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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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.

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?

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

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

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

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)

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.

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

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

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.

P. 5023, L 26: these glaciers had a ‘total’ area

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.

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.

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.

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

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.

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

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

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

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

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

P5026, L. 27: through the study of sediments

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?)

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.

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)

P5028, L. 3-5: this sentence is poorly written and lacks the reference period. The methods used for estimations are not mentioned

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

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.

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?

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).

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.

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?

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

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.

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

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?

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 neighbouring glaciers that were analysed in previous studies (e.g. Marti et al., 2015, and references cited therein).

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

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

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.

P5032, L. 25: please clarify

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.

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.

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).

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

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?

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 themeaning. 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.

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

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?

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

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

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.

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

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

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

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.

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.

Figure 3: 1980 or 1981?

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

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.