and they have also undergone significant ~~deglaciation~~retreat. In 2005, these glaciers had an area of 495 hectares (González-Trueba et al., 2008) and in 2008 they had a total~~n~~ 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 20th century and the beginning of the 21st century were similar to those observed from 1860 to 1900, immediately after the end of the LIA. A similar conclusion has been reached by Marti et al. (2015) for the Ossue Glacier (French Pyrenees).

Most studies agree that global warming is responsible for the observed glacier shrinkage and the recent acceleration of this shrinkage. The temperature increase has been particularly strong since the end of the LIA, and also since the 1970s in most mountain ranges of the world (Haeberli and Beniston, 1998; Beniston et al., 2003; Nogués-Bravo et al., 2008; Gardent et al., 2014). Global warming has increased the equilibrium line altitudes (ELAs) and reduced the accumulation ablation ratios (AARs) of glaciers, so that most glaciers are not in equilibrium with current climatic conditions (Mernild et al., 2013) and many of them cannot survive for much longer (Pelto, 2010). In the case of the Pyrenees, the annual air temperature has increased a minimum of~~at least~~ 0.9ºC since the end of the LIA (Dessens and Bücher, 1998; Feulliet and Mercier, 2012). More recently, Deaux et al., (2014) reported~~, showing~~ an increase of 0.2ºC decade^{-1} ~~between~~

for the period between 1951 and 2010 ~~(Deaux et al., 2014)~~. This explains the ~255 m increase in the elevation of the ELA in the glaciers of the Maladeta Massif 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 air temperature during the ablation season are thought to be the principal causes of recent glacier decline in the southern (Spanish) side of the Pyrenees (Chueca et al., 2005).

Glaciers are very good indicators of climate change due to their high sensitivity to anomalies in precipitation and air temperature (Carrivick and Brewer, 2004, Fischer et al., 2015). However, establishing a direct relationship between annual fluctuations of climate and the changes in area and mass of a particular glacier is difficult, because only glaciers of ~~medium or~~ small size respond rapidly to changes in annual snowfall and snow/ice melt, whereas large glaciers respond much more slowly (Marshall, 2014). Moreover, very small glaciers may develop and evolve for reasons unrelated to the regional long-term monthly or seasonal climatic ~~changes~~evolution, such as avalanches and 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 ~~that~~ respond to climate fluctuations, although this relationship is also ~~explained~~ 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~~of~~

~~changes in glaciers with changes in climate~~ (Chueca et al., 2007; Cogley, 2009; Fischer et al., 2015). In the Pyrenees, there are very few estimations of ice volume loss~~lost ice volumes~~ (Del Río et al., 2014; Sanjosé et al., 2014; Marti et al., 2015), although abundant research has examined recent changes of glaciated surface areas (Chueca et al., 2005, López-Moreno et al. 2006; González-Trueba et al., 2008). Annual estimates of glacier mass fluctuations based on glaciological method were only performed in the Maladeta Glacier (Spanish Pyrenees) and the Ossoue Glacier (French Pyrenees), and these indicated the mean glacier~~ice~~ depth loss ~~of ice thickness~~ was 14 m during the last 20 years in the Maladeta Glacier, and 22 m in the Ossoue Glacier (Arenillas et al., 2008; René, 2013; Marti et al., 2015). Other studies in the Spanish Pyrenees compared digital elevation models (DEMs) derived from topographic maps of~~for~~ 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 in the recent evolution of the Monte Perdido Glacier, the third largest glacier in the Pyrenees. We document changes in the glacier surface area from 1981 to 2006 and provide updated information on volumetric changes by comparing DEMs derived from topographic maps of 1981~~0~~ and 1999 (Julian and Chueca, 2007), a new DEM obtained in 2010 from Airborne LIDAR, and four successive Terrestrial Laser Scanning (TLS) ~~runs~~ surveys that were performed during the autumns of 2011, 2012, 2013, and 2014. We examined these data ~~along with~~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 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

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The Monte Perdido Glacier 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 next studies examined the extent and made descriptions of the status of the~~and other characteristics~~ of ice masses and the features of the moraines deposited during the LIA (Gómez de Llarena, 1936; Hernández-Pacheco and Vidal Box, 1946; Boyé, 1952). More recent studies have established the location of moraines to deduce the dynamics and extent of LIA glaciers (Nicolás, 1981 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 after the 1970s (Nicolas, 1986; García-Ruiz et al., 2014). The two remaining glacier bodies, which are currently unconnected, are ~~currently~~ referred in 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~~over~~ the ~~ice body~~glacier and its marked steepness (≈40º).

There has not been a direct estimation of the current location of the ELA in the upper Cinca valley, but studies at the end of the 20th and beginning of the 21st century placed it at about 2800 m in the Gállego Valley, west of the OMPNP (López-Moreno, 2000), and at about 2950 m in the Maladeta Massif, east of the OMPNP (Chueca et al., 2005). The mean annual air temperature at the closest meteorological station (Góriz at 2250 m a.s.l.) is 5.03ºC, 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. ~~Previous research estimated the mean annual precipitation was about 2000 mm in Marboré Lake (Del Valle, 1997), with most precipitation occurring during spring and autumn.~~

3 Data and methods

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3.1. Comparison of DEMs

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

The 1981 DEM was obtained from the cartography published by the Spanish *Instituto Geográfico Nacional* (IGN) (Sheet 146-IV, Monte Perdido; Topographic National Map Series, scale 1:25000). This map was published in 1997 and its cartographic restitution was based on a photogrammetricy flight in September1981. 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 photogrammetricy flight in September 1999. The 2010 DEM was obtained from an airborne LIDAR flight (MDT05-LIDAR) made by the IGN in late summer of 2010 in the context of the National Plan for Aerial Orthophotography (NPAO).

The Root Mean Squared Error (RMSE) for vertical 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 the studied glaciers. The results showed good agreement with the accuracy indicated by the IGN in almost all areas although 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 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 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 combined data accuracy (Rolstad and others, 2009). In any case, 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 Root Mean Squared Error (RMSE) for vertical 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. The combined vertical RMSE for the 1981-1999 DEMs comparison is < 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 could alter the combined data accuracy (Rolstad and others, 2009). In any case, 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).~~

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~~The root mean squared error (RMSE) for vertical accuracy calculated by the IGN for their digital cartographic products at the 1:25000 scale is ± 1.5 m for the 1981 and 1999 DEMs, and ± 0.2 m for the LIDAR-derived DEM of 2010. The combined vertical~~

RMSE for comparison of the 1981 and 1999 DEMs is ±2.12 m, and is less than ±1.8 m for comparison of the 1999 and 2010 DEMs. Vertical RMSE values were used to estimate error bars to provided values of glacier changes in both analyzed periods. These combined vertical RMSEs were considered precise enough for our purposes, because changes in ice depth in our analyses were generally much greater than these values. The estimation of ice volume changes was performed in ArcGIS (ESRI, Inc.) by the use of the tool "cut-and-fill" for comparing pairs of glacier surface DEMs (1981-1999 and 1999-2010). The glacial perimeters associated with each DEM date were retrieved from aerial photographs (1981: *Pirineos Sur* Flight, September-1981, scale of 1:30000, 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 error bars to estimated glaciated areas and their temporal changes. A resampling procedure using cubic convolution was used to generate the final rectified images.

The most recent estimates of the evolution of the glacier were from annual TLS surveys. LIDAR technology has developed rapidly in recent years, and terrestrial and airborne LIDAR have been used in diverse geomorphology studies, including monitoring changes in the volume of glaciers (Schwalbe et al. 2008, Carturan et al., 2013b). The device used in the present study is a long-range TLS (RIEGL LPM-321) that uses time-of-flight technology to measure the time between the emission and detection of a light pulse to produce a three-dimensional point cloud from real topography. The TLS used in this study employed light pulses at 905 nm (near-infrared), which is ideal for acquiring data from snow and ice cover (Prokop, 2008, Grünewald et al., 2010; Egli et al., 2011), a minimum angular step width of 0.0188º, 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 a frontal view of the glacier with minimal shadow zones in the glacier and a scanning distance of 1500 to 2500 m. We also used indirect registration, also called target-based registration (Revuelto et al., 2014), so that scans from different dates (September of 2011 to 2014) could be compared. Indirect registration uses fixed reference points (targets) that are located in the study area. Thus, 11 reflective targets of known shape and dimension are placed at the reference points at a distance from the scan station of 10 to 500 m. Using standard topographic methods, we obtained accurate global coordinates for the targets by use of a differential global positioning system (DGPS) with post-processing. The global coordinates were acquired in the UTM 30 coordinate system in the ETRS89 datum. The final precision for the global target coordinate was 0.05 m in planimetry and 0.1 m in altimetry. Invariant elements of the landscape surrounding the ice bodies (identifiable sections of rocks and cliffs) were used to assess measurement accuracy. Ninety percent of the reference points had elevation difference lower than 40 cm, and there was no apparent relationship between scanning distance and observed error. Such 40 cm of deviations was considered to add error bars to the calculated ice depth and mass loss rates. The conversion of mean ice elevation change to annual mass budget rates was done applying mean density of 900 kg m^{-3} (Chueca et al., 2007; Marti et al., 2015). The assumption of this value neglects the existence of a~~, considering that the~~ 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 ~~the~~ lack of additional information forced us to 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. ~~zone was nearly absent (Chueca et al., 2007; Marti et al., 2015).~~

3.2 Climatic data

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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 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 necessary to define the accumulation and the ablation season in a subjective manner based on our experience. We are aware that May and October are transitional months between accumulation and ablation conditions depending of the especific annual conditions. However, we set these periods because 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 in Góriz were contrasted with three otherIn addition, we analyzed the trends of monthly series and for the accumulation and ablation periods during the 1981-2013 period, available for three observatories (see Figure 1) with precipitation data (Pineta, Aragnouet and Canfranc), and three for 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 data when the periods 19831-1999 and 2000-2010 are compared. 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 longer ti

4. Results

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4.1. Climatic evolution and variability from 1983 to 2014

Figure 2 illustrates the high interannual variability of climate in the study areaGóriz station since 1983. The average maximum air temperatures in Góo´zriz during the snow accumulation and ablation seasons had no significant trends, with Mann-Kendalltau-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 ~~only~~ statistically significant ($p < 0.05$)~~ during the accumulation period (Figs. 2c and 2d)~~. The interannual air temperature range was larger for the accumulation period (~5ºC) than for the ablation period (~2.5ºC). Table 1 shows that t~~T~~he evolution of temperature in Góriz is line with the observed in the three other meteorological stations (Mediano, Aragnouet and Canfranc), with no statistically significant trends for maximum or minimum temperature, for the accumulation nor~~and~~ ablation periods during the period 1983~~23~~-2013. At monthly basis, the four analysed observatories only detected a statistically significant increase in May and June; and a statistically significant decrease in November and December for both, maximum and minimum temperature. The Mann-Whitney test did not revealed statistically significant differences in the medians of the series for the accumulation and ablation ~~periods~~seasons in any observatory– when the periods 1983-1999 and 2000-2010 were compared.

Precipitation 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 Góriz during May, and ~~relatively low~~a ~~dominance of positive~~near zero tau-b coefficients for the ~~rest~~most of the ~~years~~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 ~~was found~~ a statistically significant increase ~~in Aragnouet~~ in May, and ~~in~~ Pineta ~~during~~in March. No statistically differences in the median of precipitation during the accumulation and ablation seasons of the 1983-1999 and 2000-2010 periods in any of the analyz~~s~~ed 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 longer climate series. Thus, the 1955-3013 period exhibit a statistically significant ($p<0.05$) warming during the ablation period, and the accumulation exhibited positive tau-b values but 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.

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 ~~one of the driest recorded years~~with a rather dry accumulation period (~~close to the 25th~~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 temperatures respectively), and the accumulation period of 2013 to 2014 was very wet (78th percentile) and ~~mild~~around average respectivelly, with air temperatures ~~well~~ around or

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below the ~~below~~ average (22th and 48th percentiles for maximum and minimum temperatures respectively) during the ablation months.

4.2 Glacier evolution from 1981 to 2010

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Figure 4~~3~~ shows two photographs of the glacier taken in late summer of 1981~~0~~ and 2011. A simple visual assessment shows the fast degradation of the glacier during this 30 year period. In 1981, the upper and lower glaciers were no longer united (they became disconnected from 1973 to 1978), and they exhibited a ~~concave~~ 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~~1~~ shows the surface area of the ice in 1981, 1999, and 2006. From 1981 to 1999 the glacier lost 4.5±0.19 ha (1.5±0.06 ha in the upper glacier and 3.0±0.13 in the lower glacier), corresponding to an overall rate of 0.25±0.01 ha yr^{-1}. From 1999 to 2006, the glacier lost 5.4±0.24 ha (2.0±0.09 ha in the upper glacier and 3.4±0.15 ha in the lower glacier), corresponding to an overall rate of 0.77±0.23 ha yr^{-1}, more than three-times the rate of the previous 18 years.

Comparison of the elevation of the glacier's surfaces derived from the DEMs (1981 to 1999 *vs.* 1999 to 2010) also indicates an acceleration of glacier wastage over time (Figure 5~~4~~). During the 1981-1999 period, the ice thickness decreased by an average of 6.20±2.12 m in the upper glacier and 8.79±2.12 m in the lower glacier (8.35±2.12 m overall); thus, the mean rate of ~~ice~~ glacier thickness decay was 0.34±0.11 m and 0.48±0.11 m yr^{-1} (0.46±0.11 m yr^{-1} overall, or 0.39±0.1 m w.e. yr^{-1}), respectively. Moreover, the changes in glacier thickness had spatial heterogeneity. No sectors of either glacier had increased thicknesses, but some small areas of the lower glacier remained rather stationary, with declines in thickness less than 5 m. The largest losses of ~~ice~~ 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 was 7.95±1.8 m in the upper glacier and 9.13±1.8 m in the lower glacier (8.98±1.8 m overall); corresponding to rates of 0.72±0.16 m and 0.81±0.16 m yr^{-1} (0.8±0.16 m yr^{-1} overall, or 0.72±0.14 m w.e. yr^{-1}), respectively. The spatial pattern of ice losses resembled the pattern from 1981-1999, but areas of noticeable glacier losses are also found eastward. ~~with t~~The smallest decreases are found ~~in the eastern and~~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

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Figure 65 shows the differences in ice 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 76 shows the frequency distribution of ice depth change measured over the glacier for these periods.

The period of mid-September 2011 to mid-September 2012 was very dry during the accumulation period and very warm during the ablation period. These conditions led to dramatic declines of ice glacier depth, with an average decrease of 2.128 1.94±0.4 m (21.082592±0.4 m in the upper glacier and 2.1231.97±0.4 m in the lower glacier). Ice thinning affected almost the entire glacier (the aAccumulation Ablation Rarea 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 m. The few scattered points indicating depth increases in the middle of the lower glacier are likely to be from the motion of the existing crevasses.

Conditions were very different from 2012 to 2013, with a rather wet accumulation period and very cool ablation period. These conditions led to changes that contrasted sharply with those of the previous year, in that large areas of the glacier had increased ice thickness. Most of these increases did not exceed 1-1.5 m, and most were in the highest elevation areas of both ice bodies. Nonetheless, during this year, large areas remained stable (AAR was 54%) and some areas even exhibited noticeable ice losses (more than 1.5-2 m in the upper and lower glaciers). Despite the excellent conditions for glacier development from 2012 to 2013, the average increase of glacier thickness was only 0.34±0.4 m (0.32±0.4 m in the upper glacier and 0.38±0.4 m in the lower glaciers). Very similar conditions occurred in 2013-2014, with very wet accumulation months and below average air temperature during the ablation period. Again, there were large areas with moderate increases in thickness (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 0.070.08±0.4~~1~~ ~~–~~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~~672.1~~±0.4 m (0.58~~64~~±0.36 m w.e. yr^{-1}), with some regions experiencing losses greater than 6 m. Only the areas of the eastern part of the lower glacier that were at high elevations (around the rimaye) exhibited some elevation gain during this period (accumulation ~~ablation~~area ratio, AAR, for the three years was 16%), and this was typically less than 2 m. Interestingly, the areas with greatest and lowest ice losses during 1981-2010 were similar to those with the greatest and lowest ice losses during 2011-2014, indicating a consistent spatial pattern of glacier shrinkage over time.

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5. Discussion and conclusions

The results of this study indicate that the recent evolution of the Monte Perdido Glacier was similar to that of many other glaciers worldwide (Marshall, 2014, Vincent et al., 2013), especially those in Europe (Gardent et al., 2014; Abermann et al., 2009; Scotti et al., 2014; Marti et al., 2015) where glacier shrinkage began at the end of the LIA and has clearly accelerated after 2000. More specifically, the annual loss of area of the Monte Perdido Glacier was three-times greater from 2000 to 2006 compared to the 1981-1999 period; and the loss of ice thickness from 1999 to 2010 was double the rate observed from 1981 to 1999. Acceleration in glacier shrinkage has been also reported in the Ossoue Glacier (French Pyrenees), where mass balance decline during the period 2001-2013 (−1.45 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 decline of snow accumulation. Climate data (1983-2014) of a nearby meteorological station, and three other Pyrenean meteorological stations, suggests that 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 compared to 1999-2010. Precipitation in the four analyzed stations during the accumulation period and maximum annual snow depth in Góriz were also stationary or slightly increased. The accelerated degradation of the Monte Perdido Glacier suggests that such tendency cannot be only cannot simply be explained by an intensification of climate warming or by the sharp decline of snow accumulation. Climate data (1983-2014) of a nearby meteorological station, and three other Pyrenean meteorological stations clearly refute this hypothesis, suggests that most of the year temperature has not exhibited statistically significant trends. The Mann-Whitney test did not reveal statistical differences in temperature when because air temperatures remained stationary during the ablation period (i.e. average maximum temperature was 13.4 and 13.6 ºC for the periods 1983-1999 is compared toand 1999-2010, respectively), and pPrecipitation in the four analysed stations during the accumulation period and maximum annual snow depth accumulation during accumulation periodin Góriz were also stationary or slightly increased. (average precipitation was 1013 and 1028 mm; and average maximum annual snow depth in April was 104 and 131 cm for the periods 1983-1999 and 1999-2010 respectively). Previous studies of the Pyrenees and surrounding areas showed that air temperature has

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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 detected in the three temperature series analyzed for this study during the period 1995-2013. 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 shift in NAO evolution toward more negative evolution that affected to the most recent evolution of temperature and precipitation over the Pyrenees. Thus, no temporal trends of both variables are found near the Monte Perdido Peak, when the study period starts in the 1980s and the effect of the cold and wet period of the 1960s to 1970s is removed. Thus, Vicente-Serrano et al. (2010) found that the increased occurrence of very wet winters after the 2000s was associated with frequent strong negative NAO winters. In agreement, Buisan et al. (2015) indicated that for the period of 1980 to 2013 the overall number of snow days in the Pyrenees remained stationary and even slightly increased in some locations. In a most recent research, 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) ~~also~~ support the view that southern Europe and some other regions of the world have undergone clear moderations of the warming trends that were reported at the end of the 20th century. Nonetheless, it is necessary to bear in mind that the longest climatic records or dendroclimatological reconstructions for the Pyrenees still point out the period considered in this study (1980-2014) as a very strong positive anomaly of temperature and a dry period compared to the period spanning since the end of the LIA (Büngten et al., 2008; Deaux et al., 2014; Marti et al., 2015). ~~However, m~~More research is needed to fully assess the implications of~~ it is interesting to note that~~ the temperature increase detected in May and June~~ has exhibited a statistically significant (p<0.05) increase~~ 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 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.~~,~~

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The mass loss rates presented in this study for the different periods (0.39±0.1 and 0.72±0.14 m w.e. yr^{-1} for 1980-1999 and 1999-2010 periods respectively) are similar to the reported by Chueca et al., (2007) and Marti et al. (2015) for the Maladeta massif (0.36 m w.e. yr^{-1} for the 1981-1999 period; and 0.7 m w.e. yr-1 for the 1991-2013). The most recent mass balance values obtained for the Monte Perdido Glacier are more similar to those reported for the Swiss Alps (Fischer et al., 2015), or the best preserved glaciers in some areas of the Italian Alps (Caturan et al., 2013 a); but much lower to the most retreating glaciers in the Alps (Carturan et al., 2013b) or the one reported in the Ossoue Glacier (French Pyrenees, -1.45 m w.e. yr-1 for the 1983-2014). The smaller rates in the Spanish side of the Pyrenees compared to the later may be explained by the location of the remnant ice bodies in Southern side of the range, confined in the most elevated and the best topographic locations (higher snow accumulation and radiation shilding) in their respective cirques (López-Moreno et al., 2006). Oppositely, the Ossue glacier still has maintained a considerable glacier tongue in an easting slope. In this context, the only explanation for the rapid degradation of the Monte Perdido Glacier after 1999 is that the progressive warming observed since the end of the LIA was responsible of a dramatic reduction in the accumulation area~~-ablation~~ ratio (AAR), and most of this glacier is currently below the current ELA (at 3050 m a.s.l. during the period 2011-2014, Figure ~~5D~~6D). This leads to a clear imbalance that is very likely to be exacerbated by negative feedbacks~~, in that significant ice losses occur during unfavorable years and even during “normal” years (with little accumulation or warm ablation seasons)~~. Because of this imbalance, the glacier cannot recover ice losses during periods with favorable conditions (high accumulation and/or little ablation 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 depth during this three years period was 1.936~~72.1~~±0.4 m, roughly one-fourth of the loss from 1981 to 2000, and from 2000 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 the whole glacier (AAR<4%) affects indicate 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 accumulation, but if the many do not and the retained snowpack of good years is lost in bad years, then in fact no accumulation persists. Thus, the behavior observed for the Monte Perdido glacier during the studied period is very

Con formato: Inglés (Estados Unidos) 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 2005 and 2012 they were also characterized by low winter precipitation. As mentioned before, also the feedbacks from decreased albedo and increasing slope of the glaciers ~~might~~must 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 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 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

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Con formato: Fuente: Times New Roman, Inglés (Estados Unidos) glacier may serve as a model for studies of the evolution of glaciers in other regions of the world that have similar characteristics now and in the future.

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Figure captions

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Figure 1. Monte Perdido study area and extent of ice cover at the end of the Little Ice Age (according to the map of Schrader [1874]) and in 2008. 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 the stations of Aragnouet, Canfranc, Mediano (only temperature) and Pineta (only precipitation) during the period 1955-2013. Numbers inform of the Tau-b values of the trends. Asterisks indicate statistically significant trends ($p<0.05$).

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Figure 4~~3~~. Photographs of the Monte Perdido Glacier during the late summer of 1981~~0~~ and 2011.

Figure 5~~4~~. Changes in ~~ice thickness~~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 65. Changes in ice thicknessglacier 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 76. Changes in ice thicknessglacier 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 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 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	.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*	0.3*	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	.316*	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	**-0.3***	-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	

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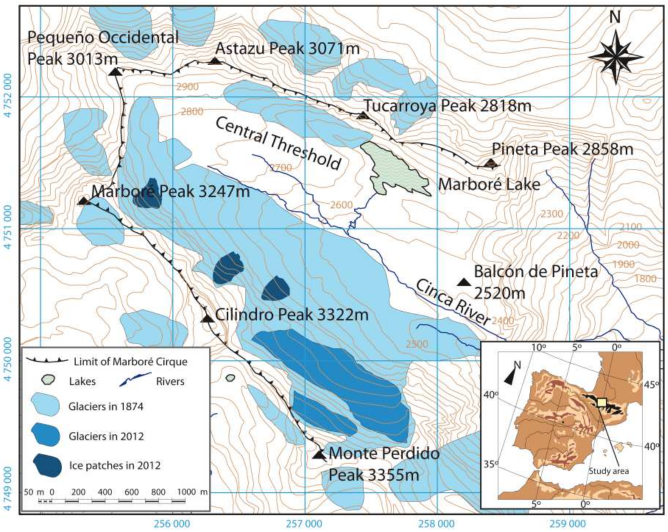
Table 2~~1~~. Surface area (ha), loss of surface area (ha), and annual rate of surface area loss (ha yr^{-1}) of the Monte Perdido Glacier.

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


Pequeño Occidental Peak 3013m
Astazu Peak 3071m
Tucarroya Peak 2818m
Pineta Peak 2858m
Central Threshold
Marboré Lake
Marboré Peak 3247m
Balcón de Pineta 2520m
Cinca River
Cilindro Peak 3322m
Monte Perdido Peak 3355m
N
Limit of Marboré Cirque
Lakes
Rivers
Glaciers in 1874
Glaciers in 2012
Ice patches in 2012
Study area
256 000
257 000
258 000
259 000
4 752 000
4 751 000
4 750 000
4 749 000

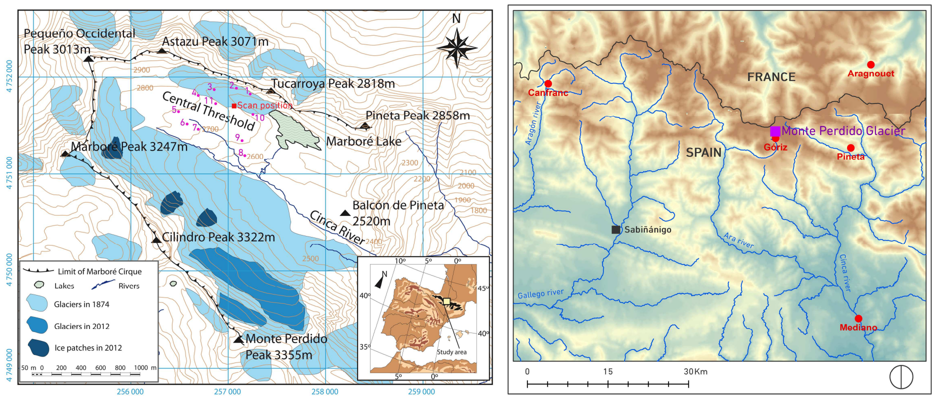

Pequeño Occidental Peak 3013m
Astazu Peak 3071m
Tucarroya Peak 2818m
Pineta Peak 2858m
Central Threshold
Scan position
Marboré Lake
Marboré Peak 3247m
Balcón de Pineta 2520m
Cinca River
Cilindro Peak 3322m
Monte Perdido Peak 3355m
Limit of Marboré Cirque
Lakes
Rivers
Glaciers in 1874
Glaciers in 2012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

Figure 1.

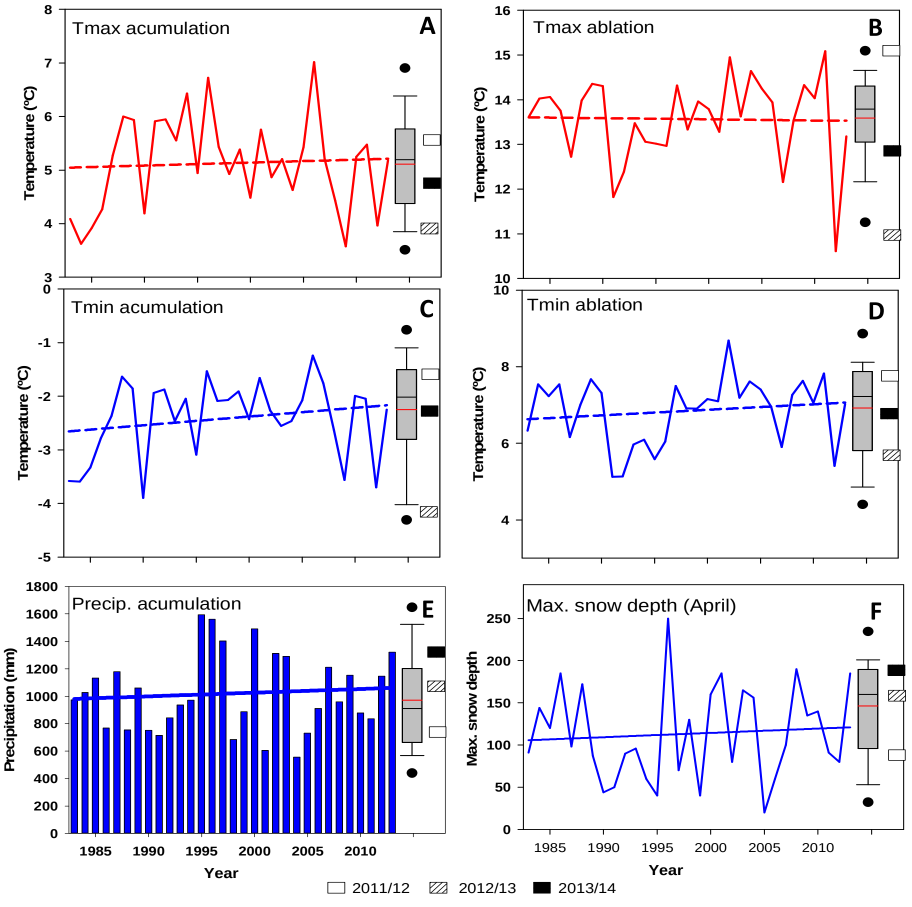

Tmax acumulation
A
Temperature (ºC)
Tmax ablation
B
Temperature (ºC)
Tmin acumulation
C
Temperature (ºC)
Tmin ablation
D
Temperature (ºC)
Precip. acumulation
E
Precipitation (mm)
Max. snow depth (April)
F
Max. snow depth
1985
1990
1995
2000
2005
2010
Year
2011/12
2012/13
2013/14

Figure 2-.

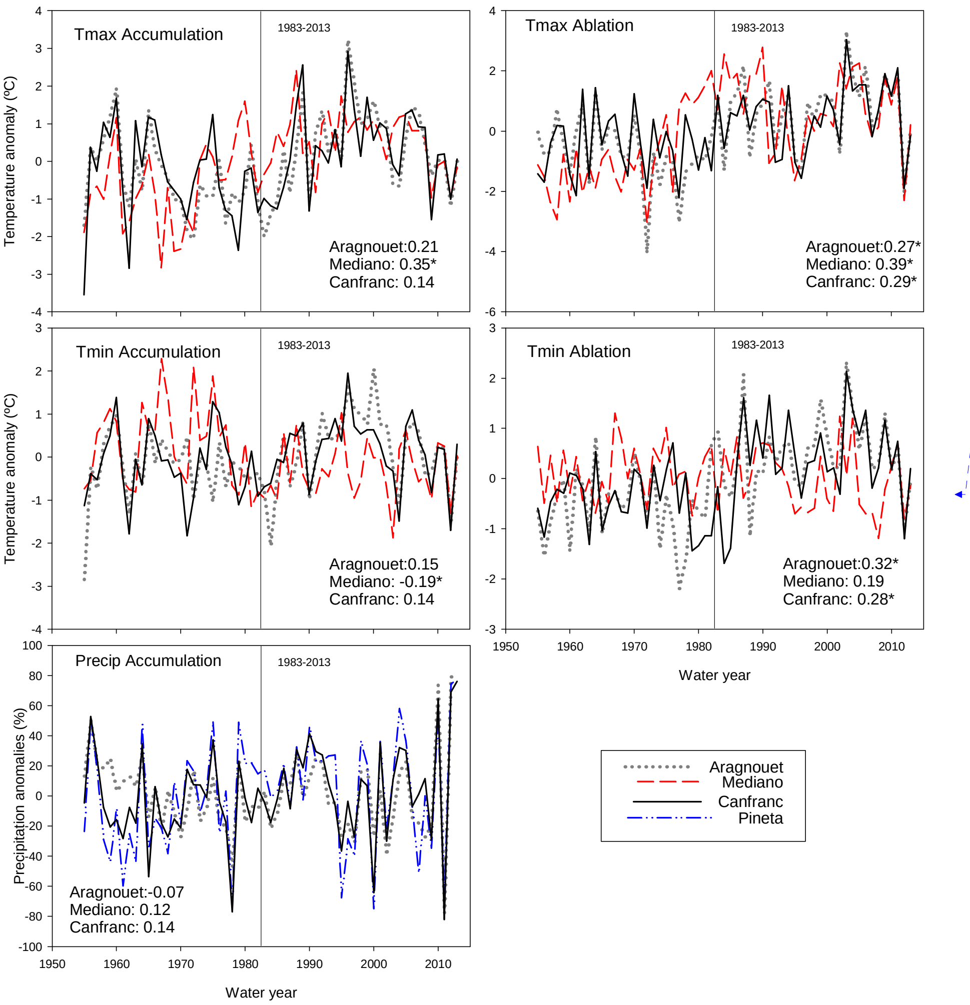


Figure 3.

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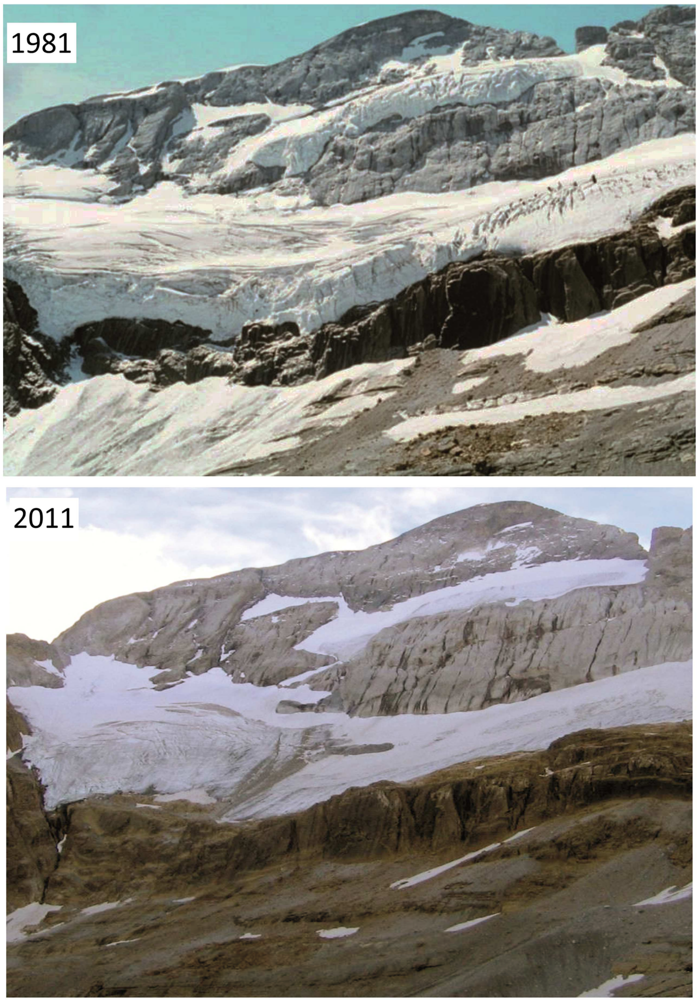


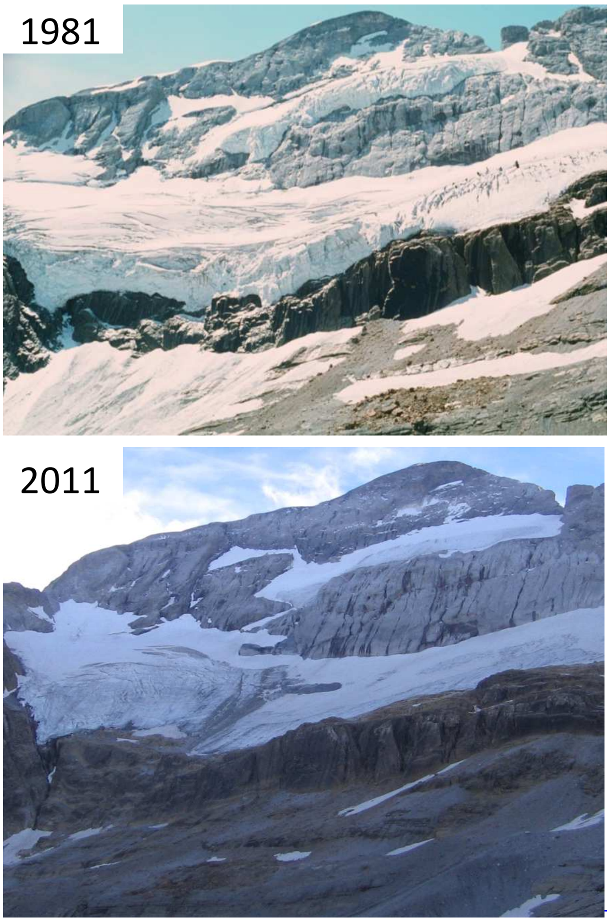
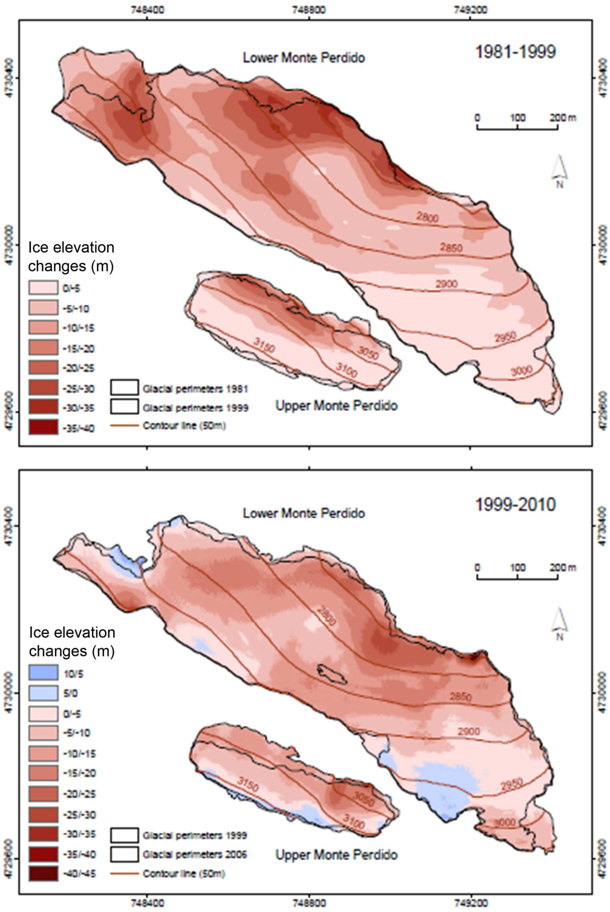
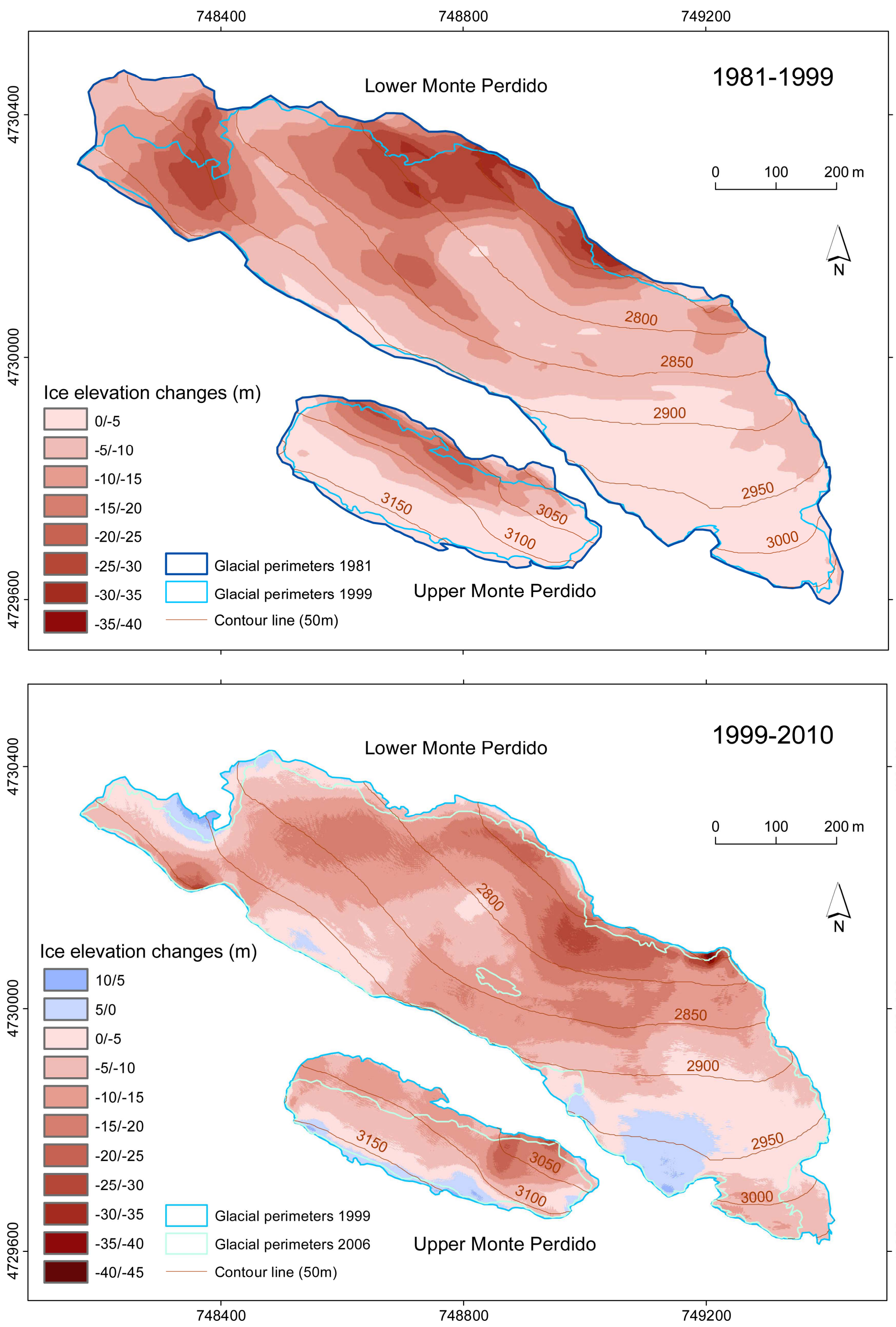


Figure 43.



748400
748800
749200
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
4730400
4730000
4729600
Lower Monte Perdido
1999-2010
Ice elevation changes (m)
10/5
5/0
0/-5
-5/-10
-10/-15
-15/-20
-20/-25
-25/-30
-30/-35
-35/-40
-40/-45
Glacial perimeters 1999
Glacial perimeters 2006
Contour line (50m)
Upper Monte Perdido



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
Lower Monte Perdido
1999-2010
Ice elevation changes (m)
10/5
5/0
0/-5
-5/-10
-10/-15
-15/-20
-20/-25
-25/-30
-30/-35
-35/-40
-40/-45
Glacial perimeters 1999
Glacial perimeters 2006
Contour line (50m)
Upper Monte Perdido

Figure 54.

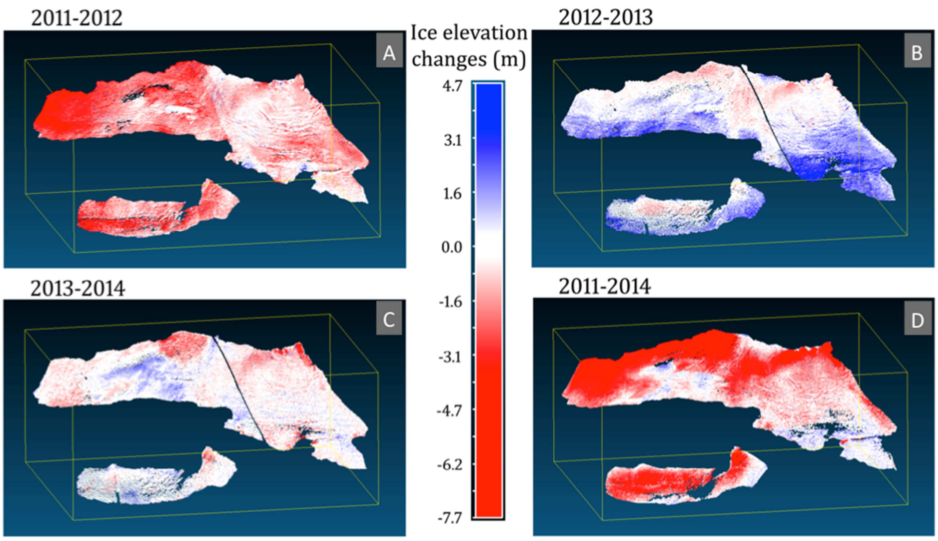


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Figure 6.5

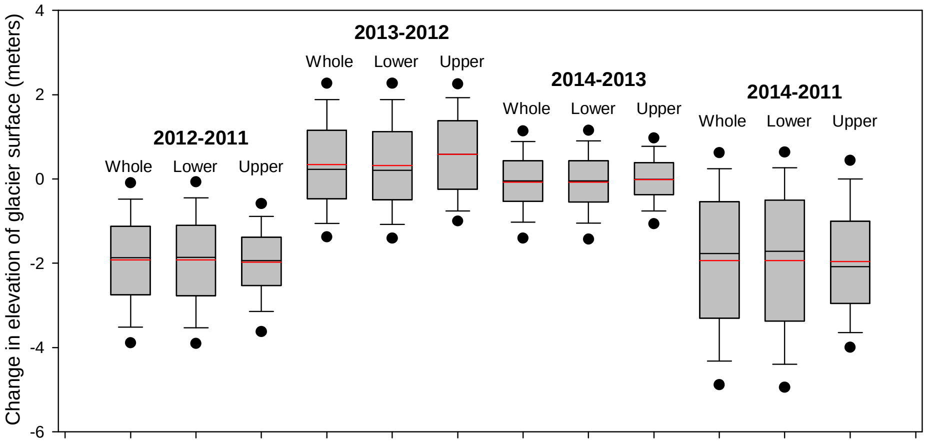

Figure 7.6

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