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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.

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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) luca.carturan@unipd.it 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 tat 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

-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

-P. 5022, L 11: please replace 'doubling' with the exact percent increase . Answer: Done is 1.85 times faster rate of ice volume loss.

-P. 5022, L 12: ...has decreased 'by' (also in the following).ç Answer: Done, thanks.

-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$\pm$0.4 m, -0.64$\pm$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."

-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)".

-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."

-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 (-0.13 m w.e. yr-1) was about twice that for the period of 1933 to 1959 (-0.7m w.e. yr-1).

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

-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."

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

-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.

-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 0.9°C since the end of the LIA (Dessens and Bücher, 1998; Feulliet and Mercier, 2012). More recently, Deaux et al., (2014) reported an increase of 0.2°C decade-1 for the period between 1951 and 2010." As, we explained to reviewer 1, this disagreement 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.

-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) .

-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 depends on local topographic characteristics. We think that that sentence reflects properly that idea.

-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.

-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).”

-P5025, L. 12: the relationship between glacier changes and climatic changes -P5025, L. 14: there are very few estimations of ice volume loss -P5025, L. 19: and these indicated that the total loss of ice -P5025, L. 23: topographic maps of 1981 and 1999.... and reported losses of -0.36 (please correct also in the following) -P5026, L. 2: (TLS) surveys -P5026, L. 3: these data in connection with data on precipitation -P5026, L. 6: cooler than in the last decades -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: All the suggested changes have been done

-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.

-P5026, L. 21: and many following (I’m not sure what you mean) studies

-P5026, L. 21-22: other characteristics. Which characteristics?

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....”

-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, disappeared after the 1970s” We think is clear we are doing reference to the lower glacier.

-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 40°) 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 (≈40°)."

-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 0.55°C to 0.65°C every 100 m, the annual 0°C isotherm should be roughly at 2950 to 3150 m a.s.l., 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 panel of Figure 1.

-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.

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

-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: The DEMs from the photogrammetric flights were directly provided by the National Cartographic Service (Instituto Cartográfico Nacional), and the accuracy we are reporting is the one the Service provided. There is not specification about how the accuracy was estimated (sinle-pixel or single- point estimate). Taking into consideration this question we have modified slightly the paragraph as follows: "The Root Mean Squared Error (RMSE) for vertical accuracy calculated by the IGN for their digital car-

tographic 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 (photogrammetric 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)".

-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.

-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.

-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 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."

-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 varying some studies (using Mann-Whitney test to compare 1983-199 and 2000-2010 periods). 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 neighbourhood 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 submission) are fully consistent with the new added stations. All of them shows a generalised 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). 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.

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

-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 unnecessarily the text, and it difficults the reading. -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 ephemeral snow cover, but difficult

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.

-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=2 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&STA 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 neighbouring glaciers that were analysed 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 signnificant difference between the 1983-1999 and 2000-2010 periods.

-P5032, L. 13: 1980 or 1981? Can you report the exact dates? Answer:1981, it has been corrected along the whole manuscript.

-P5032, L. 16: please check if ‘concave’ is what you intend. Maybe convex? Answer: It is convex. Thanks for detecting the error.

-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 behaviour 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.

-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 behaviour 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.

-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”.

-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

-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.

-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.

-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.

-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 has been maintained in time. However, as it is not possible to check right now which of the elements dominate, we think is better not introduce this discussion and just report this fact.

-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 condi-

tions 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 anlysis) gives 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 behaviour 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".

- 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.

-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.

-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 favourable conditions (high accumulation and/or little ablation in the frame of the 1983-2014 period)."

-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.

-P 5037, L. 25: it is unclear how the rock outcrops can decrease the albedo Answer: We agree the sentence was unclear. The outcrops 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" - P 5037, L. 26: why the western part is losing thickness faster? 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: -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

-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.

-Figure 3: 1980 or 1981? Answer 1981.

-Figure 4: the outlines from different years have the same colours and cannot be distinguished. Answer: We have modified the figure accordingly

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.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/9/C2549/2015/tcd-9-C2549-2015-supplement.pdf

Interactive comment on The Cryosphere Discuss., 9, 5021, 2015.

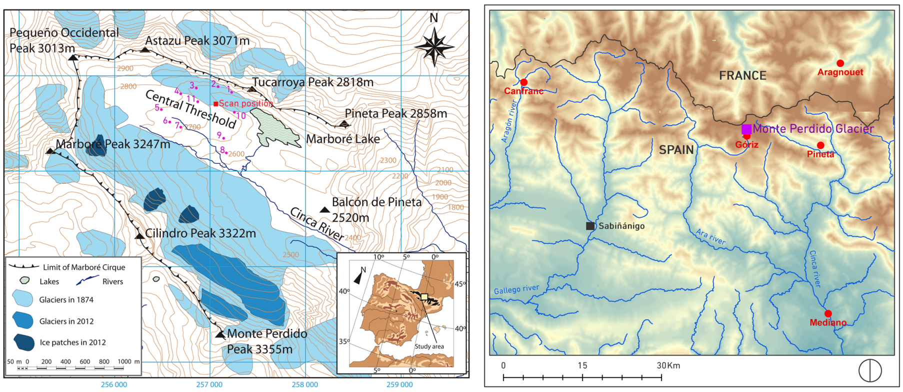
Pequeño Occidental Peak 3013m
Astazu Peak 3071m
Tucarroya Peak 2818m
Central Threshold
Scan position
Pineta Peak 2858m
Marboré Lake
Marboré Peak 3247m
Balcón de Pineta 2520m
Cinca River
Cilindro Peak 3322m
Monte Perdido Peak 3355m
Limit of Marboré Cirque
Lakes
Rivers
Glaciers in 1874
Glaciers in 2012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

Fig. 1.

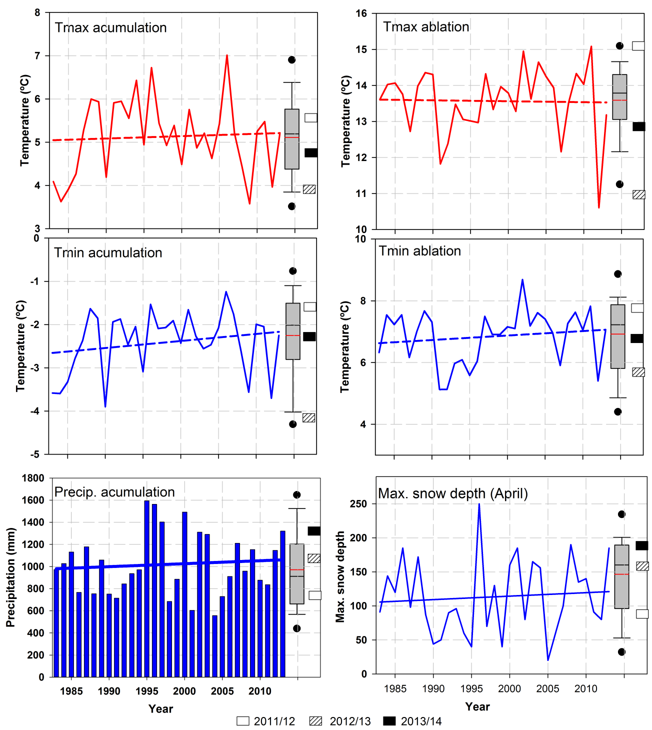
Tmax acumulation
Tmax ablation
Tmin acumulation
Tmin ablation
Precip. acumulation
Max. snow depth (April)
Temperature (ºC)
Precipitation (mm)
Max. snow depth
Year
2011/12
2012/13
2013/14

Fig. 2.

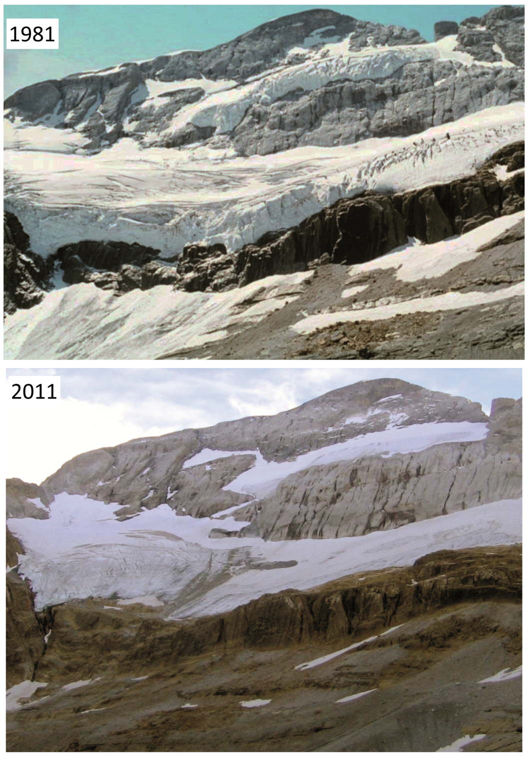
1981
2011

Fig. 3.

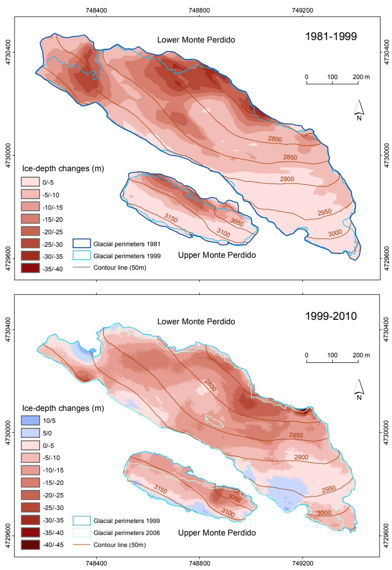
748400
748800
749200
Lower Monte Perdido
1981-1999
0 100 200 m
N
2800
2850
2900
2950
3000
3050
3100
3150
Ice-depth changes (m)
0/-5
-5/-10
-10/-15
-15/-20
-20/-25
-25/-30
-30/-35
-35/-40
Glacial perimeters 1981
Glacial perimeters 1999
Contour line (50m)
Upper Monte Perdido
4730400
4730000
4729600
Lower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

Fig. 4.

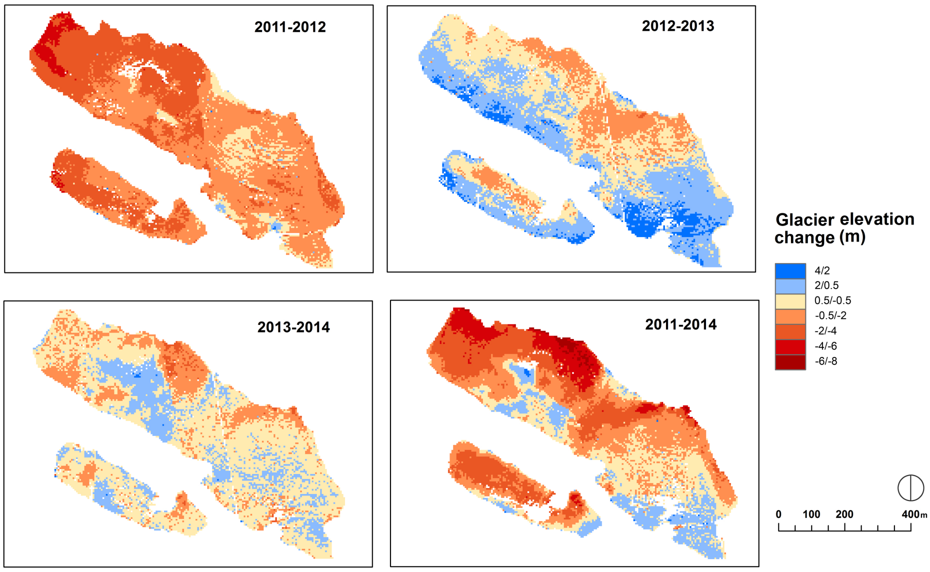

Fig. 5.

	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	

Table 1. Tau-b values of the trends for the period 1982-2013 for temperature and precipitation in the analysed 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.

Fig. 6.