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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. 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).

- 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.”

-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 0.9°C 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 0.9°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”. 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). -5024-17: And many are in disequilibrium and cannot survive (Pelto, 2010). Answer: Added, Thanks. -5025-20: is the mass change in m or m w.e.? 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”. -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.

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 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 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."

-5027-12: do not need "currently" twice in this line.

Response: Changed

-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

-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

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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.

-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.

-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,

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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 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."

-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

-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

-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

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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). "

-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 phase over the glacier that might be relevant for the mass and energy balance of the glacier specially 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.

-5037-8: Again what have been the AAR during recent years. The loss of ice thickness across the glacier 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 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."

-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.

-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.

- Figure 3: Top photograph overexposed a bit, bottom photograph underexposed, both could be adjusted to better view glacier surface. 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.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/9/C2535/2015/tcd-9-C2535-2015-supplement.pdf

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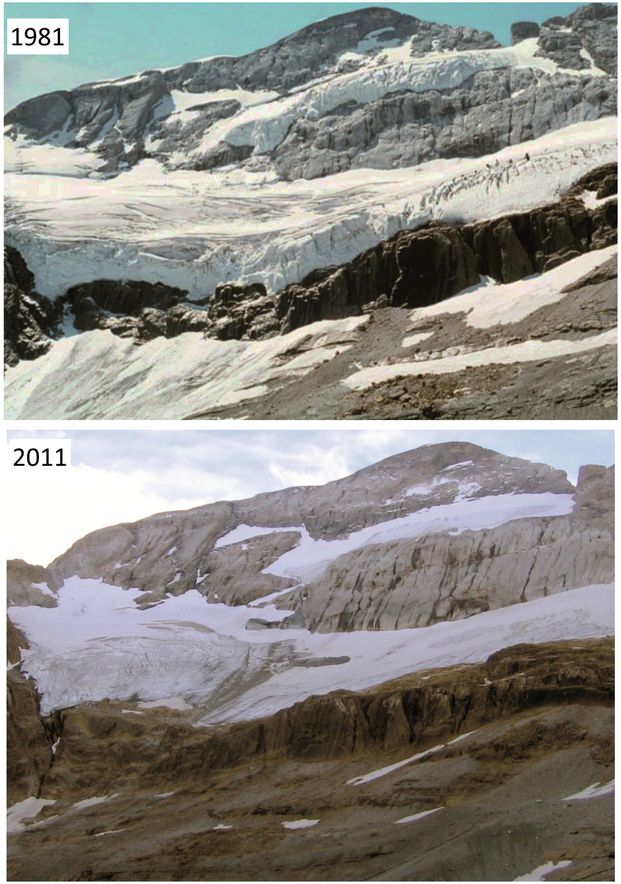

Fig. 1.

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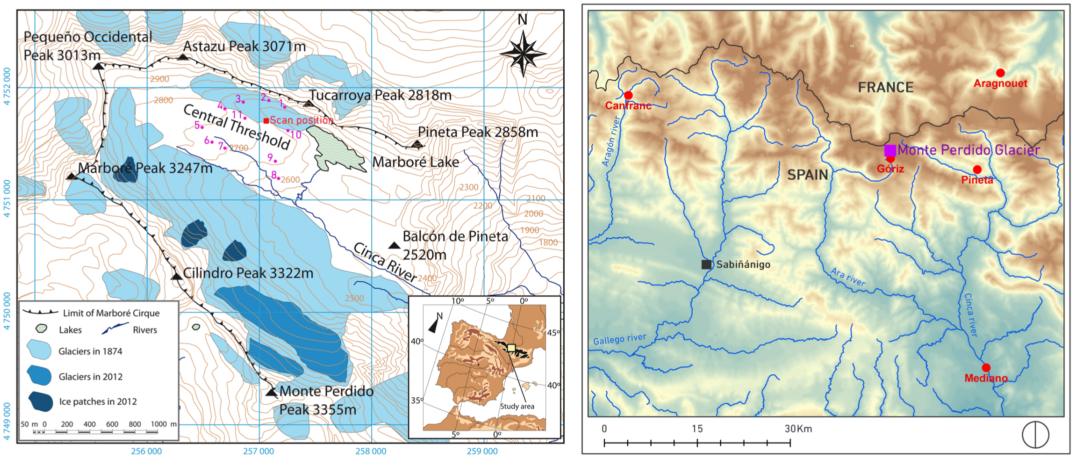

Fig. 2.

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	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. 3.

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