(1) comments from Referees, (2) author's response, ***(3) author's changes in manuscript.***
Regarding author's changes, a marked-up manuscript version has been included at the end of this point-by-point response.

Reviewer #1 : General comments

We would like to thank Reviewer#1 for his/her encouraging comments and suggestions. We agreed with most of them as detailed below in the point-by-point response.

Despite some comments (most of them minor) on the content and the analyses, my major concern is on the presentation of the manuscript as it results quite difficult to be followed. I recommend several changes in the structure of the manuscript and I also encourage to check carefully the English. I am not English speaker but I have noticed a numerous mistakes and in general it results hard to be read.

The manuscript was edited by the American Journal Experts (AJE) for proper English language before submission (the certificate can be checked online at https://secure.aje.com/certificate/verify using the following code : 7D86-4248-2DE6-554A-A32F). However, we will strive to improve the readability in a new version of the manuscript. If the Editor requires further editing we can ask for another review.

The most important changes in the structure of the manuscript are: - I would drastically reduce the length of the methods section and I would add specific information on the different techniques (glacier mass balance, geodetic techniques, GPR, radar, etc) as supplementary material. Otherwise, it results unbalance the length of the methods section and the one devoted for presenting results.

To reduce the length of the methods section, we have moved systematically the details on the errors estimation for each metric to the supplementary materials. We now only expose in the text the results of the errors estimations (also summarized in Tab.2 and 3). We believe that this considerably simplify the methods section. Relevant passages are p.2441 l.4 to l.19., p.2444 l.5 to l.18., and p.2446 l.16 to p.2447 l.24.

- I would move the presentation and discussion of figures 11 and 12 to results sections. Specifically, figure 11 should be moved to section 5.4 (linkage between glaciers evolution and climate) and Figure 12 should be presented in section 4.5.

Thank you for this comment. We have moved Fig. 11 and Fig. 12 to the Results section as suggested.

I would rewrite the conclusions section as it contain information that does not summarize the main findings, but are hypothesis that should be presented in discussion.

The conclusion has be rewritten to summarize the main results, namely i) Main phases of the Ossoue glacier evolution since LIA based on the combination of its reconstructed metrics ii)

Comparison with other glacier reconstructions in the Pyrenees and the Alps iii) Comparison with meteorological time series iv) estimated date of Ossoue glacier disappearance.

Regarding the methodology, I do not have major comments, except that prior to correlate mass balance and climatic series, both should be previously detrended. As authors correlate series that both exhibit significant trends, the correlation between them may be spuriously enhanced.

We thank the referee for this suggestion. We now indicate the correlations after detrending with a linear fit in the revised version (Tab. 5). The correlations remain similar or even higher than previously reported, except for the correlation between the CRU mean annual temperature and the annual glaciological mass balance (-0.66 instead of -0.74).

Minor comments

I think that references of Chueca-Cía et al., 2007; Trueba et al., 2007 and López- Moreno et al., 2006b should be used in more detail to support different parts of the introduction section.

We agree that these papers are important to present the context of our study. However we are a bit puzzled because we have already cited these references several times. In particular they are the key studies in the Section 2 devoted to "Glaciers study in the Pyrenees"

- Chueca et al., 2007 was cited:
    - in introduction (p2434 line 23: "*Pyrenean glaciers are strongly out of balance with regional climate and are retreating quickly (Chueca et al., 2007)*")
    - in Section 2 (p2435 line 19: "*In the middle of the 19th century, after advance and recession phases, the Pyrenean glacier fronts reached positions close to their maximum LIA extent. At that time, the area of Pyrenean glaciers is estimated to be slightly over 20 km2 (Chueca et al., 2007)*", p2437 line 12: "*the reconstruction of the fluctuations of the [...] Maladeta and [...] Glaciers throughout the 20th century (Gellatly et al., 1994;Chueca et al., 2003; Cía et al., 2005; Chueca et al., 2007*)", p2438 l2: "*In the Pyrenees, these local influences are expected to have introduced spatial disparities in ice shrinkage, promoting in particular steep north and northeast glacier cirques, located below the highest summits (Chueca et al., 2007, 2008)*".
- Trueba et al., 2007 was cited:
    - in section 2 (p2435 l16: *"LIA climate cooling in the Pyrenees led to the formation and advance of glaciers in fifteen massifs where there are up to one hundred cirques (Trueba et al., 2008)"*.
    - in section 4 (p.2439 l23: *"the glacier front was actually in contact with its moraine at the middle of the 19th century, i.e., at the estimated end of the LIA in the Pyrenees (Trueba et al., 2008)"*.
- López-Moreno et al., 2006b was cited:

    -"Future work is necessary to better understand the effect of local topography on the spatial variability of glacier mass balance. This influence is expected to augment in the future as the glacier retreats (López-Moreno et al., 2006a, b)."

page 2434- Why does temperature range decreases over time? Which variable (Tmax or Tmin) is exhibiting a sharper trend to cause such effect on diurnal range?

According to Bücher and Dessens, 1991, the temperature range decrease over the 1882-1970 period is due to the sum of a very significant increase in the daily minimum temperature (+2.11 °C) and a decrease in the maximum temperature (-0.45 °C). Over 1882-1984, Dessens and Bücher, 1994, confirmed these trends by observing that the mean night-time temperature has increased by 2.39 °C/100 yr, while the mean daytime temperature has decreased by 0.50 °C/100 yr. As a consequence, the mean annual diurnal temperature range has dropped by 36%/100 yr.

We have modified the following sentence:
pp.2434 l7: "*A mean annual temperature increase of 0.83 °C has been observed over 1882–1970 with a significant decrease in the mean annual diurnal temperature range (2.89 °C per century)**, mainly due to a significant increase in the daily minimum temperature.**"

Study site: Authors should provide information about mean temperatures over the glacier and the estimation of the elevation of the ELA.

Unfortunately there is no long term air temperature measurement on the glacier so we cannot indicate the mean annual temperature. However, we now indicate the mean annual temperature from the closest meteorological station located in Gavarnie village (operational until 2012, elevation 1380 m asl, 11 km in the north east from Ossoue glacier, elevation difference from the glacier plateau is about 1700 m) in Section 3 (Study site):

p.2438 l.20. "The closest meteorological station (Gavarnie, 11 km, 1380 m a.s.l.) recorded a mean annual temperature of 7.68 °C and a mean precipitation of 1450 mm over 1992–2012."

Regarding the equilibrium line altitude (ELA), we did not refer to this concept for Ossoue glacier since there are only three occurrences of positive mass balance in the stake measurements dataset over the whole period of record (88 measurements). (see p.2447 l.6). However, to respond to this comment we computed the altitude of a zero mass balance using a least-squares linear fit of the stake mass balances as a function of elevation for each year (2002-2013). We found four years for which the regression coefficient R^2 is greater than 0.6. The median value of the ELA for these years is 3190 m asl (glacier maximal elevation is 3210 m asl). We now include this result in the supplementary.

More references should support the use of Pleiades for estimating changes in glaciers altimetry.

We agree that the use of Pléiades imagery is new in glaciology. We did not emphasize this point because there is a published paper on this specific aspect (Marti et al., 2014, cited p2442, l9). To our knowledge, the first publication which mentioned a DEM generated from

Pléiades stereo images in a glaciological context is Wagnon et al., 2013. In 2014, Berthier et al. published an evaluation of the potential of Pléiades stereo images over five evaluation sites, where simultaneous field measurements were collected. The study demonstrated the value of Pléiades DEMs for measuring seasonal, annual and multiannual elevation changes with an accuracy of 1 m, or even better. We now refer to this two publications in this added sentence:
p.2247 l8. Pléiades stereo images have been successfully used to measure geodetic mass balances of mountain glaciers with an accuracy of about 1 m (Wagnon et al, 2013, Berthier et al., 2014).

Section 4.6. Which is the resolution of CRUTEM 4 ?

We have included this information in this sentence:
"We extended the Pic du Midi temperature time series with the CRUTEM 4 **(5°×5° gridded version)** dataset over the period 1858–1890 (Jones et al., 2012)."

Section 5.1 presents mixed the information on changes in the length of the glacier and on the area. I would clearly separate.

We have created a new subsection in order to separate this two metrics assessments (see also the proposed restructuration here below) :
5.1.1 Length variations
5.1.2 Area variations

I would remove the supplied information about the depth of the moulins as it result very uncertain and it is not easy to interpret the progressive increase of their depth.

We have simplified this information by replacing this paragraph:
p.2453 l16: "As a verification of these data, we provide here the depth of the main moulins that have been measured regularly since 2004 by glacial speleologists: 30 m in 2004, 38 m in 2005, 36.5 m in 2006 and 41.5 m in 2009. However, these values should be considered minimum estimates of the glacier thickness because they do not necessarily reach the bedrock."
by:
"Moulins were explored over the 2004-2009 summer in the plateau of Ossoue glacier. The depth of the explored moulins ranged from 30 m to 41.5 m. Given that the bedrock was never reached according to the speleo-glaciologistst, the ice thickness obtained by GPR is consistent with these depth measurements."

I would recommend to remove section 5.3 it can be used to summarize results in discussion and/or conclusions sections.

Thank you for this suggestion. We agree that the text in Sect. 5.3 could be moved to the Discussion. Also in line with the comments by the Reviewer #2, we have restructured the results section in a revised version as follows:

5 Results
5.1 Ossoue glacier metrics variations
5.1.1 Length variations
5.1.2 Area variations
5.1.3 Mass variations
5.1.4 Mains phases of variations
5.2 Comparison with Pyrenean and Alps glaciers variations
5.3 Comparison with meteorological time series
5.4 Ice thickness maps

We think that this will clarify the presentation of the results.

Reviewer #2 : General comments

This paper presents a comprehensive assessment of long-term changes in a Pyrenean glacier. The authors have compiled an extensive basis consisting of various field data and geodetic surveys that allow reconstructing the evolution of Ossue Glacier since the end of the Little Ice Age. As glaciers in the Pyrenees are not well studied (e.g. in comparison to glaciers in the Alps) this article is a valuable addition to the literature. Furthermore, the processes determining the mass balance and the response of very small glaciers to climate change is not yet well known and new process understanding can be transferred to glaciers in other mountain ranges.

However, a considerable amount of work is required before this paper can be accepted. Most of my substantive comments refer to the presentation of the material. The paper is significantly too long at present with too many tables (see comments below). Furthermore, the description of some approaches needs to be clarified.

We thank the Reviewer for these encouraging comments and for the time he/she spent on our manuscript. As emphasized by the Reviewer we compiled many datasets, each with a different level of uncertainty and it is not easy to present them with all the necessary details in a concise manuscript. Based on the reviewer's suggestions we tried to improve the presentation of the datasets, methods and results in the revised manuscript as explained below.

Substantive Comments:

(1) Positioning of study: The actual aim of the study should be better specified. What do the authors want to find out with their data compilation ? Was is the main research question ?

The main goal of the study is to reconstruct the variations of a Pyrenean glacier since the end of the Little Ice Age. As mentioned by the Reviewer, the glaciers in the Pyrenees are not well studied. The large dataset collected on Ossoue glacier may contribute to understanding the evolution of the Pyrenean glaciers. To our knowledge there is no published mass balance reconstruction in the Pyrenees extending back to the early 20th century. The available reconstructions prior to the 80s are based on glacier length and/or area. Once this main objective is achieved, we also aimed at comparing the Ossoue glacier evolution with reconstructions in the Alps and other meteorological records to see if the glacier reflects the regional climate fluctuations. A final objective was to give a rough estimation of the glacier disappearance date based on the GPR-derived ice thickness map.

We have reworked the introduction to better emphasize these objectives. As proposed below, we also have re-organized the Results section to respond to each of these objectives:

5 Results
5.1 Ossoue glacier metrics variations
 5.1.1 Length variations
 5.1.2 Area variations
 5.1.3 Mass variations
 5.1.4 Mains phases of variations
5.2 Comparison with Pyrenean and Alps glaciers variations
5.3 Comparison with meteorological time series
5.4 Ice thickness maps

The argument of utilizing glaciers as a climate archive is somewhat delicate in my opinion as long-term meteorological measurements in the Pyrenees (also at high elevation, Pic du Midi) exist, and are used to interpret glacier data.

The reviewer is right that the temperature record at the Pic du Midi and the precipitation record at Tarbes extend back to 1882 and thus cover a large part of our reconstruction (1850-2013). However, the Tarbes station is located at 360 m a.s.l. and thus may not be representative of the precipitation regime in the high-elevation areas of the Pyrenees. The high Pyrenees are exposed to much higher precipitation rates and are the main contributor to the river discharge (López-Moreno et al., 2004). Before the 1990s, there is very little measurements of precipitation, especially above 1500 m (Soubeyroux et al., 2011). Precipitation data exists at the Pic du Midi from 1882 but the data are not reliable for climatic analysis (Dessens and Bucher, 1997).

Glacier are recognized as independent climate proxies (Oerlemans, 2005, Haeberli et al., 2007). The glacier evolution reflects a combination of various meteorological factors which are not limited to the air temperature and precipitation. Chueca et al. 2005 and 2007 highlighted the value of the Pyrenean glaciers as proxies to monitor the recent climate change, as they respond with a short lag time to climatic fluctuations, due to their small sizes and latitudinal location.

The Ossoue glacier reconstruction provides another high-elevation climate proxy in the Pyrenees. Detecting common trends between independent proxies may make reconstructions more credible, whereas identifying differences may help for critical interpretation on meteorological drivers or even data quality.

However, I am sure that various other interesting questions could be defined and be addressed with the Ossue data set.

We agree that the use of Ossoue data as a climatic archive remains limited, especially due the low temporal resolution of the dataset (e.g. mass balance). We have reconsidered the introduction section to diminish the emphasis put on the climatic interest.
We removed:
p. 2434 l28: "The objective of this paper is to reconstruct the evolution of Ossoue Glacier based on these data to provide further information on the Pyrenean climate since the end of the Little Ice Age (LIA)."
and replaced it by:
"The objective of this paper is to reconstruct the evolution of Ossoue Glacier based on these data to provide further information:
– on the evolution of a Pyrenean glacier since the end of the LIA.
– on the comparison between Pyrenean and Alps glaciers evolution
– on the potential climate drivers of Ossoue glacier.
– on the likely evolution of the Ossoue Glacier in the near future."

We will aso remove the first paragraph of the introduction:
p. 2433 l.20 to l.23: "Southern Europe is projected to be a hotspot of climate change over the 21st century, with increasing temperatures and decreasing precipitation (IPCC, 2013). Among other consequences, water resources, including snowmelt from mountain areas, could be affected while water demand should will likely increase (EEA, 2012; IPCC, 2013)".

(2) Length of the paper: More than half of the tables could be removed without a loss in clarity. Furthermore, also the text could be shortened and be made more concise which facilitates the reading. I provide specific suggestions below.

We moved Tables 1, 3, 4, 5, 7, 8 and 9 and Figures 2 to the supplementary materials. We removed Table 6 and Figure 10. We also shortened the methods section by moving systematically the details on the errors estimation for each metric to the supplementary materials (in agreement with the suggestion of Reviewer #1).

(3) Glacier indicators: One subtopic of the paper are the so-called "glacier indicators". This part is weak and could be completely removed. First, it does not become clear what "glacier indicators" are (the term also seems to be inappropriate).

Thank you for this comment. We realized that the term "glacier indicators" was probably not the most appropriate to refer to the length, area or the mass balance. We now refer to these variables as "glacier metrics" in the revised version of the manuscript.

Second, the definition is highly qualitative.

To determine the sign of variations for each glacier metrics, we remove the thresholds based on an absolute value, which defined the "marked" classes, whether positive or negative (see table 6, e.g. -10 m in a "marked" length variation, or +1 m w.e. in a "marked positive" mass balance variation). These thresholds were indeed subjective and thus questionable. However, we keep the definition of a "no variation" class when the metric variation is within the estimated random error range. Therefore, we now consider three classes: negative, positive and no variations. We think that this approach is more rigorous and also will facilitate the interpretation of the results, in particular the comparison with the glaciers reconstruction in the Alps.

Third, it remains unclear what can actually be learned from this analysis. A more quantitative approach would be more beneficial. Lastly, the presentation of the glacier indicators (Results, Discussion) is very short and leaves the reader with more questions than answers.

We have worked on this issue and we have included two new figures to enhance the analysis of our multi-source reconstruction (Fig.5 and 10 in the new version of the manuscript). This figure compares the evolution of various glacier variations in the Pyrenees and the Alps from the literature.

(4) Calculation of geodetic mass balances: For the calculation of elevation changes, glacier is subdivided into two regions: (1) the area ice-covered in both DEMs and (2) the margin (only covered by one DEM). This approach is uncommon to studies of glacier volume change and geodetic mass balances and it makes interpretation of the results more difficult. For the calculation of the geodetic mass balance see e.g. Zemp et al. (2013). In response to this comment Table 10 and the text should be revised.

We agree with the Reviewer. Actually, the right method to calculate a geodetic mass balance depends on the purpose of the investigation (Cogley et al., 2011). As often in glacier study, our mass balance calculation is based on a mix of reference-surface and conventionnal mass balance approaches. The reference-surface balance is the glacier-wide mass balance that would have been observed if the glacier surface topography had not changed since a reference date. The time-invariant surface, called the “reference surface”, is defined at some convenient time within a mass-balance programme, often at the start (Elsberg et al. 2001). For glacier-climate investigations, the reference-surface balance is recognized as a more relevant quantity, while the conventional mass balance approach, which require repeated mapping of glacier hypsometry at intervals appropriate to the rate of change of the surface geometry, is more relevant in the framework of hydrological applications (Cogley et al., 2011).
We will no longer split the glacier into two regions to calculate the geodetic mass balance for the revised version. As suggested by the reviewer, we now consider the equation of Zemp et al. (2013) to calculate the geodetic mass balance rate. Therefore, the equation (2) (numbered 3 in last version) have be modified as follows:

$$B_{geod.a} = \frac{\Delta V}{\overline{S}} \times \rho \times \frac{1}{N} \quad (2)$$

where $\overline{S}$ is the average glacier area of the two survey dates assuming a linear change through time, and N is the number of years in the period of record (PoR).

The table 2 (numbered 10 in last version) have been modified accordingly.

(5) Future of Ossue Glacier: The simple assessment of future glacier evolution should be revised / rethought. It is, for example, unclear why the authors define thickness classes that are “multiples of 1.5”. The simplest approach would be to subtract the average distribution of surface mass balance 2011-2013 (in ice equivalent) from the measured thickness distribution in each year. This would be transparent, easy to describe and also account for the more negative mass balances in glacier center (page 2459, lines 10-20)

We agree that our thickness classes were a bit confusing. Therefore, we followed the Reviewer’s suggestion to generate ice thickness projection (Fig. 13):

i) we interpolated on a 4m resolution grid the mean point mass balances measured at the stake locations over 2001-2013 on the current glacier outline (2011). The interpolation technique is the same that we used to generate the DEMs of the study, and is based on a discretized thin plate spline technique (Anudem 5.3, Wahba, 1990; Hutchinson, 2011). This interpolation is consistent with the glaciological method. The mean rate after interpolation is -1.5 m w.e.a^{-1}, while the mean glaciological mass balance rate is -1.45 m w.e.a^{-1}.

ii) we made the assumption that this spatialized mass balance rate will remain constant in the next decades.

iii) based on this mass loss rate we calculated the ice depth on the glacier plateau at decadal intervals from 2013.

As it is based on the superficial mass balance only, this very simple projection does not take into account the effect of the basal and internal mass balances nor the dynamics of the glacier.

(6) Comparison to glaciers in the Alps: One of the most promising potential aspects of this study would be a more detailed comparison of the long-term changes in Ossue Glacier in comparison to glaciers in the Alps. Such a comparison (in terms of annual mass balance / long-term volume change) would not be difficult to achieve but very interesting regarding differences in the most important driving factors between the Pyrenees and the Alps.

Thank you for this suggestion, we now include a comparison with glaciers in the Alps (see above, Fig. 5 and 10, Tab.4).

(7) English language: Throughout the paper the language could be improved (native English speaker).

The manuscript was edited by American Journal Expert (the certificate can be checked online at https://secure.aje.com/certificate/verify using the following code : 7D86-4248-2DE6-554A-A32F). However, we will do our best to improve the readability in a new version of the manuscript. If the Editor requires it, we can ask another editing.

Details Comments:

- Page 2433, line 4: What does this elevation mean? It does not seem to be related to the study site. Should be removed.

This elevation refers to the highest peak of the Pyrenees, the Aneto Peak at 3404 m a.s.l. As it appears unclear in the manuscript, it was removed in the new version.

- Page 2436: Although this historical overview is interesting, it would benefit from some shortening

Except from a slight shortening, we have kept this section as it is because we think it provides all the necessary elements to understand the origin of the historical datasets used in the following sections.

- Page 2436, line 8: Time periods for area changes in European Alps should be given; should be consistent with that of the Pyrenees.

We assume that the reviewer actually refers to page 243**7**, line 8:
"In comparison, the area of glaciers in the European Alps decreased by 35% (Hoelzle et al., 2007)".
We replaced (Hoelzle et al., 2007) by (Zemp et al., 2006) and indicated the time periods:
p.2437 line 8: "Alpine glaciers lost 35% of their total area from 1850 until the 1970s, and almost 50% by 2000 (Zemp et al. ,2006) ".
This area changes for all Alps glaciers are based on the date of the available complete inventories.

- Equation 3: I suggest following Zemp et al (2013) here (as elsewhere in the paper). Normally geodetic mass balance is expressed in m w.e. a-1. The time components is missing in the present formulation

According to Cogley et al., 2011: "Whether to present the balance as a rate or not will depend on the context of the investigation". We agree that the mass balance expressed as a rate facilitates the comparison between the different periods of records and with the glaciers from other massif or mountain range. We now systematically refer to the geodetic mass balance first as a rate, and indicate the cumulative mass balance into parenthesis. As stated above, equation (2) has been modified accordingly:

$$B_{geod.a} = \frac{\Delta V}{\overline{S}} \times \rho \times \frac{1}{N} \quad (2)$$

where $\overline{S}$ is the average glacier area of the two survey dates assuming a linear change through time, and N is the number of years in the period of record (PoR).

- Page 2443, line 20: I do not completely agree with that. This assumption would only hold if the entire firn coverage has been completely (!) removed already by 1983. This was most likely not the case. In contrary, I expect firn thickness to be at a maximum (after some glacier mass gains) and has almost disappeared until now resulting in a volume loss with a density <900 kg m-3.

We agree with the reviewer that a snow-firn pack was most probably present in 1983, after the stable-positive mass balance period of 1948-1983. To take into account the difference of density between firn and ice, we now use a mean density of 850 kg m^{-3} with an uncertainty range of 50 kg m^{-3} (Huss, 2013) to calculate the geodetic mass balance over 1983-2001. Since 2001, the glaciological measurements indicate that the glacier summer surface is almost exclusively bare ice. From 2001, we considered a mean density of 900kg m^{-3}. The manuscript and the table 2 have be modified accordingly.

- Equation 4/5: If the systematic error (bias) is known / can be quantified, the DEM should be corrected accordingly. In that case, the error would not appear in the uncertainty assessment. Obviously, the authors were able to quantify their systematic errors. They could thus simplify this section.

We corrected the 1948 and 1983 DEMs after a vertical coregistration on the 2013 DGPS elevations. However, we could not identify a systematic error (vertical bias) on the stable bedrock between the 1924 DEM and the 2013 DGPS elevations as explained p 2443 l.8-10: "For the 1924 DEM, the elevation differences did not follow a normal distribution and it was not possible to determine the elevation bias (noted as bias $\epsilon_{bias.1924}$)".
For that reason, we introduced this notation in the text ($\epsilon_{bias.1924}$), and we mentioned this error term in the meta-data of Ossoue Glacier volumetric measurements errors (table 2 in the supplementary).
We have also considered an additional systematic error term ϵ_t due to the time lag between the raw data acquisition date and the first day of the next hydrological year, fixed to 1 October (p. 2443 l.25 in the old version). Pending a better assessment of that error term (e.g. degree-day model-based correction), we preferred to keep this term as an error rather than correcting the mass balance value, using a floating-date system (Cogley et al., 2011).

Please note that errors assessment are now part of the supplementary.

- Equation 7/8: The subscript "bias" for a random error seems to be inappropriate. Bias normally means a systematic error.

Thank you for that remark. This term has corrected accordingly in the text and in the equation (6) of the supplementary.
"The SD of the elevation difference values on stable areas was considered as to be a representative value of the vertical random error and was noted as $\boldsymbol{\sigma}_{\mathbf{coreg}}$ ".

- Page 2447, line 4: I have the impression that this approach is not feasible: When measuring surface elevation change using a dGPS both the contribution from melting and ice dynamics (flow) are measured. These results can, thus, not be directly compared to local surface mass balance and would result in a too high error estimate. Of course, the impact of glacier flow will not be very large on a small glacier but the aim is to quantify uncertainties in the range of decimetres.

We agree with the reviewer that we neglected several terms in calculating this estimation of the annualized systematic error associated to the glaciological mass balance (noted $\varepsilon_{glac.total.a}$ in the study). The terms neglected are: the internal and basal mass mass balances, and the ice mass variations due to the ice flow.

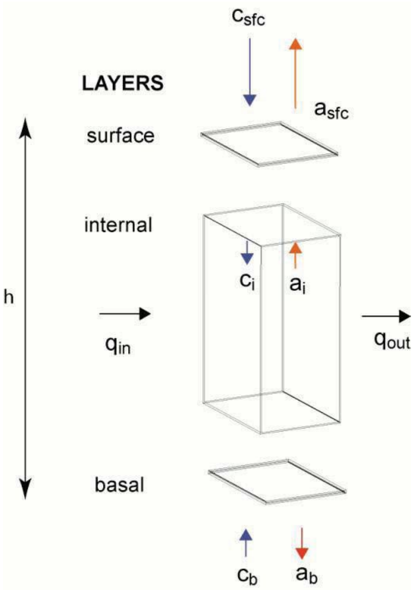

Fig. 4. The mass balance of a column of glacier ice, firn and snow (from Cogley et al. 2011).

We did our glaciological vs. geodetic method comparison in the upper area of the glacier (glaciological sectors 1 to 4). Therefore the term q_{in} is zero. We propose here an estimation of the term due to the ice flow (q_{out}) mentioned by the reviewer:

i) we make the assumption that the ice flow is 1 m a^{-1} and constant along a vertical profile. This hypothesis is based on the observed displacements of the stakes in the field (*plateau*), which were in general less that 1 m a^{-1}. We also consider that density ρ remains constant into the glacier, and is that of the ice.

ii) we calculate the volume of ice in this area (glaciological sectors 1 to 4) based on GPR-derived ice thickness.

iii) the glacier advanced by 1m over this period, hence we calculate the volume of ice V_{out} beneath a 1-m wide band at the lower periphery of the study area.

iv) we convert this volume in equivalent surface height by dividing by the area considered for the comparison.

v) we convert to m w.e. by multiplying by the ice density (assumed uniform to 0.9)

We find an equivalent surface mass loss due to ice flow of 0.03 m w.e. per year. The systematic error calculated by comparison between stake measurements and DGPS is 0.14 m w.e. As the reviewer warned, this error is overestimated due to the ice flow. However, we still consider that it is a good estimation since the effect of the ice flow remains small.

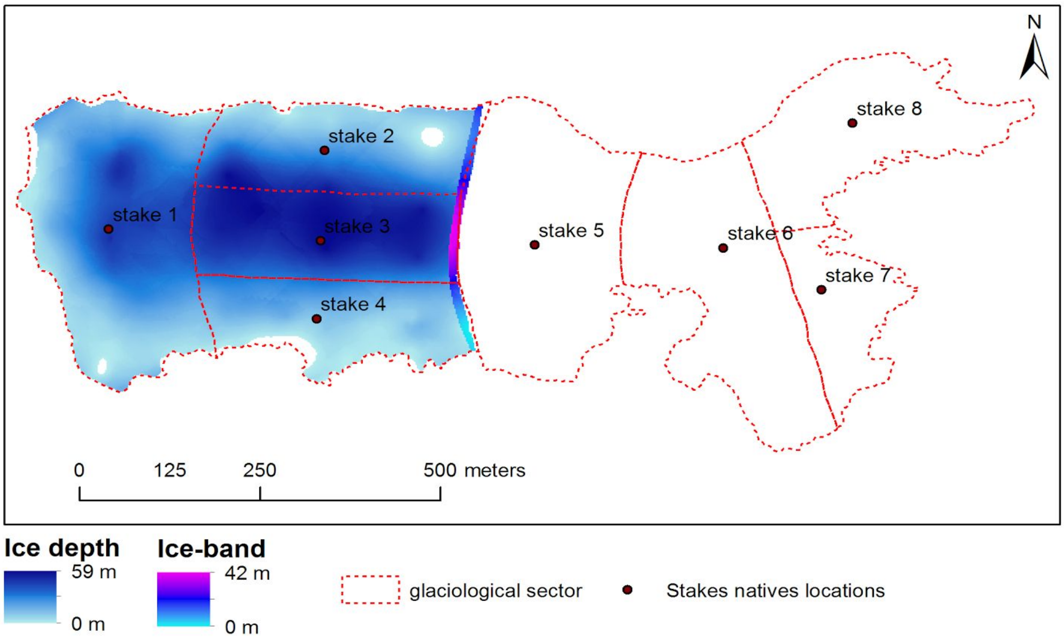

Fig. 5. Localisation of the sections of the glacier considered in the determination of the ice volume lost by the Ossoue plateau due to the ice flow.

Please note that errors assessment are now part of the supplementary.

- Page 2447, line 15: I have troubles to follow the authors' approaches here. Should be clarified.

We propose to clarify this in the text by adding the following sentence:

"To do so we used the DEMs made from the DGPS surveys performed in 2011 and 2012, as if each pixel was a (virtual) stake. For every polygon 1 to 6 (only these polygons were surveyed), we calculated the variance of the differences between both DEMs."

Please note that errors assessment are now part of the supplementary.

- Page 2447, line 21: The unit should be m w.e. a-1

Thanks for that remarks, we have correct the units of the annual total random error accordingly, in the text and in the tables. We did this correction also for the annual total systematic error (p. 2447 l.4).

- Page 2449, line 10-23: These data should be presented in a data section

These lines are actually in the Data section (4. Data sets and methods). We think that this confusion stems from the fact that the data section was too long, but the new manuscript is now shorter.

- Page 2450, line 17: What is the rationale of using Spearman's rho instead of the more often used correlation coefficient r2? The latter would, in my opinion, by easier to interpret and understand.

The temporal trends in temperature and precipitation series, as well as the correlations with the glaciological mass balances terms were analyzed by a rank correlation method, using Spearman's ρ. This statistic is prefered because it is neither sensitive to the presence of outliers nor the existence of non-linear correlations (Borradaile, 2013, and in a glaciological context: Chueca et al. 2007). We consider the correlation coefficient ρ rather than the coefficient of determination ρ^2 to keep the direction of association between the two variables, given by the sign of ρ (e.g. Thibert et al. 2013).

- Page 2452, line 9: Avoid separating "current" glacier area and margin and state geodetic balances. Consequently, most of this chapter should reformulated.

We have rewritten this subsection according to the reformulation of equation (2) and to the new approach defined to calculate the geodetic mass balance (as mentioned above).

- Page 2452, line 10: Here and throughout the paper. The stated periods are only defined by the dates of the available maps and are unrelated to actual climate variations! Interpretations should account for this.

We agree that the definition of the periods are based on the dates of the available datasets and do not necessarily coincide with climatic variations. However, the combination of metrics allowed us to partly overcome this issue. We have mentioned this limitation in the resluts section (5.1.4):
"Based on the dates of the survey reported in the available documents, we identified several phases in the fluctuations of Ossoue Glacier."

- Page 2454, line 8: What is "monthly" summer ablation? Has ablation been measured in monthly resolution?

Yes, in section 4.3, "Glaciological mass balances", we indicated that (p.2445 l.13): "Summer ablation measurements were repeated once a month until a date close to the beginning of the next hydrological year, according to the floating-date system (Cogley et al., 2011)".

- Page 2457, line 18: also here, the stated periods should discussed with care. 1999 did not mark the end of any period – recession continued until today.

We fully agree with the reviewer. We updated the recession period identified by Vincent et al. 2002 up to present in the new figure showing the Alps/Pyrenees comparison (Fig. 10).

- page 2459, lines 10-20: This a different topic (spatial distribution of surface mass balance) and should be separated from the discussion of expected future evolution.

We removed this paragraph in the new version.

Tables and Figures:

- Table 1: Could be removed. The important information (elevation range, length, location) are already given in the text. The rest is not necessary for understanding the paper. Alternatively the authors could envisage publication of this table as a supplementary material.

We have put this table into supplementary material.

- Table 2: This Table is important and should remain in the main paper. However, it would benefit of some shortening by using less text (e.g. abbreviations for methods, remove source characteristics – already available from text)

We agree to remove the source characteristics column to use less text. However, we did not use abbreviations to facilitate the reading of the table.

- Table 4: remove or put into supplementary material

We have put this table into supplementary material.

- Table 5: remove or put into supplementary material

We have put this table into supplementary material.

- Table 6: These thresholds are highly qualitative and only valid for this single glacier. I would completely remove this topic (glacier indicators) from the paper.

As discussed above, we agree that the thresholds were subjective. Therefore, we remove the thresholds that define the "marked" class, whether positive or negative. We have kept the definition of a "no variation class" within the estimated random errors range and thus we have considered only three class: negative, positive and no detected variations.

- Table 7: This information is directly shown in a figure (where it is easier to understand). Therefore, this Table is not necessary and should be moved into the supplementary material.

We agree, we have put this table into supplementary material so that anyone interested can more easily use the data.

- Tables 8 and 9: same comment as for Tab 7.

We have put this table into supplementary material.

- Table 10: This table contains important data on the direct observation of mass balance, as well as seasonal components. I suggest swapping rows and columns to make it easier to read. The cumulative MB can be omitted.

We suppose that the reviewer also refer to the table 11 in that comment (table 10 is about geodetic mass balance and do not content seasonal components nor direct observations). However, we have swapped rows and columns in table 2 (see above) as suggested by the reviewer to make it more readable.

- Table 11: also here: swap rows and columns. The symbols (B_w etc) should be explained in the caption.

Thanks for that suggestion, we have swapped rows and columns to make it more readable. As mentioned in the caption, End_w and End_s refer to the end of winter and the end of summer, respectively, in the floating date system (Cogley et al., 2011). According to the reviewer commentary, we have completed the description of the others variables in the caption:
B_w refers to the winter mass balance.
B_s refers to the summer mass balance.
$B_{glac.a}$ refers to the annual mass balance.
$B_{glac.c}$ refers to the cumulative mass balance.
We have omitted the cumulative mass balance as it is also presented in Fig. 8.

- Figures 8 and 9: Provide label for y-axis!!

The Y-axis labels have be added in the new version of the manuscript:
_Fig. 8: “Cumulative mass balances by stakes (in m w.e.)”.
_Fig 9: “Glacier length / Glacier area / Villa Russell cave height with respect to the glacier surface / Mass balance”.

- Figure 10: too small to read. Omit this topic completely (see comments above).

According to the commentary on table 6 and the reviewer recommendation, this figure have been removed, and replaced by the new Fig. 10 presented above (comparison of the Ossoue glacier reconstruction to three others Pyrenean glacier reconstructions and the three selected glaciers studies in the Alps).

- Figure 11: Provide label for y-axis, including units!! Furthermore, I would suggest to combine Figs 11 and 9 (at least for some variables) as the goal is to establish a link between variations in the glacier and climate (T, P, NAO, AMO).

We have indicated the timeline of Ossoue glacier variations (Roman numerals) in the figure 11. The Y-axis labels have be added in the new version of the manuscript:
_Mean annual temperature at Pic du Midi (deg C)
_Annual precipitation at Tarbes (mm)
_NAO Index (DJFM) (--)

_AMO Index (--)

Again we sincerely thank the Reviewer for this thorough evaluation of our manuscript.

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Evolution of Ossoue Glacier (French Pyrenees) since the end of the Little Ice Age

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Abstract

Long-term climate records are rare at high elevations in Southern Europe. HereLittle is known about the fluctuations of the Pyrenean glaciers. In this study, we reconstructed the evolution of Ossoue Glacier (42°46′ N, 0.45 km^2), which is located in the Pyrenees (3404 m a.s.l.), since central Pyrenees, from the Little Ice Age (LIA) . Glacier onwards. To do so, length, area, thickness, and mass changes indicators in the glacier were generated from historical datasets, topographic topographical surveys, glaciological measurements (2001–2013), a GPR survey (2006), and stereoscopic satellite images (2013). The glacier has receded considerably since the end of the LIA, losing 40 % of its length and 60 % of its area. Three periods of marked ice depletion can be were identified: 1850–1890, 1928–1950 and 1983–2013, as well as two periods of stabilizationor slightly growth: 1905–1928 and short-periods of stabilization: 1890–1894, 1905–1913, and a longer period of slight growth: 1950–1983; these agree with climatic datasets other Pyrenean glaciers reconstructions (Maladeta, Coronas, Taillon glaciers). Pyrenean and Alpine glaciers exhibit similar multidecadal variations during the 20th century, with a stable period detected at the end of the 1970s and periods of ice depletion during the 1940s and since the 1980s. Ossoue Glacier fluctuations generally concur with climatic data (air temperature, precipitation, North Atlantic Oscillation, Atlantic Multidecadal Oscillation). In the early 2000s, the area of the glacier dropped below 50 % of its area at the end of the LIA. Geodetic mass balance measurements over 1983–2013 indicated was $-$30.1 1.04$\pm$0.06 1.7 m w.e.($-$1a^{-1} (-31.3 $\pm$ 1.9 m w.e. yr^{-1}) whereas glaciological mass balance measurements show $-$17.36 $\pm$ 2.9was $-$1.45$\pm$ 0.85 m w.e. a^{-1} ($-$1.4517.3 $\pm$ 2.9 m w.e. yr^{-1}) over 2001–2013, resulting in a doubling of the ablation rate in the last decade. In 2013 the maximum ice thickness was 59 $\pm$ 10.3 m. Assuming that the current ablation rate stays remains constant, Ossoue Glacier will disappear midway through the 21st century.

1 Introduction

Southern Europe is projected to be a hotspot of climate change over the 21st century, with increasing temperatures and decreasing precipitation (IPCC, 2013). Among other consequences, water resources, including snowmelt from mountain areas, could be affected while water demand should will likely increase (EEA, 2012; IPCC, 2013).

The Pyrenees are a mountain range in southwestern Europe spanning ∼430 km from the Bay of Biscay (Atlantic Ocean) to the Mediterranean Sea. According to regional climate model projections, the thickness and duration of its snowpack could decline over the 21st century (López-Moreno et al., 2009). However, analysis of snow depth observations over 1985–1999 in the Spanish Pyrenees showed contrasting trends, with increasing snow depth above 2200 m elevation and decreasing snow depth below 2200 m (López-Moreno, 2005). Tree-ring time series from living trees and in situ relict samples, collected at elevations of 2200–2450 m a.s.l., have allowed the reconstruction of 1260–2005 summer temperatures in the Pyrenees. The data confirmed warming in the twentieth century warming (Büntgen et al., 2008). The (Büntgen et al., 2008). For recorded data, the longest meteorological time series in the French Pyrenees began in 1882 at an astronomical observatory located on the Pic du Midi (2862 m a.s.l.). A mean annual temperature increase of 0.83 °C has been observed over 1882–1970 with a significant decrease in the mean annual diurnal temperature range (2.89 °C per century), mainly due to a significant increase in the daily minimum temperature (Bücher and Dessens, 1991; Dessens and Bücher, 1995). Recent work on data homogenization within the framework of the Pyrenean Climate Change Observatory depicts a uniform warming at the massif scale for the massif over the last sixty years, and highlights a significant warming signal from the 1980s onwards (Soubeyroux et al., 2011; Camberlin and Yves, 2014)

Due to the paucity of meteorological measurements, Pyrenean climate proxy records are crucial to reconstruct past climate fluctuations at secular scales and high altitudes. Glaciers are considered robust climate proxies (WGMS, 2008; Zemp et al., 2009). The Pyrenees hosts the European southernmost glaciers in Europe, all below the 43° N latitude. Their small sizes ($< 1\,\mathrm{km}^2$), relatively low elevations, and southern locations make them particularly vulnerable to climate warming (Grunewald and Scheithauer, 2010). Pyrenean glaciers are strongly out of balance with regional climate and are retreating quickly (Chueca et al., 2007). quickly retreating (Chueca et al., 2007). While Pyrenean glaciers are in jeopardy, little is known about their evolution since the end of LIA. Their comparisons with other mountain range glaciers (e.g. Alps) are rare, and hampered by the fragmented dataset (Gellatly et al., 1994; Chueca et al., 2007). Due to the paucity of meteorological measurements, especially at high altitude, Pyrenean climate proxy records are useful to complete past climate fluctuations at secular scales. A part of this is that glaciers are considered robust climate proxies (WGMS, 2008; Zemp et al., 2009); their reconstruction may provide further independent evidences that the climate is changing. More generally, however, retreat of Pyrenean glaciers could affect local ecosystems by diminishing the beta diversity in Pyrenean streams (Finn et al., 2013). Furthermore, natural patrimony and the visual perception of the high mountain landscape could also be irrevocably affected (Deline and Ravanel, 2009; Moreau, 2010; René, 2013).

The Ossoue Glacier ($42^{\circ}46'$ N, $0.45\,\mathrm{km}^2$) is the second largest glacier in the Pyrenees. In comparison with that of other pyrenean Pyrenean glaciers, the evolution of Ossoue Glacier is well documented, with observations starting at the end of the 19th century. These include historical datasets, topographic maps, aerial images, and stakes measurements.

The objective of this paper is to reconstruct the evolution of Ossoue Glacier based on these the available data to provide further informationon the Pyrenean climate :

- on the evolution of a Pyrenean glacier since the end of the Little Ice Age (LIA). LIA.
- on the comparison between Pyrenean and Alpine glacial evolution
- on the potential climate drivers of Ossoue glacier.
- on the likely evolution of Ossoue Glacier in the near future.

The first section gives a brief review of glaciers studies studies on glaciers in the Pyrenees (Sect. 2). After From there, and after describing the site of Ossoue Glacier (Sect. 3), the data, and the methods used (Sect. 4), we propose a reconstruction of various indicators including that includes various glacial metrics (i.e., glacier length, area, and mass balanceof) for Ossoue Glacier (Sects. 4 and 5). We use ground penetrating radar (GPR) measurements collected in 2006 to estimate the ice depth in the upper part of the glacier. 5.1). The combination of these indicators allows usmetrics allows us, for the first time, to depict a consistent evolution of the glacier since the LIAfor the first time. Finally, we discuss the response of the glacier to past climatic changes (. We compare the timeline of Ossoue glacier fluctuations with that of Pyrenean and Alpine glacial reconstructions (Sect. 5.2) and with the meteorological timeseries (temperature, precipitation)and . We also mention a possible connection with the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO)(Sect. 6). 5.3). We use ground penetrating radar (GPR) measurements collected in 2006 to estimate the ice depth in the upper part of the glacier and to estimate the evolution of the glacier thickness in the coming decades (Sect. 5.4). The implications and the limitations of the results are discussed in section 6, and summarized in section 7.

2 Glaciers studies in the Pyrenees

The last favorable period to glacier development in the Pyrenees was the Little Ice Age (LIA), which occurred between the 14th and 19th centuries (Grove, 2004). LIA climate cooling in the Pyrenees led to the formation and advance advancement of glaciers in fifteen massifswhere , in which there are up to one hundred cirques (Trueba et al., 2008). In the middle of the 19th century, after the respective advance and recession phases, the Pyrenean glacier fronts reached positions close to their maximum LIA extent. At that time, the area of Pyrenean glaciers is estimated to be have been slightly over 20 km^2 (Chueca et al., 2007). Since then, their area covered 8 km^2 in 1984 (Serrat-Ventura, 1988), 6 km^2 in 2004 (Chueca et al., 2004) and approximately 3 km^2 in 2013 (René, 2014).

Due to their remote locations and small sizes, Pyrenean glaciers have not benefited from long-term glaciological studies (Grove, 2004). ~~Early~~ That said, early topographic measurements were made by "Pyreneists", alpinists who became enthusiasts in the exploration and observation of the Pyrenees (de Carbonnières, 1801; von Charpentier, 1823; Trutat Eugène, 1876; Schrader, 1895). ~~The~~ However, it was not until the *Commission Internationale des Glaciers* (CIG) was created in 1894 in Zürich~~and~~, which led thereafter to the present-day International Association of Cryospheric Sciences (IACS) (Radok, 1997; Jones, 2008), that the situation slightly improved. Its first president, the Swiss scientist François-Alphonse Forel, promoted the organized monitoring of glaciers in the Pyrenees for comparison to the evolution of the glaciers in the Alps (Forel, 1887; Gellatly et al., 1994). Prince Roland Bonaparte established and communicated to the Commission the first regular observations of glacier frontal variations between 1874 and 1895 (Bonaparte, 1892). Next, Gaurier monitored the glaciers over the period 1904–1927, which was interrupted by World War I (Gaurier, 1921). On the French side of the Pyrenees, *Eaux et Forêts*, the French national agency in charge of forest and water management, took over the measurements in ~~year~~ 1932, and after World War II, during the ~~period~~ 1945–1956 period (Mercanton, 1956). At the end of the 1970s, under the initiative of François Valla from the *Centre Technique du Génie Rural et des Eaux et Fôrets* and with the support of the *Parc National des Pyrénées*, the first, to our knowledge, mass balance measurements in the Pyrenees ~~to our knowledge~~ were performed at Ossoue ~~Glacier~~ and Taillon glaciers between 1978 and 1984 (with only qualitative data taken in 1983 and 1984) (Pont and Valla, 1980; Pont, 1985). This initiative led to the creation of the *Groupe d'Etudes des Glaciers des Pyrénées* (GEGP), a collaborative group comprising the *Institut National de l'Information Géographique et Forestière* (IGN) and researchers at Pau University. Two topographic maps, dated from 1948 and 1983 (and shown below), were produced by the GEGP (Cazenave-Piarrot et al., 1987). However, this group lasted only a few years, so that, for the period between 1957 and 2001, only raw terrestrial and aerial images are available for reconstructing glacier front and area variations. Since 2001, a group of volunteer glaciologists called the *Association Moraine* have performed regular glaciological field measurements (René, 2014). On the Spanish side, the institutional program *Evaluación de Recursos Hídricos Procedentes de Innivación* (EHRIN) has monitored Spanish glaciers since the 1990s. Since 1991, this program has collected an uninterrupted glaciological mass balance time series of the Maladeta Glacier (still ongoing WGMS, 2008). ~~The ablation stake measurement protocol in Spain and France was established in collaboration with glaciologists from the *Laboratoire de Glaciologie et Géophysique de l'Environnement* (Grenoble, France), which facilitates comparison between glaciers fluctuations in the Pyrenees and Alps.~~

In spite of all these efforts, observations of the Pyrenean glaciers remain scarce and irregular. Hence, there are few available reconstructions of glacier evolution since the LIA, and quantitative studies are even rarer. A brief review of Pyrenean glacier evolution is given in Chueca and Julian (2004). On the Spanish side of the Pyrenees, the ice-covered area has decreased by 74 % since the end of the LIA (Chueca et al., 2008). In comparison, ~~the area of glaciers in the European Alps decreased by~~ Alpine glaciers lost 35 % ~~(Hoelzle et al., 2007)~~of their total area from 1850 until the 1970s, and almost 50 % by 2000 (Zemp et al., 2006). Field measurements completed by early maps, paintings, terrestrial and aerials photographs have allowed the reconstruction of the fluctuations of the Taillon, Maladeta, and Coronas Glaciers throughout the 20th century (Gellatly et al., 1994; Chueca et al., 2003; Cía et al., 2005; Chueca et al., 2007). The results of these studies are consistent with ~~a general glacier~~ general glacial recession since the LIA. Each glacier experienced alternating periods of strong recession ~~and~~ with periods of stability or limited readvance. In particular, there seems to be a common period of strong recession after 1850, a period of readvance or stability between 1960 and 1980, and a period of strong recession from the mid-1980s until now.

~~The main driver of these glacier~~ One of the main drivers of these glacial changes since the LIA is ~~the~~ regional temperature increase (Grunewald and Scheithauer, 2010). Periods of low precipitation were identified without evident trends~~. Investigation into~~ ; however, research has been lacking in order to identify potential connections to larger-scale atmospheric patterns~~has been less common. The NAO controlled~~ . Generally, there are correlations with the NAO affecting the snow accumulation in the Pyrenees during the second half of the 20th century, in particular at ~~high-elevation~~ high-elevations (López-Moreno et al., 2007, 2011). The AMO was more recently identified as a possible driver of multi-decadal variations in river flow and precipitation in southwest France, including the Pyrenees (Giuntoli et al., 2013; Boé and Habets, 2014).

Local topo-climatic effects, such as avalanching, wind-drifted snow~~or shading~~ , or shading, may significantly influence accumulation and ablation processes. In the Pyrenees, these local influences are expected to have introduced spatial disparities in ice ~~shrinkage, promoting in particular~~shrinkages; in particular, to have promoted steep north and northeast glacier cirques, located below the highest summits (Chueca et al., 2007, 2008).

3 Study site

Ossoue Glacier (42°46′15″ N, 0°08′40″ W) is located in the central part of the Pyrenees, beneath the border pass of Cerbillona. It belongs to the Vignemale Massif, which owes its name to the eponymous highest peak of the French Pyrenees (3298 m a.s.l.) (Fig. 1). ~~It~~ The glacier is an east-facing cirque~~glacier. Its main characteristics are given in Table **??**. The~~ . Its bedrock comprises metamorphic limestone ridges and quartzite rocks ~~of Devonian age~~from the Devonian period.

Ossoue Glacier is the largest glacier of the French Pyrenees and had an area of 0.45 km^2 in 2011. It is characterized by a large plateau on the upper part (mean elevation 3105 m a.s.l., elevation range 3030–3200 m). The plateau constitutes two thirds of the overall area, and is located on a gentle slope (8°)~~. The~~ , while the lower part of the glacier has a steeper slope ($> 20°$). Therefore, the elevation distribution along the 455 m elevation range is characterized by a relatively high median value (3076 m a.s.l. in 2013~~; Tab **??**~~). Ossoue Glacier has ~~a~~ typical “alpine morphology”, being significantly longer (1400 m) than ~~wider~~ it is wide (400 m), and terminating in a double tongue.

Ossoue Glacier is 150 km from the Atlantic coast and is thus under the influence of the North Atlantic westerlies, which bring abundant precipitation (Chueca et al., 2008). The ~~mean annual precipitation at the~~ closest meteorological station (Gavarnie, 11 km, 1380 m a.s.l.) ~~is~~ recorded a mean annual temperature of 7.68 C° and a mean precipitation of 1450 mm over 1992–2012. The glacier is fed mainly during winter by direct precipitation and wind-blown snow. Avalanching is most likely not a significant source of nourishment for ~~the~~ Ossoue Glacier. The surrounding crest walls exhibit limited ~~superficies~~ surfaces propitious for snow interception. Thus, Ossoue Glacier carries little debris on its surface, and topographic shading is quite limited. Dust particles are frequently observed on the snow surface, which likely affects glacier albedo and snowmelt in summer. The first day of the local hydrological year is fixed ~~to~~ on the 1st of October (Cogley et al., 2011). The melting period ~~extends generally~~ generally extends from the end of May to the beginning of October. We thus consider the hydrological summer during (JJAS). Moulins are often observed during that period in the glacier upper area.

Ossoue Glacier was irregularly monitored throughout the 20th century, but has been quite well monitored since 2001 (Tab. 1).

4 Data sets and methods

4.1 Topographic surveys

4.1.1 Early sources

As is usual in glacier reconstructions, our data come from various sources (Tab. 1). ~~Distances between the glacier snout and reference points (spits, marks) on specific dates were measured in situ or from photographs or aerial images.~~ Moraines allow us to determine the glacier extent at dates estimated to be close to the end of the LIA. The testimony of Henri Passet establishes that the glacier reached the summit of the left lateral moraine in 1865 (Grove, 2004). A photograph taken in 1885 by Joseph Vallot provides evidence that Ossoue Glacier was still close to its moraines at this date. The Etat-Major map edited in 1851 by the French army also provides similar evidence. The map has an estimated accuracy of 15 m in planimetry. Two elevation points located on the front of the glacier are marked at 2458 and 2471 m a.s.l. Currently, both points are located on the glacier moraine. At these locations, the present elevations are 2447 and 2491 m a.s.l. It is remarkable that the difference in elevations are only 11 and 20 m, which gives us further confidence in the fact that the glacier front was actually in contact with its moraine at the middle of the 19th century, i.e., at the estimated end of the LIA in the Pyrenees (Grove, 2004; Trueba et al., 2008).

Length measurements were based on field observations reported by various authors (Reid-Muret, 1906, e.g. Commission internationale des glaciers) and complemented with estimations from photographs or aerial images.

The Villa Russell is a cave, accessible from the glacier at 3201 m a.s.l. It was extruded by Henry Russell and his employees in 1881 (Fig. 3, Tab. 1). Vertical measurements between the glacier surface and the cave threshold were made beginning in 1882.

We collected three paper topographic maps from 1924, 1948, and 1983 (Fig. 4 and Tab. 1). The map dated from 1924 is a 1 : 20 000 scale topographic map with 20 m contour lines. It was created by Alphonse Meillon, a pyrenean topograph-alpinist from the *Club Alpin Français* and Etienne de Larminat, a military cartographer (Meillon and de Larminat, 1933). Its implementation involved both field measurements and triangulation from photographs. Most of the photographs were terrestrial photographs, but, in a unique collaboration, military aerial photographs were also used to fill the gaps in a unique collaboration framework information gaps (Guilhot, 2005). The maps from 1948 and 1983 feature 2 m contour linesmaps , and were drafted by GEGP (Sect. 2). Elevation contour lines were generated by manual restitution from stereoscopic airborne photographs (Cazenave-Piarrot et al., 1987). Both maps have a 1 : 2500 scale and were projected in Lambert 3 (the official French coordinate projection system until 2001). We digitized these maps at 1270 dpi.

We also collected summer aerial photographsdated , which date from 1924, 1948, and 1983available in , made available from the IGN in digital format. The latter two photographs exhibit crevasses features matching crevasse features that match the aforementioned topographic maps, which indicates that they were used as stereospcopic images the stereoscopic images used to generate the contour lines in the first place. We used these photographs to delineate the glacier outline and compute the glacier area, because we found that the glacier outline on the topographic maps was either incomplete or inaccurate. We also used the Etat-Major map (dated 1851) to compute the glacier area. We preferred the outline derived from the moraine position to that from this map to determine of this map in determining the glacier outline in and around the 1850s.

Orthorectification, photointerpreation, lengthphotointerpretation, length, and area measurements (based on graphical or digital sources) were performed in GIS (ArcGis 10.2 from Esri©).

Because there was no projection information available for 1924, the map was geo-referenced by extracting GCPs from a digital reference map at 1 : 25 000 scale (IGN Scan 25). For the 1948 and 1983 maps, the coordinates of the graticule intersections registered on the paper map allowed a direct geo-referencing of the scanned maps. The estimated accuracy in planimetry is 5 for the 1924 map and 2 for the 1948 and 1983 maps.

Topographic maps and georeferenced orthoimages (outlines) were assessed in planimetry using a 2010 aerial image orthorectified by the IGN as reference. We associated a random error to outline positions due to glacier margin interpretation, resolution or scale of the documents. From these errors, we generated buffers to estimate randoms errors in area, most likely resulting in error overestimations (Hoffman et al., 2007). We estimated the randoms errors in cave height with respect to the glacier surface and in glacier front position based on a subjective assessment of the reliability of the observations as reported in the historical documents (Tab. 1). We calculated total random errors in length, area and height (Villa-Russell) variations registered between two dates t_1 and t_2 by calculating the root sum of squares of each random errors:

$$\sigma_{\text{indicator.total.PoR}} = \sqrt{\sigma^2_{\text{indicator}.t_1} + \sigma^2_{\text{indicator}.t_2}}$$

To scale the error to an annualized value of a N-years period of record (with $N = t_2 - t_1$), we considered two cases: (i) if the indicator value at t_2 was deduced from the indicator value at t_1, then we divided by $\sqrt{N}$ (e.g., in the case of the field measurements on the glacier

~~front), or (ii) if both indicator values were calculated independently, we divided by N (e.g., in areas variations based on diachronic aerial images).~~

On the three digitized maps, contour lines were ~~sampled densely~~ densely sampled to generate close elevation points. Two ~~m~~ (m)DEMs were generated by ~~an interpolationmethod~~interpolation, based on a discretized thin plate spline technique (Anudem 5.3, Wahba, 1990; Hutchinson, 2011).

4.1.2 Recent surveys

The length, area, and height (Villa-Russell) measurements have ~~been~~ continued in the 2000s.

To complete the historic ~~DEMs~~ DEM time series, two DGPS surveys (DGPS receivers Trimble GEO XH 2008 and 6000) were performed on ~~3 September~~ September 3^{rd}, 2011 and ~~6 October~~ October 6^{th}, 2013 (Tab. 1). Post-corrections, based on a 40-km-distant base from the French geodetic permanent network (RGP), were applied. Two ~~m~~ (m) DEMs were generated from the elevation point canvas, applying the same interpolation method previously mentioned. The estimated random error on the DGPS DEM is 0.6 m.

A Pléiades stereo pair was acquired from over Ossoue Glacier on ~~23 September~~ September 23^{rd}, 2013. Pléiades stereo images have been successfully used to measure geodetic mass balances of mountain glaciers to within an accuracy of about 1 m (Wagnonet al., 2013; Berthier et al., 2014). We generated a 2 m horizontal resolution DEM with 1 m vertical resolution and 1.8 m vertical accuracy (GeoView©software 6.6, Marti et al., 2014). In this study, the Pléiades DEM was used to generate the surface elevation of the deglaciated margin between 1983 and 2013. To map the differences in surface elevation on the glacier between 1983 and 2013, the DGPS surface elevation was used because it was acquired closer to the end of the summer.

4.2 Geodetic mass balances

The DEMs generated for 1924, 1948, 1983, 2011, and 2013 allowed us to establish a geodetic mass balance over an 89 year period. Consecutive DEMs were subtracted on a pixel by pixel basis. Volume changes derived by ~~differencing~~ differentiating DEMs is based on the following equation (Zemp et al., 2013):

$$\Delta V = r^2 \sum_{k=1}^{K} \Delta h_k \qquad (1)$$

where K is the number of pixels covering the glacier at the maximum extent, Δh_k is the elevation difference at pixel k, and r is the pixel size (2 m in this study).

~~We~~ Since we have very little information on the generation of the maps based on terrestrial (1924) or aerial photogrammetry (1948, 1983)~~.~~, DEMs were assessed on stable terrain following the technical recommendations given in Racoviteanu et al. (2010). A GCPs dataset was generated from DGPS points~~collected on 23 October~~ , collected on October 23rd, 2013, on the frontal margin of the glacier, i.e., on a snow and ice free bedrock surface. DEMs were not horizontally shifted, given the good absolute localization of the sources (5 m for 1924, 2 m for 1948 and 1983), and the limited ~~superficies covered~~ surface cover outside the glacier that would be needed to perform such an ~~adjustement~~adjustment.

The ~~differences between the DEM and the DGPS elevation values were normally distributed for 1948, 1983 and 2013. The mean elevation difference found for each DEM was noted as ϵ_{bias} ($\epsilon_{\text{bias.1948}} = -1.8$, $\epsilon_{\text{bias.1983}} = -1.4$, and $\epsilon_{\text{bias.2013.}P} = -1.37$ for the 2013 Pléiades DEM) and was uniformly added to all the elevation values. For the 1924 DEM, the elevation differences did not follow a normal distribution and it was not possible to determine the elevation bias (noted as $\epsilon_{\text{bias.1924}}$). Hence, no correction was applied to this DEM. The SD of the elevation difference values on stable areas was considered as to be a representative value of the vertical random error and was noted as σ_{bias}. The random error term due to the interpolation process was calculated to be 0.5 for 2011 and 2013 DGPS data. The~~ annualized geodetic mass balance ~~B_{geod}~~ $B_{\text{geod.a}}$ was calculated through the following formula : (Zemp et al., 2013):

$$B_{\text{geod}\,\text{geod.a}} = \frac{\Delta V_{\text{PoR}}}{\bar{S}}.\rho\left(\frac{\Delta V_{\text{gla}}}{A_{\text{gla}}} + \frac{\Delta V_{\text{marg.gain}}}{A_{\text{marg.gain}}} + \frac{\Delta V_{\text{marg.loss}}}{A_{\text{marg.loss}}}\right).\frac{1}{N} \quad (2)$$

where ρ is the mean density (see detail below). A_{gla} is the area that is glaciated in both DEMs. $A_{\text{marg.loss}}$ is the deglaciated area; $A_{\text{marg.gain}}$ is the area where the glacier advanced. The mean density was assumed to be 900 between 1924 and $\bar{S}$ is the average glacier area of the two survey dates assuming a linear change through time, and N is the number of years in the period of record (PoR). Between 1948 , and between 1983 and 2013, because the firn zone was nearly absent during those periods. We neglected the errors associated with this density assumption. In 1983, because a firn zone was likely present, 2001, we used a mean density ρ of 850 kg m^{-3} with an uncertainty range of ±50 kg m^{-3} (Huss, 2013) . For that period, we calculated an error term σ_{dc} associated with the uncertainty range due to density conversion. For every period, we considered an additional systematic error term ϵ_t due to the time lag between the raw data acquisition date and the first day of the next hydrological year, fixed to 1 October (when the elevation surface is expected to reach its annual minimum). The error ϵ_t was computed by multiplying the mean ablation rate observed during this period of the year over 2001–2013 (from stake measurements) by the duration of the time lag. At this stage we preferred to keep this term as an error rather than correcting the mass balance value, using a floating-date system (Cogley et al., 2011). Before 1948, we considered a nearly absent firn zone. Since 2001, the glaciological measurements indicate that the glacier summer surface is almost exclusively bare ice. In both cases, we considered a mean density of 900 kg m^{-3}. For details in the errors estimations, please refer to the supplementary document.

Following Zemp et al. (2013) the mean annual systematic error may be expressed as:

$$\epsilon_{\text{geod.total.a}} = \frac{\epsilon_{\text{geod.total.PoR}}}{N} = \frac{\epsilon_{\text{geod.DEM.PoR}}}{N}$$

$$= \frac{\epsilon_{\text{bias}} + \epsilon_t}{N}$$

where PoR is period of record and N is the number of years in the PoR. After co-registration ϵ_{bias} is assumed to be 0, and therefore:

$$\overline{\epsilon_{\text{geod.total.a}}} = \frac{\epsilon_t}{N}$$

The mean annual random error may be expressed following (Zemp et al., 2013):

$$\overline{\sigma_{\text{geod.total.a}}} = \frac{\sigma_{\text{geod.total.PoR}}}{N} = \frac{\sqrt{\sigma^2_{\text{geod.DEM.PoR}}}}{N} = \frac{\sqrt{\sigma^2_{\text{bias}} + \sigma^2_{\text{dc}}}}{N}$$

Note that for scaling random errors at annual time steps, division is by the number of years (Zemp et al., 2013). The values of ϵ_{bias}, ϵ_t, σ_{bias}, σ_{dc} and the resulting errors in DEM differences are given in Table **??**. Annualized systematic and random errors are presented in Table 2.

4.3 Glaciological mass balances

Since 2001, Ossoue Glacier has been monitored by systematic winter and summer mass balance measurements performed by Association Moraine*Association Moraine*. These are available on the WGMS website (Id: 2867). The direct glaciological method was used here (Ostrem-Brugman, 1991; Cuffey and Paterson, 2010). The protocol was similar to that used for the Saint-Sorlin and Argentière Glaciers in the Alps (Gerbaux et al., 2005; Vincent, 2002), and followed the technical recommendations of the GLACIOCLIM observation network (GLACIOCLIM, 2001; René, 2013). At eight sites (Fig. 3), the winter and annual mass balances were determined by two specific methods: (1) the end of winter snow depthend-of-winter snow depth, with respect to the previous summer surfacewas , measured using snow probesand the , and near-surface snow densitywas , calculated by drilling and weighting weighing calibrated cores; and (2), the annual mass balancewas , determined by inserting 10 m ablation stakes (five 2 m sections) into the ice. Summer ablation measurements were repeated once a month until a date close to the beginning of the next hydrological year, according to the floating-date system (Cogley et al., 2011).

These point observations were spatially integrated using an area extrapolation method. The glacier surface was divided into eight polygons centered at each ablation stake. The polygon borders were determined through empirical considerations based on field observations, elevation , aspectaspect, and mean slope (Tab. ??, Fig. 3). Further details are given in the supplementary material. The winter mass balance at a specific site k can be expressed as:

$$b_{\mathrm{w}.k} = \rho_{\mathrm{snow}.k} h_{\mathrm{snow}.k} \tag{3}$$

where $\rho_{\mathrm{snow}.k}$ is the density calculated at site k and $h_{\mathrm{snow}.k}$ the snow depth accumulated during winter on the previous summer surface.

The glacier-wide winter mass balance B_{w} was obtained by summing the contribution from each polygon:

$$B_{\mathrm{w}} = \sum_k b_{\mathrm{w}.k} W_k \tag{4}$$

where W_k is the fractional surface area of the polygon k within the glacier(Tab. ??). . The W_k values were updated in 2006 and 2011 to reflect the evolution of the glacier geometry.

The annual mass balance was calculated using the same spatial integration method. If the field operator noted the disappearance of the winter snow layer, and the presence of older firn from a previous year, a density of 600 kg m^{-3} was applied to that layer. If ice was observed, a constant density $\rho_{\mathrm{ice}} = 900$ kg m^{-3} was used. Lower densities values were not used because of the continuous glacier shrinkage observed since the 1980s.

These glaciological mass balance terms can be expressed in the following equation (Cogley et al., 2011):

$$B_{\mathrm{glac.a}} = B_{\mathrm{w}} + B_{\mathrm{s}} \tag{5}$$

where $B_{\mathrm{glac.a}}$, B_{w} and B_{s} designate the glacier-wide annual, winter, and summer mass balances, respectively.

The summer balance B_s was calculated as the difference between the two measured mass balance terms.

Annual systematic and random errors in the glaciological data series can be expressed as follows (Zemp et al., 2013):

$$\overline{\epsilon_{\text{glac.total.a}} = \frac{\epsilon_{\text{glac.PoR}}}{N}}$$

$$\overline{\sigma_{\text{glac.total.a}} = \frac{\sum_{t=1}^{N}\sigma_{\text{glac.a.PoR}}}{\sqrt{N}} = \frac{\sqrt{\sum_{t=1}^{N}\sigma^2_{\text{glac.point}.t}+\sigma^2_{\text{glac.spatial}.t}+\sigma^2_{\text{glac.ref}.t}}}{\sqrt{N}}}$$

where PoR indicates the period of record, N is number of years in the PoR and point refers to the field measurement at the location point, spatial to spatial integration, and ref to the changing glacier area over time.

The value of $\epsilon_{\text{glac.total.a}}$ was computed from the DPGS surveys performed in 2006 and 2011 as follows: (i) we calculated the mean elevation difference between both DEMs over polygons 1 to 4 (only these sectors were covered in 2006); and (ii) we calculated a mean geodetic mass balance assuming a density of 900 . We compared this geodetic mass balance to the corresponding glaciological mass balance. We obtained a difference of -0.68 for $N = 5$, which gives $\epsilon_{\text{gla.total.a}}$ = +0.14

We estimated random errors due to the field measurements following the guidelines provided by Gerbaux et al. (2005). Given that only three occurrences of positive mass balance were observed over the whole period of record (88 measurements), the entire glacier was considered as an ablation zone over this period for the estimation of the errors (i.e we neglected the errors associated with the residual snow from the previous year). The mean annual error in the specific mass balance is $\sigma_{\text{glac.point.a}} = 0.15$ The specific mean winter mass balance error is $\sigma_{\text{glac.point.w}} = 0.35$ (Tab. **??**).

Next, we estimated the random error due to the spatial integration $\sigma_{\text{glac.spatial.a}}$ to compute the glacier-wide glaciological mass balance from the specific mass balances. This was done using the DEMs made from the DGPS surveys performed in 2011 and 2012. For every polygon 1 to 6 (only these polygons were surveyed), we calculated the variance of the differences between both DEMs. The six variances values were aggregated based on

Eq. (4), after rescaling the area weights. We obtained a mean value of 0.88 However, this error value is likely too high, because, in part, it propagates the errors included in the DGPS DEMs. Therefore, we took $\sigma_{\text{glac.spatial.a}} = 0.7$ We neglected the error term $\sigma_{\text{glac.ref.a}}$ due the changes in glacier area (Zemp et al., 2013). In sum, we estimated an annual total random error of $\sigma_{\text{glac.total.a}} = 0.85$

The stake measurements performed from 1979 to 1985 followed similar protocol as that described above, except that the glacier was divided into 5 longitudinal sectors (Pont, 1985). We used the same annual total random error as for 2001–2013All the details on the errors calculation are given in the supplementary material.

4.4 Glacier indicators combinationComparison with other glaciers in the Pyrenees and the Alps

The Ossoue Glacier indicators Ossoue Glacier metrics mentioned above were pieced together to create a coherent time-line detect the main phases of glacier fluctuations. We defined five threshold values to classify variations in each glacier indicator over the period of record. We defined classes of markedly positive variations, positive variations, markedly negative variations, negative variations and a class of "no significant variation". Classification in a positive or a negative class was based on whether the absolute annualized variation was equal or greater than the annualized random error Metrics variations were not considered significant if they were within the estimated error range. We identified periods of glacier accumulation or stabilization, periods of ice depletion, and undetermined periods. We selected others glacier reconstructions from the literature (Tab. ??). If this condition was not fulfilled, the variation was classified as not significant for the period of record. From this classification, we qualitatively determined periods of stable-positive or negative evolution.

4.5 Geophysical surveys

A ground penetrating radar (GPR) survey was performed on 30–31 of August 2006 in the upper area of Ossoue Glacier. The GPR apparatus used was a PulseEkko 100 (Sensors and Software Inc.) with 504 and Fig. 2). For the Pyrenees, we considered the following glacier reconstructions (Sect. 2):

– Taillon (42.69° unshielded antennas. Three longitudinal profiles (W–E) running from the top to the slope transition of the glacier and four transverses profiles (N–S) were surveyed. The horizontal step was 0.5N, −0. 04° . The topography was acquired in real-time using a Leica DGNSS. In the radargrams strong reflectors identified at long two-way traveltimes were assumed to be the glacier bed. Hyperbolic features were used for electromagnetic (EM)velocity determination. An EM velocity of 0.16E, northeast-oriented, 2530–2800 was determined for the ice and was used to migrate the data. The thickness of the glacier was determined along the profiles at an horizontal resolution of 10 m. At the glacier margins the thickness was assumed to be zero (Saintenoy et al., 2013). The glacier thickness and surface elevation in 2006 were interpolated by ordinary kriging after second order trend removal (ESRI ArcGIS®, Geostatistical Analyst tool). Subsequently a map of the subglacial bedrock elevation was generated. Based on the standard error map associated with kriging, we excluded the area in the prediction map where the kriging error was greater than $\sigma_{\text{krig}} = 10$, 0.08 . From the 2013 glacier DEM and the bedrock map, we generated a 2013 glacier ice thickness map (Fig. 12). The mean random error for the subglacial elevation was calculated as follows:

$$\sigma_{\text{subglacial.total}} = \sqrt{\sigma^2_{\text{GPR}} + \overline{\sigma_{\text{krig}}}^2 + \sigma^2_{\text{bias.2006}}}$$

where σ_{GPR} is the spatial resolution of the survey (2km^2 in 2011), (Gellatly et al., 1994)

– Maladeta (42.65°), estimated from the spacing of the antenna elements, $\overline{\sigma_{\text{krig}}}$ is the mean error from the kriging (6N, 0.64°) and $\sigma_{\text{DEM.2006}}$ the random error of the 2006 DEM (1.5E, northeast-oriented, 2870–3200 m). We obtained: $\sigma_{\text{subglacial.total}} = 6.5$altitude range and 0.27 . The same mean error was used in the ice thickness determination in 2013 (i. e. we neglected the error introduced by the 2013 DEM). The kriging error associated with the maximum ice depth recorded in 2006 is $\sigma_{\text{krig.max}} = 10$km^2 in 2011), (Cía et al., 2005)

– Coronas (42.63° . Therefore, we propagated these errors into the 2013 maximum ice thickness (same location)and we calculated an error value of 10.3N, 0.65° E, southwest-oriented, 3100–3240 m and 0.02 km^2 in 2011, ice patch since the 2000s) (Chueca et al., 2003)

These reconstructions were mostly based on length and area variations, but also used others sources when they were available (e.g. a short stake measurement timeseries in Taillon Glacier at the end of the 70s). In the Alps, we considered the main phases identified by:

– Vincent (2002) and updated by Six et al. (2014) on four well-studied glaciers: Saint-Sorlin, Gébroulaz, Argentière, and Mer de Glace glaciers.

– Thibert et al. (2013) on Sarennes Glacier.

– Huss et al. (2010) based on thirty Swiss glaciers.

Due to the morphological differences between the Alpine and Pyrenean glaciers, we considered only the Alpine glacier reconstructions which, were based on mass variations (i.e., not the glacier length or area).

4.5 Climatic data

To infer potential drivers of for Ossoue Glacier variations, we used several climatic datasets, including three mean monthly air temperature datasets.

- The closest meteorological station to Ossoue Glacier was located at Gavarnie, in the same valley (1380 m elevation, 11 km east of the glacier, time series from January 1991 to May 2012).

- To cover the glacier reconstruction period, we also used the temperature time series recorded at the Pic du Midi observatory (~~42.936~~42.93° N, ~~0.142~~0.14° E, 2874 m a.s.l., 30 km north-east of the glacier). The time series was homogenized, and gaps were filled from January 1881 to May 2011 (Bücher and Dessens, 1991; Courraud, 2011). We used raw data from 2011 to October 2013.

- We extended the Pic du Midi temperature time series with the CRUTEM 4 dataset (5° x 5° gridded version) over the period 1858–1890 (Jones et al., 2012). The mean annual difference between these datasets due to the elevation difference between the stations was removed from the CRU dataset (-13.07 °C).

All temperatures time series correlated well (Spearman's $\rho > 0.96$, p values < 0.05). ~~We performed correlations between air temperature and Ossoue Glacier mass balance measurements over the period 2001–2013.~~ Temperature time series were averaged over summer periods (JJAS), winter periods (NDJFMA), and hydrological years (beginning ~~1 October) . To reconcile the different recording periods of the meteorological and glaciological measurements, summer and annual mass balances were linearly interpolated by using a fixed date system (1 October, Cogley et al., 2011). The mass balances terms B_w were extrapolated to 31 May. Due to some missing data, it was not possible to calculate the mean annual temperature for several months at Gavarnie over the period 2002–2012. Thus we did not correlate these data with the annual mass balance.~~ 01 October)

We also used two monthly precipitation datasets:

- Monthly precipitation was recorded at the Gavarnie Valley station simultaneously with the temperature (see above for station location; period of record: January 1991 through May 2012).

– Monthly precipitation was recorded over the period 1882–2013 at Tarbes-Ossun Météo-France station (43.18° N 0.00° E, 360 m elevation, 50 km north- east of the glacier). These data were homogenized until 2000 and used as raw data since then (Moisselin et al., 2002).

Both precipitation datasets showed a significant correlation (Spearman's $\rho = 0.56$, p value $<$ 0.010.05). We calculated annual and winter precipitations (NDJFMA). October and May precipitation values were not considered because the precipitation was as often liquid as solid in these months, and thus presumably does did not contribute significantly to accumulation on the glacier.

We performed correlations between precipitation the meteorological data (temperature and precipitation) and Ossoue Glacier winter and annual mass balance measurements over the 2001–2013 periodconsidering . To reconcile the different recording periods of the meteorological and glaciological measurements, summer and annual mass balances were linearly interpolated by using a fixed date system (annual mass balances 1 October, winter mass balances 31 May)(01 October, Cogley et al., 2011). The mass balances terms B_w were extrapolated to May 31st. Due to some missing data, it was not possible to calculate the annual mean annual temperature and precipitation for several months at Gavarnie over the 2002–2012 period . Thus, period 2002–2012. Thus we did not correlate these data with the annual mass balance. Mass balances and meteorological timeseries were detrended using a least-square linear fit prior to the correlation analysis.

We also considered the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO). Both indices represent fluctuations in the North Atlantic climate and have been successfully used in glacier-climate linkages (Six et al., 2001; Huss et al., 2010; Thibert et al., 2013).

– For the NAO we used a winter (DJFM) index based on the monthly 1850–1999 Climate Reasarch Unit (CRU) dataset, completed by Tim Osborn's 2000–2013 NAO Update (Jones et al., 1997; Osborn, 2006). We applied a 5 yr moving average filter to smooth the signal.

– For the AMO, we used the monthly index calculated from the Kaplan sea surface temperature dataset over 1861–2009 (Enfield et al., 2001).

4.6 Geophysical surveys

A ground penetrating radar (GPR) survey was performed on 30–31 of August 2006 in the upper area of Ossoue Glacier. The GPR apparatus used was a PulseEkko 100 (Sensors and Software Inc.) with 50 MHz unshielded antennas. Three longitudinal profiles (W–E) running from the top along the slope transition of the glacier, and four transversal (N–S) profiles, were surveyed. From this data, a bedrock map was generated (see supplementary). From the 2013 glacier DEM and the bedrock map, we generated a 2013 glacier ice thickness map (Fig. 12).

To estimate the ice thickness maps in the next decades, we generated ice thickness projections based on a static approach (Fig. 13):

– we interpolated, on a 4 m resolution grid, the mean point mass balances measured at the stake locations over 2001-2013 on the current glacier outline (2011). The interpolation technique is the same used to generate the DEMs. This interpolation is consistent with the glaciological method. The mean rate after interpolation is -1.5 m w.e. a^{-1}, while the mean glaciological mass balance rate is -1.45 m w.e. a^{-1}.

– we made the assumption that this spatialized mass balance rate will remain constant in the next decades.

– based on this mass loss rate we calculated the ice depth on the glacier plateau at decadal intervals from 2013.

As it is based on the superficial mass balance only, this method estimating the future ice depth does not take into account effects from basal and internal mass balances, nor the dynamics of the glacier.

5 Results

5.1 Front, outlines and area Ossoue glacier metrics variations

5.1.1 Length variations

Our reconstruction of the Ossoue Glacier front and area shows significant glacier retreat since the LIA, with intermittent stationary phases (Fig. 9).

From 1850 to 1889, the Ossoue Glacier front retreated by 346 m ($-8.8\,\mathrm{m\,a^{-1}}$). During the following fifteen years (1889–1904), the front position was quite stationary, retreating by 11 m between 1892 and 1893 and by only 9 m between 1899 and 1904. In the year 1904–1905 period, however, however the Ossoue Glacier front retreated by 23 m. The following periods were characterized by stability (1905–1911) and progression (1911–1927). In our dataset, the glacier reached its most position of greatest advanced position of the 20th century advance in 1927 (Tab. **??**). in 1927.

5.1.2 Area variations

The area of Ossoue Glacier at the end of the LIA, based on moraines moraine locations, was 112.6 ± 10 ha. The glacier area extracted from the "Etat Major" map (dated near 1851) is 115 ± 20 ha. Between the end of the LIA and 1924, the area of Ossoue Glacier decreased by 20 %. The area decreased by a further 10 % over the period 1924–1948 period. During the period 1948–1983 period, the front retreated by 315 m until 1963, and then advanced by 156 m, although the changes in area over this period were low (−3 %). Over 1983–2002, the area decreased by 17 % with a notable width reduction on the slope transition. In the early 2000s, the area of Ossoue Glacier was less than 50 % of the its area at the end of the LIA(Tab. **??**). .

Changes in glacier geometry mainly occurred in the lower part of the glacier. In the upper part, the glacier shape remained almost unchanged until 1983. From 1983 to 2013, glacier width reduced dramatically at the slope transition between the plateau and the tongue of the glacier.

5.2 ~~Mass changes and ice thickness~~

5.1.1 Mass variations

Since 1924, Ossoue Glacier has lost a mean of ~~59~~60 m w.e. over the current glacier area (Fig. 9). The two periods of marked ice depletion, 1924–1948 and 1983–2013, were interrupted by a stable period between 1948 and 1983.

Between 1924 and 1948, the glacier lost −~~33.5~~1.42 m w.e. a^{-1} (−34.1 ± 8.8 m.w.e.~~(−1.39)over the 1948 glacier area and −25.5 ± 8.8 over the deglaciated margin~~). The ice depletion signal was strongest in the central part of the glacier (Fig. 7).

The ~~period~~ 1948–1983 period is the only period with observed positive geodetic mass balance variation, with a ~~cumulative value of~~ rate of +0.13 m w.e. a^{-1} (+~~5.8~~4.8 ± 2.6 m w.e.~~over the 1983 glacier area (+0.16~~). However, a notable depletion was observed on the tongue (Fig. 7). ~~On the deglaciated margin, depletion was −7.9 ± 2.6~~ The glacier advanced over a very small area (1 ha) with a mean ice growth of 6.5 m w.e.. An area of higher accumulation is localized on the lower part of the glacier, below the slope transition (Fig. 7). At the end of that period, using ablation stakes, François Valla and Henri Pont measured mass gains of +0.81 m w.e. in 1978~~,~~; +0.26 m w.e. in 1979~~,~~; +0.17 m w.e. in 1980~~,~~; and 0 m w.e. in 1981 and 1982. In 1983 and 1984, they considered the mass balances to be “negative” but did not provide quantitative information (Pont, 1985).

Over 1983–2013, the glacier lost −~~30.1~~1.04±0.06 ~~1.7~~w.e.a^{-1} (-31.3 ~~over the 2013 glacier area (−1) and −22.6~~ ± ~~1.7~~1.9 ~~over the deglaciated margin.~~m w.e.) . A marked pattern of ice depletion occurs along a longitudinal profile on the upper part of the glacier (Fig. 7). This phenomenon ~~increases~~ increased glacier convexity in that zone, which was once named ~~as~~ *Plateau des Neiges* in older maps.

If we consider the 2013 glacier area as a common integration area for all the periods, the absolute value of the geodetic mass balance increased over 1924–1948 (−35 m w.e.) and 1948–1983 (+6.1 m w.e.).

Between 2001 and 2013, superficial mass loss on Ossoue Glacier given by the glaciological method is 17.36 ± 2.9 m w.e. (-1.45 m w.e. a^{-1}) (Fig. 8). The strongest mass losses were registered at the lowest elevated stakes (stakes 7 and 8). The mass balance was negative every year since the stake measurements began except in 2012–2013 with a value of +0.22 m w.e. (René et al., 2014). In 2008 the mass balance was only slightly negative.

5.1.2 Mains phases of variations

Taken together, all the metrics suggest a clear retreat of Ossoue Glacier since the end of the LIA (Fig. 9). Based on the dates of the survey reported in the available documents, we identified several phases in the fluctuations of Ossoue Glacier:

- 1850–1890 (40 years, noted phase I in Fig. 9): between these dates, all the length variations are negative for all three survey dates (1874,1885,1889). Between 1882 and 1889, however, Russell noted some thickening and thinning at *Villa Russell*, with high interannual variability.

- 1890-1928 (38 years, phase II): the length variations are null from 1891 to 1899, and within the range of errors between 1892 and 1893 (i.e. no significant variations). Afterwards, length variations are negative until 1905. Between 1890 and 1894, Russell noted a period of stabilization at *Villa Russell* (II.a). Then, several irregular thinnings were observed at the following survey dates (1895,1898,1902,1904), interrupted by a thickening between 1898 and 1901. From 1905 to 1911, no length variations were observed for the six survey dates. Between 1911-1921, the length is increasing, but the variation is not significant. From 1905, the glacier is thickening at Villa Russell until 1913 (II.b). The glacier is significantly thinning at Villa Russell between 1913 and 1927. The length variation is positive, but not significant between 1921 and 1927.

- 1928–1950 (22 years, phase III): In spite of a large estimated error, the mass balance variation (1924-1948) is significant and markedly negative. Area variations is also negative between 1924 and 1948, and between 1948 and 1950. The glacier is thinning at Villa Russell until 1950 (survey dates for significant variations: 1937, 1945, 1950). The length variations are negative for all survey dates in that stage (1928, 1935, 1950).

- 1950–1983 (33 years, phase IV): the area variations are small and not significant between 1950 and 1953, and between 1953 and 1983. Negative length variations are observed until 1962, and positive afterwards. The geodetic mass balance is slightly positive over the 1948-1983 period. At *Villa Russell*, the glacier is thickening at the surveyed dates (1952, 1953, 1967). In 2006, 1953, the estimated mean ice thickness was 29.3 ± 6.3 (max.74.8 ± 10.2)glacier reaches the threshold of the *Villa Russell*, and is above the threshold in 1967. Between 1967 and 1983, a slight thinning is observed. The glaciological mass balance is positive from 1978 to 1980, zero in 1981 and 1982, and negative in 1983, giving an estimate of 25 ± 6.5 (max. 59 ± 10.3) in 2013 1984 (qualitative assessment for these two dates).

- 1983–2013 (Fig. 12). In 2011, another GRP survey (Del Rio et al., 2012) indicated a maximum depth of 45 and an average depth of 30 . Despite the discrepancies in ice thickness, both studies suggest similar bedrock morphologies.As a verification of these data, we provide here the depth of the main moulins that have been measured regularly since 2004 by glacial speleologists: 30 in 2004, 38 in 2005, 36.5 in 2006 and 41.5 in 2009. However, these values should be considered minimum estimates of the glacier thickness because they do not necessarily reach the bedrock.

5.2 Trends observed from glacier indicators

Taken together, all indicators suggest a clear retreat of Ossoue Glacier since the end of the LIA (Fig. **??**)years, phase V): from 1983, all the significant length and area variations observed are negative. At *Villa Russell*, the only positive variations are observed between 1987 and 1991, and 2007-2008. The geodetic mass balance is negative between the two dates of survey that define that phase. The annual glaciological mass balances are all negative since 2001, except for the hydrological year 2012-2013. We identified

From the above considerations, we defined three periods of marked ice depletion, when these indicators the metrics consistently indicate a negative trend: 1850–1890, 1928–1950 and 1983–2013.1850-1890, 1928-1950, and 1983-2013 (noted I, III, and V in Fig. 9). By the same reasoning, two three periods are characterized by stability or slightly growth: 1905–1928 and 1950–1983.slight growth: 1890-1904, 1905-1913, and 1950-1983 (noted II.a, II.b, and IV, respectively in Fig. 9).

5.2 Linkage Comparison with climatePyrenean and Alpine glaciers variations

Correlations between the Pyrenean and Alpine glaciers exhibit similar multidecadal variations during the 20th century. The ice depletion was particularly intense in the 1940s and since the 1980s. The stable period detected at the end of the 1970s is also evident in all the glaciers at both mountain ranges (Fig. 10). The Ossoue, Maladeta, and Coronas glaciers present consistent variations: ice depletion in the 1930s and 1940s, transition in the 1950s, stable period from the 1960s to the 1980s, and ice depletion since the 1980s. The Taillon Glacier variations appear more specific, but coincide with the ice depletion phase which had started in the 1980s. The Taillon Glacier and Ossoue Glacier fluctuations present further consistencies: around 1910 (II.b), in the 1930s (III), and around 1980 (IV). In the French Alps, two steady-state periods, 1907–1941 and 1954–1981, and two periods of recession, 1942–1953 and 1982–2013, were deduced from four glacier mass balances time series (Vincent, 2002; Six et al., 2014). These periods are in good agreement with that of Ossoue and Maladeta glacier variations. However, it seems that the glacier retreat phase of 1928–1950 (III) identified from Ossoue Glacier data started about a decade later in the Alps. In the Swiss Alps, (Huss et al., 2010) detected two short periods of mass gain (1910s and late 1970s) and two periods of rapid mass loss (1940s and late 1980s to present). These variations are also consistent with Ossoue Glacier variations (periods III, IV and V).

5.3 Comparison with meteorological time series

Correlations between Ossoue Glacier mass balances time series (2001–2013) indicate that the annual mass balance is mainly dependent on the summer mass balance, and that the winter mass balance has less influence (Spearman's $\rho = 0.84$ for summer mass balance and $\rho = 0.65$ for winter mass balance).

The link between ablation and air temperature ~~is~~ was verified at Ossoue Glacier~~through the high and~~ , as shown by the following significant (p value < 0.05) correlations:

- between monthly summer ablation and monthly air temperature time series over 2002–2013 (~~$\rho = -0.81$~~ $\rho = -0.8$ for Gavarnie valley station, ~~$\rho = -0.74$~~ $\rho = -0.75$ for Pic du Midi station, which is located farther from the glacier, and $\rho = -0.8$ for the regional CRU time series). ~~Mean~~

- between mean summer air temperature and summer-wide mass balance B_s (June–September) ~~are also correlated, although only significantly with the Gavarnie dataset (~~~~$\rho = -0.72$~~ ($\rho = -0.76$ for Gavarnie, ~~$\rho = -0.52$~~ $\rho = -0.71$ for Pic du Midi and ~~$\rho = -0.66$~~ $\rho = -0.72$ for the CRU time series). ~~The high correlation between the different time seriesover the common period of records ($\rho > 0.96$, p values < 0.05) give us confidence that the mean summer temperature at Pic du Midi is related to B_s.~~

- between annual mass balance and mean annual temperature ($\rho = -0.66$ for the CRU time series)

The link between annual mass balance and mean annual temperature is weaker in the Pic du Midi time series than in the CRU time series (~~$\rho = -0.45$~~ $\rho = -0.57$ for Pic du Midi~~and $\rho = -0.74$ for the CRU time series). The correlation is only significant with the CRU dataset. This may~~). This may be due to the use of raw data in the Pic du Midi time series, starting from 2011, or to the limited period ~~of record of~~ for glaciological mass balance records (annual mass balance measurements only began in 2001). However, due to the good correlation between the CRU and the Pic du Midi temperature datasets, we also considered that the mean annual temperature at Pic du Midi is linked to $B_{\text{glac.a}}$ over the longer ~~period~~ 1890–2013 period. The elevation of the Pic du Midi station (2874 m a.s.l.) is close to that of ~~the~~ Ossoue Glacier front (2755 m a.s.l.); thus, we ~~used principally~~ principally used this dataset to identify temperature trends over historical periods.

~~Precipitations~~ Precipitation records at Gavarnie and Tarbes are significantly correlated with the winter mass balances ($\rho = 0.71$ for Gavarnie, $\rho = 0.69$ for Tarbes, which is located farther from the glacier). The link between annual mass balance and annual precipitation is significant in the Tarbes dataset ($\rho = 0.66$). Thus, we conclude that the Tarbes time series can be used to identify trends in precipitation that are linked with Ossoue Glacier fluctuations.

The mean annual temperature over the hydrological year (starting ~~1 October)~~ October 1^{st}) over 1858–2013 is -1.1 °C, and the mean summer temperature (JJAS) ~~over 1858–2013 are -1.1 and~~ is 5.1 °C~~, respectively.~~ . Both timeseries present a linear trend over the period ($\rho = 0.38$ for annual, $\rho = 0.28$ for summer). This correlation is stronger if we limit the period to 1882–2013 ($\rho = 0.54$ for annual, $\rho = 0.51$ for summer). The annual precipitation and the winter precipitation (NDJFMA) over 1882–2013 are ~~1068.2~~ 1068 and 556 mm, respectively. No trend was observed in precipitation timeseries.

Analysis of temperature and precipitation trends over the ~~six periods from a~~four long-periods stemming from the combination of ~~indicators (~~glacier metrics (I, III, IV, and V, Fig. ~~??~~9) reveals four significant trends (Tab. 6):

- The mean annual temperature over 1858–1890 may have continuously decreased. Over the same period, the mean summer temperature (JJAS) is ~~slightly~~ 0.5 °C higher than the mean summer temperature over 1858–2013 (5.3 °C).

- Both short-periods of glacier accumulation (II.a and II.b) present annual (-1.3 °C and -1.4 °C) and summer (4.6 °C and 4.1 °C) temperatures lower than that of the means over 1858-2013 (-1.1 °C and 5.3 °C). The precipitation at Tarbes station over 1890–1994 and 1905–1913 is also higher than the mean over 1882-2013.

– The annual precipitation trend over 1950–1982 is positive ($\rho = 0.42$) and $\rho = 0.4$) and its mean is equal to the mean precipitation over 1882–2013 (1068 mm). Winter precipitation is higher than the mean recorded over 1882–2013 (586.2586 mm). The annual mean temperature (−1.4 °C) and mean summer temperature (4.8 °C) are lower than the means over 1858–2013.

– The last period considered (1983–2013) shows positive trends in both mean annual and mean summer temperature, with the highest registered mean temperatures (−0.4 °C for annual and 6.1 °C for summer).

Figure 11 provides insight into the possible linkage between the evolution of Ossoue Glacier and the regional-scale climate. The 1960–1980 period is characterized by a succession of negative phases in the NAO. This coincides with a period of relative glacier growth or stability (positive variations in various glacier lengths, areas, and mass balances). AMO warm phases occurred during 1860–1880, and 1940–1960, and cool phases during 1905-1925 and 1970–1990 (Enfield et al. (2001)). The AMO index presents some potential correlations with Ossoue Glacier variations: periods I and III of ice depletion, in regards to the AMO warm phases; and periods II.b and IV, to the AMO cold phases (Fig. 11).

5.4 Ice thickness maps

In 2006, the estimated mean ice thickness was 29.3 ± 6.3 m (max. 74.8 ± 10.2 m), giving an estimate of 25 ± 6.5 m (max. 59 ± 10.3 m) in 2013 (Fig. 12). In 2011, another GRP survey (Del Rio et al., 2012) indicated a maximum depth of 45 m and an average depth of 30 m. Despite the discrepancies in ice thickness, both studies suggest similar bedrock morphologies. Moulins were explored over the 2004-2009 summers at the Ossoue glacier plateau. The depth of the explored moulins ranged from 30 m to 41.5 m. Given that the bedrock was never reached according to the speleo-glaciologist, the ice thickness obtained by GPR is consistent with these depth measurements.

Over the subsequent decades, the mean and the maximum ice depths at the Ossoue Glacier plateau would rapidly decrease: 22 m (mean) and 48 m (max.) in 2023, 17 m and 38 m in 2033, 11 m and 27 m in 2043, and only 3 m and 7 m in 2053 (Fig. 13).

6 Discussion

Using multiple datasets, we generated five independent time series of glacier indicators metrics (length, area, thickness at Villa Russell, and geodetic and glaciological mass balances variations) to reconstruct the evolution of Ossoue Glacier since the end of the LIA (Fig. ??9). The indicators metrics give a generally consistent chronology of glacier fluctuations since the LIA, although there are some discrepancies. We should bear in mind that the indicators metrics do not directly reflect the same glaciological processes. The time series of frontal variations offers the best temporal resolution to of the onset of glacier changes, but these changes are strongly influenced by ice dynamics. Glacier motion is dependent on mass variations on of the upper part of the glacier, but the response time is largely unknown. Areal variations depend on ice thickness at the edges only. Thickness variations registered at Villa Russell are the result of accumulation and ablation variations at the northern periphery of the glacier only, which could be prone to snow drifting. Volumetric mass changes generated by the geodetic method are mostly the result of the surface energy budget but also include internal and basal mass variations, which remain difficult to estimate. Glaciological mass balance reflects balances reflect the link between energy and mass budget wellproperly, but can only be measured at a limited sample of points of at the glacier surface. However, these indicators metrics are all sensitive to the glacier mass changes, with different times scales and intensities of response time scales and response intensities. For instance, between 1948 and 1983, the mass balance was positive, but yet frontal variations were negative until 1963. This can likely be explained by the delay in the response time of frontal response to glacier mass changes. In the case of Ossoue Glacier, it is note-worthy that the indicators metrics over the study period reveal a consistent signal (Fig. ??9).

The evolution of Ossoue Glacier is consistent with the reconstructed evolutions of other Pyrenean glaciers. ~~It is in good agreement with Cía et al. (2005) (Maladeta Glacier, 42.65 N, 0.64 E, northeast-oriented, 2870–3200 altitude range and 0.27 area in 2011) and with Chueca et al. (2003) (Coronas Glacier, a glacieret or ice patch since the 2000s, 42.63 N, 0.65 E, southwest-oriented, 3100–3240 and 0.02 in 2011) and Gellatly et al. (1994) (Taillon Glacier, 42.69 N, −0. 04 E, northeast-oriented, 2530–2800 , 0.08 in 2011)~~Some discrepancies might be due to the nature of the metrics used in the reconstruction, or due to the local topo-climatic influences. Considering an accuracy of ±5 years, the study was able to identify two common stable periods ~~could be identified~~ (1905–1930 and 1955–1985), as well as two periods of marked ice depletion (1850–1900 and from the mid-1980s until now). The evidence of strong marked ice depletion found in this study for Ossoue Glacier between 1924 and 1948 (−~~1.39~~1.42 m m.w.e a^{-1}) should be considered with caution given the high uncertainties in the altimetry restitution process. However, reconstructions of other Pyrenean glaciers over comparable periods tend to corroborate this result. Between approximately 1928 and 1957, the length of the Coronas Glacier decreased from 600 to 350 m, while its area decreased from 19 to 8.6 ha and its equilibrium line altitude (ELA) increased from 3065 to 3122 m (Chueca Cía et al., 2001). During the ~~period~~ 1935–1957 ~~,~~ period, the Maladeta Glacier lost 15 ha (−0.68 ha a^{-1}) and its length decreased by 80 m. This retreat is assumed to be due to a warm anomaly detected in the second half of the 1940s (Cía et al., 2005). The Maladeta Glacier mass balance time series (1991–2013) ~~shows a~~ is in good agreement with Ossoue glaciological mass balances time series over the ~~period~~ 2001–2013 period (Fig. 9). During the 1990s, the Maladeta mass balance values were slightly negative. If we compare the Ossoue geodetic mass balance during 1983–2013 (−~~1~~1.04 m w.e. a^{-1}) and the Ossoue glaciological mass balance during 2001–2013 (−1.45 m w.e. a^{-1}), we can deduce that the 1983–2001 Ossoue ablation rate was approximately −~~0.7~~0.76 ~~. This result is~~ m w.e. a^{-1}. These results are consistent with the ~~aforementioned variations of the Maladeta Glacier~~ variation of the mean annual mass balance of the Maladeta Glacier: −0.2 m w.e. a^{-1} over 1991–2001 and −1.03 m w.e. a^{-1}, over 2001–2013 (Fig. 9).

~~In the French Alps, which is the nearest glaciated massif to the Pyrenees, two steady-state periods (1907–1941 and 1954–1981) and two periods of recession (1942–1953 and 1982–1999) were deduced from four glacier mass balances time series (Vincent, 2002). This further~~ The comparison between Pyrenean and Alpine glacier fluctuations suggests that there is a common climatic driver governing ~~fluctuations in Pyrenean and Alpine glaciers since the LIA.~~

~~Figure 11 provides insight into the possible linkage between the evolution of the Ossoue Glacier and the regional-scale climate. The period 1960–1980 is characterized by a succession of negative phases of the NAO, this coincides with a period of relative glacier growth or stability (positive variations in various glacier lengths, areas and mass balances). Ossoue Glacier~~ glacier fluctuations in both mountain ranges. Ossoue Glacier seems to be anti-correlated with the NAO. Similar results were reported by Six et al. (2002) and Marzeion et al. (2014) for glaciers ~~of~~ in the southern Alps. In addition, variations in the AMO index also appear relatively similar to variations in the combined Ossoue Glacier ~~indicators~~ metrics throughout the 20th century ~~.~~ (Fig. 11). This result is consistent with previous studies on the influence of the multidecadal internal variability of the North Atlantic circulation on the Northern Hemisphere climate (e.g., Enfield et al., 2001) and on Alps glacier fluctuations(Huss et al., 2010).

Variations of Ossoue Glacier ~~indicators~~ metrics are in good ~~agreements~~ agreement with meteorological data: periods of ice depletion are generally characterized by lower values of mean precipitation and temperatures (Tab. 6). The evolution of Ossoue Glacier may be partially explained by observed trends, with a significant positive trend in 1950–1982 ~~precipitations~~ precipitation (a stable period for the glacier) and a significant constant rise in mean annual and summer temperature since 1983 (a period of depletion for the glacier). The ~~periods~~ 1850–1890 and 1983–2013 periods are marked by ice depletion, although the mean air temperature time series have opposite and significant trends. Frontal variations and mean air temperature variations, over the 1850–1890 interval, point to a shorter period of marked ice depletion, 1850–1874, with lesser depletion over the 1874–1890 period. By the same reasoning the selected 1928–1950 period of ice depletion ~~period~~ may have been more pronounced in the 1937–1950 "subperiod" than over the 1928–1937 "subperiod". In the Alps, the 1942-1950 period is characterized by extraordinarily high rates of mass loss (Huss et al., 2008; Vincent et al, 2009).

The future evolution of Ossoue Glacier depends on climatic changes, but is also constrained by the remaining ice volume. Considering the remaining ice depth in 2013 and assuming that the Assuming that Ossoue Glacier mass balance follows the same trend as that recorded during 2001–2013(−1.45), the glacier should totally disappear in 40 years . To further illustrate this, the ice thickness map (Fig. 12)was divided with thickness classes that are multiples of 1.5, i. e., a value close to the current annual mass loss rate. Thus, this map gives a rough estimation of the evolution of the glacier area every eight years. Based on this map and the past evolution of the glacier, we 13). We anticipate that the glacier may split into two parts at the slope transition (Fig. 3) in the near future. At this location the glacier may be particularly thin, and there is an abrupt change in the glacier slope. The lowest part may soon no longer be fed by the ice flow from the upper area and could thus rapidly disappear. This separation would drastically change the morphology of Ossoue Glacier from an active glacier to a glacieret or ice patch. Such glacier fragmentation has been regularly observed on Pyrenean glaciers, e.g., the neighboring Petit Vignemale and Oulettes Glaciers.

However, future evolution of Ossoue Glacier based on interpretation of Fig. 12 13 was made under several strong assumptions: (i)the mass balance patterns are uniform, , basal and internal mass balances were neglected; (ii)ice motion can be neglected, , ice motion was neglected; and (iii), the mass loss in the future decades will occur at the same pace as during the last decade. Our data suggest that the uniform mass balance assumption is questionable. Geodetic measurements over 1983–2013 show a clear depression in the central part of the glacier, which indicates that the glacier evolves toward a more convex topography. Stake measurements over 2001–2013 reflect the influence of the glacier topography, principally in the ablation period (Tab. **??** and Fig. 8). Accumulation processes do not show a vertical gradient, but may show a north–south gradient in the upper part, most likely driven by the accumulation of wind-blown snow. Elevation is the main factor that

~~separates the three groups of stakes: above the glaciological mass balance (stakes 1 to 3), slightly beneath (stakes 3 and 5) and beneath (stakes 7 and 8). Stake 6 shows uncommon behavior that is most likely influenced by greater ice motion at that location. The influence of the aspect explains the discrepancy between stake 2 and stake 4, while slope seems to explain the higher melting rate at stake 3 compared to the lower-elevation stake 5. Future~~ In short, future work is necessary to better understand the effect of local topography on the spatial variability of glacier mass balance. This influence is expected to ~~augment~~ increase in the future as the glacier retreats (López-Moreno et al., 2006a, b).

~~If the~~ The reconstruction and the future evolution of Ossoue glacier does present large uncertainties, and the influence of the climate fluctuations on the glacier metrics variations are complex; however, considering the current ablation rate~~continues,~~ , it seems doubtless that Ossoue Glacier will disappear halfway through the 21st century. Its large, markedly convex, plateau (two thirds of the present-day area) has allowed the accumulation of a significant amount of ice at high altitude (3105 m) during favorable periods. ~~However,~~ On the contrary, its eastern orientation and low shading may have a large influence on the high rate of summer ablation (e.g. in comparison to the Maladeta Glacier). Henceforth, due to the limited interval range of the plateau (3030–3200 m, slope 8°), any future rise of the lower limit of the glacier (2755 m in 2013) would drastically modify the responses of the ~~indicators~~ metrics of Ossoue Glacier to future climate fluctuations.

7 Conclusions

Ossoue Glacier is one of the southernmost glaciers in Europe. Using ~~an exceptional~~ a large archive of historical datasets and recent accurate observations, we generate consistent time series of various glacier ~~indicators~~ metrics, such as length, area, elevation variations, and mass changes since the LIA at high temporal resolution. The dominant trend is a retreat over the 20th century, which was interrupted by two stable ~~periods, 1906–1924 and 1960–1983.~~ short-periods, 1890–1894 and 1905-1913, and a longer stable period, 1950–1983.

The evolution of Ossoue Glacier is in good agreement with those of other Pyrenean glacier reconstructions (Maladeta, Coronas, Taillon glaciers), suggesting the possibility of long-term high-elevation climate reconstruction in the Pyrenees. The comparison between Pyrenean and Alpine glacial fluctuations highlights similar multidecadal variations during the 20th century. The ice depletion was particularly intense in the 1940s and since the 1980s, while a stable period detected at the end of the 1970s is also evident in all the glaciers from both mountain ranges. This result may suggest that there is a common climatic driver governing glacier fluctuations of both mountain ranges.

The time resolution of the generated metrics for Ossoue Glacier allows us to extract consistent glacial changes over various periods. These periods appear to be roughly in phase with hemispheric climate proxies, such as the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation. The 1960–1980 stable period may be partially explained by anti-correlation to the NAO index. We found that the ablation rate may have doubled in the last decade, likely as a result of the recent climate warming.

The evolution of Ossoue Glacier is in good agreement with that of other Pyrenean glacier reconstructions (Maladeta, Coronas, Taillon Glaciers) suggesting the possibility of long-term high-elevation climate reconstruction in the Pyrenees.

The time resolution of the generated indicators allows us to extract consistent glacier changes over various periods. These Ossoue Glacier fluctuations generally concur with climatic data, suggesting that Ossoue Glacier is a good regional climate proxy. However, it remains difficult to isolate the relative contribution of precipitation and air temperature changes to the reconstructed mass balance variations. This could be achieved with a temperature index model or a more sophisticated glacier model (e.g., Gerbaux et al., 2005).

The eastern orientation and low shading of Ossoue Glacier make it particularly vulnerable to climate fluctuations, although its relatively high elevation supports large amounts of snow accumulation . Windblown snow could also increase accumulation on some parts of the glacier.

Future studies should focus on topo-climatic drivers of Ossoue Glacier mass balance in an effort to better understand the link between its past temporal evolution and regional climate change.

More generally, retreat of Pyrenean glaciers could affect local ecosystems by diminishing the beta diversity in Pyrenean streams (Finn et al., 2013). Natural patrimony and the visual perception of the high mountain landscape could also be irrevocably affected (?Moreau, 2010; René, 2013)has allowed the accumulation of a significant amount of ice at high altitudes. In 2013, the maximum ice thickness was 59 ± 10.3 m. Assuming that the current ablation rate stays constant, Ossoue Glacier will disappear midway through the 21st century.

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Table 1. Meta-data of Ossoue Glacier topographic survey. Ci indicates the contour interval (m) of the topographic maps. The last column refers to random errors calculated for each type of metric measurements. For volumetric measurements, we give the random error at the elevation associated with the DEM.

Metric	Period	Method	Source characteristics	Institution (surveyed by)	Estimated error
Length variations	1850	Moraine observation	Glacier deposits	Association Moraine	10 m
	1885	Photointerpretation	Photograph	Vallot J.	10 m
	1889–1895	Length measurements (field)	–	Bonaparte R.	10 m
	1904–1928	"	–	Gaurier L.	10 m
	1935–1953	"	–	Eaux et Fôrets	5 m
	1957	Photointerpretation	Aerial image	IGN	10 m
	1962; 1970	"	Photograph	Grove JM; Jolfre J.	5 m
	1982–1986; 1990	"	"	GEGP; Clos B.	3 m
	1995	"	Aerial image	IGN	3 m
	2001–2013	Field observation	–	Association Moraine	1 m
Area variations	1850	Moraine contour digitalization	Glacier deposits	Association Moraine	10 ha
	1851	Glacier contour digitalization	Etat-Major map	French army	20 ha
	1924; 1948	"	Aerial images	IGN	4 ha
	1950; 1953	Field measurements	–	Eaux et Fôrets	5 ha
	1983; 1988; 1992	Glacier contour digitalization	Aerial images	IGN	4 ha
	2002–2011	Topographic survey	GPS	Association Moraine	2 ha
Height variations at Villa Russell	1881–1895	Height measurements (field)	Artificial cave	Russell H.	0.8 m
	1901–1913	"	"	Gaurier L.	0.5 m
	1927; 1937	"	"	Gaurier L. Chenuau	0.5 m
	1945–1953	"	"	Eaux et Fôrets	0.5 m
	1983–1987	"	"	GEGP	0.5 m
	2002–2013	"	"	Association Moraine	0.5 m
Volumetric measurements	1924	Terrestrial photogrammetry (DEM)	1 : 20 000 map; Ci = 20 m	A. Meillon	8.6 m
	1948	Airborne photogrammetry (DEM)	1 : 2500 map; Ci = 2 m	IGN; GEGP	2 m
	1983	"	1 : 2500 map; Ci = 2 m	IGN; GEGP	1.6 m
	2006	Topographic survey (DEM)	DGPS; Base < 1 km	Sissyphe-EGID	1.5 m
	2006	"	GPR; 50 Mhz Antenna	–	6 m
	2013	"	DGPS; Base < 40 km	GEODE-CESBIO	0.6 m
	2013	Satellite photogrammetry (DEM)	Pléiades stereo pair	CNES	1.8 m

Table 2. Ossoue Glacier volumetric variations (ΔV_{ice} in km^3) and associated cumulative geodetic mass balance $B_{\text{geod.PoR}}$ (in m w.e.) and geodetic mass balance rate $B_{\text{geod.a}}$ (in m w.e. a^{-1}). We considered a mean density of $d = 850 \pm 50$ kg m^{-3} for 1948–1983 and 1983–2001, and 900 kg m^{-3} otherwise. The term $\overline{\sigma_{\text{geod.total.a}}}$ refers to the annualized randoms error.

Period of Records (PoR)	1924–1948 (24)	1948–1983 (35)	1983–2013 (30)
ΔV_{ice}	-0.0324 km^3	$+0.0044$ km^3	-0.0219 km^3
$B_{\text{geod.PoR}}$	-34.1 m w.e.	$+4.8$ m w.e.	-31.3 m w.e.
$B_{\text{geod.a}}$	-1.42 m w.e. a^{-1}	$+0.13$ m w.e. a^{-1}	-1.04 m w.e. a^{-1}
$\overline{\sigma_{\text{geod.total.a}}}$	± 0.37 m w.e. a^{-1}	± 0.07 m w.e. a^{-1}	± 0.06 m w.e. a^{-1}

Table 3. Ossoue Glacier mass balance time series measured by glaciological methods (in m w.e.). End_w and End_s refer to the end of winter and the end of summer, respectively, in the floating date system (Cogley et al., 2011). $B_\text{glac,a}$ means annual glaciological mass balance, B_w refers to the winter mass balance, and B_s refers to the summer mass balance.

Year	End_w	End_s	B_w	B_s	$B_\text{glac,a}$
2002	30 May	03 Oct.	2.09	−2.93	−0.85
2003	6 Jun.	27 Sept.	3.23	−4.11	−0.88
2004	29 May	10 Oct.	3.55	−4.77	−1.22
2005	28 May	25 Sept.	2.58	−5.07	−2.49
2006	25 May	08 Oct.	1.95	−4.66	−2.71
2007	25 May	20 Oct.	2.66	−4.04	−1.38
2008	06 Jun.	12 Oct.	3.24	−3.35	−0.12
2009	30 May	12 Oct.	3.15	−4.78	−1.63
2010	29 May	09 Oct.	3.01	−3.47	−0.46
2011	28 May	09 Oct.	2.12	−4.56	−2.44
2012	26 May	14 Oct.	2.36	−5.78	−3.42
2013	07 Jun.	06 Oct.	3.79	−3.57	+0.23
Mean 2001–2013	-	-	2.81	−4.26	−1.45

Table 4. Meta-data of glacier variations from the literature used in this study for comparison between Ossoue and others Pyrenean and Alps glacier fluctuations.

Glacier name	Id number on figure	Main metric	Distance from Ossoue	Publication
Taillon	1	Length Variations	30 km	(Gellatly et al., 1994)
Maladeta	2	Area variations	80 km	(Chueca et al., 2003)
Coronas	3		80 km	(Cía et al., 2005)
Saint Sorlin	4	Glaciological mass balances	550 km	(Vincent, 2002; Six et al., 2014)
Gébroulaz	5	"	600 km	"
Argentières	6	"	650 km	"
Mer de Glace	7	"	650 km	"
Sarennes	8	"	550 km	(Thibert et al., 2013)
Swiss glaciers (30)	9	Geodetic mass balances	> 700 km	(Huss et al., 2010)

Table 5. Correlation matrix (Spearman's ρ_s) between the meteorological time series and Ossoue Glacier mass balances components after linear trends removal (calculated in a fixed date system, Cogley et al., 2011). Correlation values given in parenthesis are based on the monthly mean values. Significant correlations (p values < 0.05) are marked with asterisks. The Gavarnie time series was not complete enough to perform the correlations between the annual mass balance and the annual mean temperature and precipitation over 2002–2011; we reported a no data value (ND) in these cases.

Variables	$B_{glac.a.1\ Oct}$ mass balance	$B_{s.1\ Oct}$	$B_{w.31\ May}$	Gavarnie temperature	Pic du Midi	CRU	Gavarnie precipitation	Tarbes
Period of record	2002–2013			1992–2012	1882–2013	1858–2013	1992–2012	1882–2012
$B_{glac.a.1\ Oct}$	1	0.84*	0.65*	ND	−0.57	−0.66*	ND	0.74*
$B_{s.1\ Oct}$		1	0.2	−0.76* (−0.8*)	−0.71* (−0.75*)	−0.72* (−0.8*)	–	–
$B_{w.31\ May}$			1	ND	−0.38	0.15	0.71*	0.72*

Table 6. Mean temperature (Pic du Midi, 2874 m), mean precipitation (Tarbes, 374 m), and correlations between mean temperature and precipitation time series and time (Spearman's ρ). Time ranges are based on the interpretation of the glacier metrics (Fig. 9). Significant correlations (p values < 0.05) are marked with asterisks. For 1858–1890, the mean temperature is based on the CRU dataset.

Time range (Glacier periods)(Number of years)	Period of the year	Mean temperature	Mean precipitation	ρ_s temperature	ρ_s precipitation
1858–2013 (T °C) (131 y.) 1882-2013 (P mm)	hydrological year	−1.1 °C	1067 mm	0.38*	-0.16
	winter	–	556 mm	–	0.1
	summer	+5.3 °C	–	0.28*	–
1858–1890 (T °C) (I) (32 y.)	h. year	−1.3 °C	–	−0.6*	–
	s.	+5.8 °C	–	−0.36	–
1890–1894 (II.a) (4 y.)	h. year	− 1.4 °C	1071 mm	–	–
	w.	–	571 mm	–	–
	s.	+4.6 °C	–	–	–
1905–1913 (II.b) (8 y.)	h. year	−1.8 °C	1165 mm	–	–
	w.	–	550 mm	–	–
	s.	+4.1 °C	–	–	–
1928–1949 (III) (21 y.)	h. year	−1.2 °C	993 mm	0.23	-0.19
	w.	–	493 mm	–	-0.2
	s.	+5.1 °C	–	0.26	–
1950–1982 (IV) (32 y.)	h. year	−1.4 °C	1068 mm	0.13	0.4*
	w.	–	586 mm	–	0.28
	s.	+4.8 °C	–	0.1	–
1983–2013 (V) (30 y.)	h. year	−0.4 °C	1042 mm	0.39*	−0.12
	w.	–	567 mm	–	−0.14
	s.	+6.1 °C	–	0.43*	–

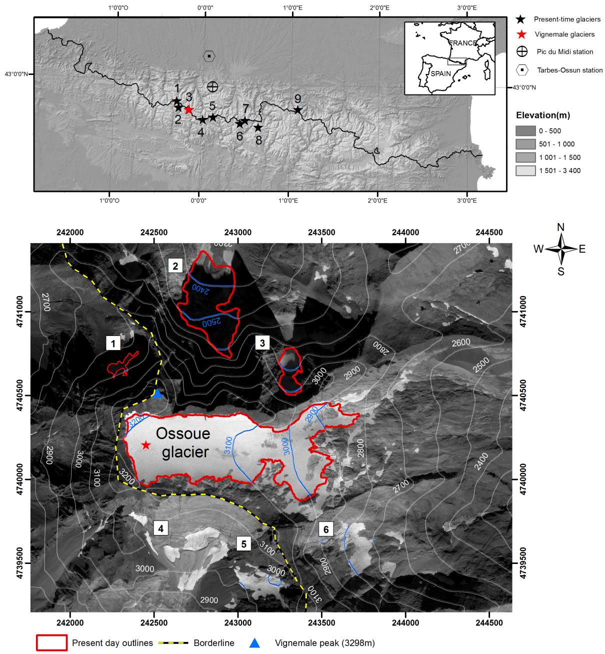

Figure 1. Top: Distribution of the present-day Pyrenean glaciers by mountain massifs: 1. Balaïtous; 2. Infierno; 3. Vignemale; 4. Gavarnie-Monte-Perdido; 5. Munia; 6. Posets; 7. Perdiguère; 8. Aneto; 9. Mont-Valier. Bottom: Vignemale Glacieret: 1. Clo de la Hount. Glaciers: 2. Oulettes du Gaube; 3. Petit-Vignemale and Ossoue. Vanished glaciers: 4. Spanish Monferrat; 5. Tapou; 6. French Montferrat. We note that the vanished glaciers were oriented to the southwest and east. Clo de la Hount is northwest-oriented and its area is less than 0.01 km^2 (2011). North-oriented glaciers Oulettes du Gaube, 0.13 km^2 (2011), and Petit Vignemale, 0.03 km^2 (2011), were one unique glacier until 1888 (Reid-Muret, 1906). Coordinate system: UTM 31° N.

Figure 2. Photo-comparison of Ossoue Glacier (Vignemale Massif): left, 1911 (Gaurier L.); right, 2011 (René P.).

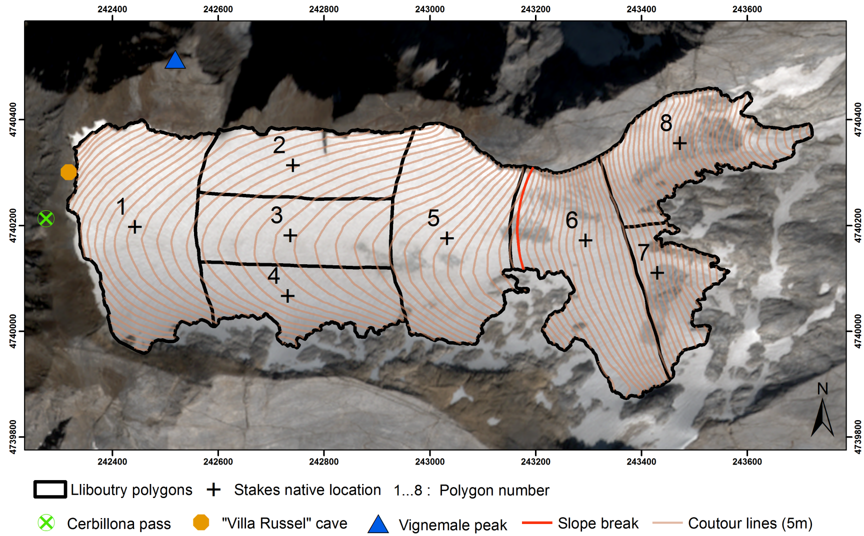

Figure 3. Distribution of stakes at Ossoue Glacier. CNES©image Pléiades MS-09-23-2013. UTM 31° N projection.

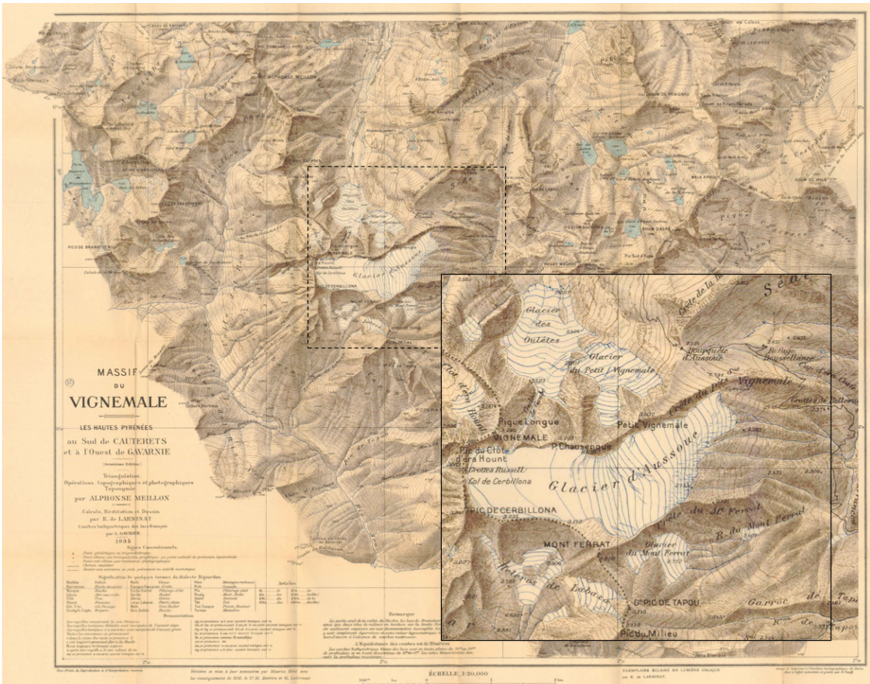

Figure 4. Map designed by Meillon and Larminat, with focus on Vignemale Glaciers, 1933 edition (Glacier data are from 1924).

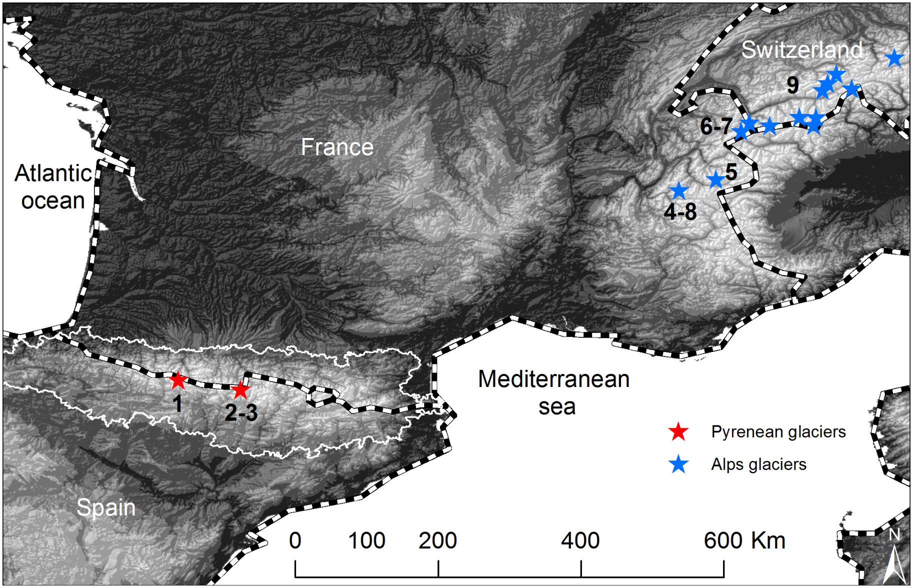

Figure 5. Location of the glaciers used for comparison with Ossoue glacier fluctuations.

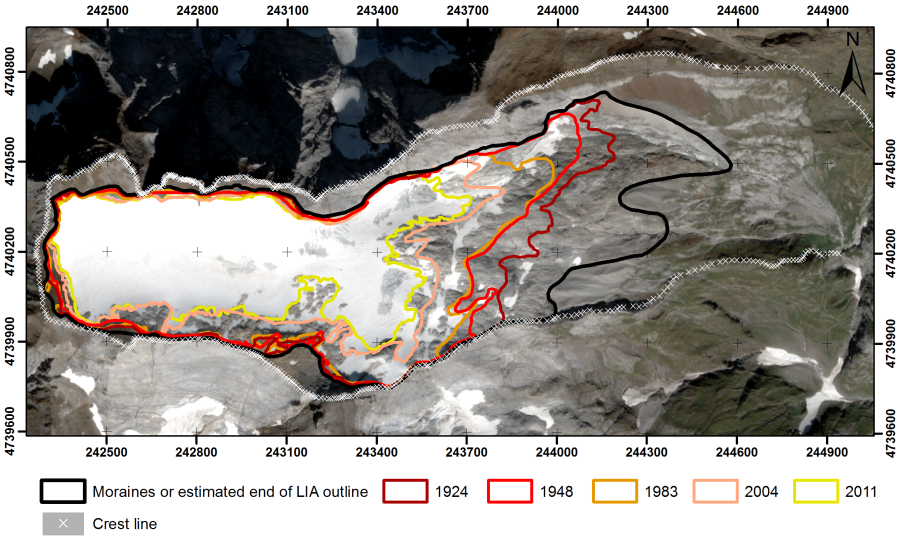

Figure 6. Evolution of Ossoue Glacier area since the LIA. The glacier outlines are superposed on a multispectral Pléiades ortho-image taken on 23 September 2013. UTM 31° N projection.

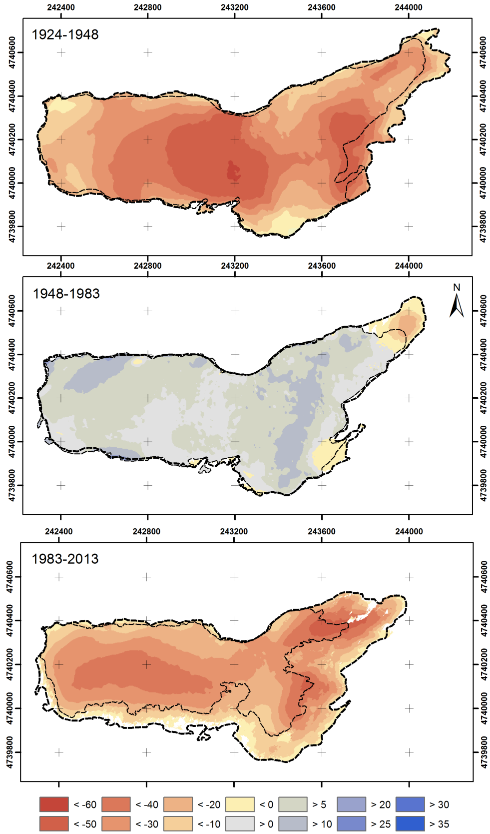

Figure 7. Elevations differences (m) on glacier (thin dashed line) and on deglaciated margins (thick dashed line) based on differences between consecutive DEMs. UTM 31° N projection.

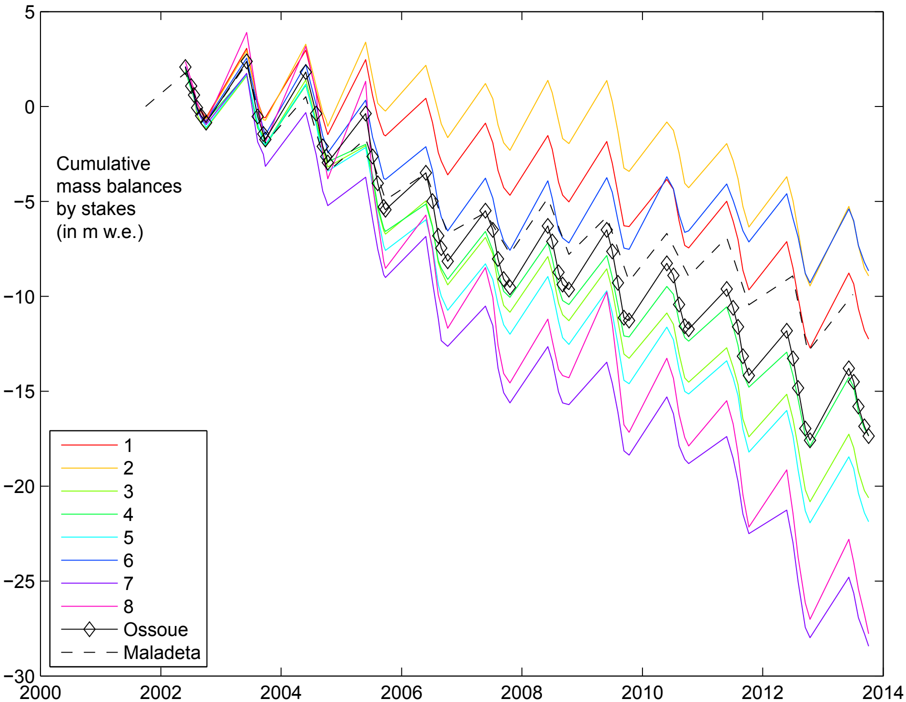

Figure 8. Glacier surface elevation variations in m w.e. at Ossoue stake locations from 2001 to 2013. For details of stake locations on the glacier, see Fig. 3 and supplementary. Maladeta Glacier is indicated by the dashed gray line.

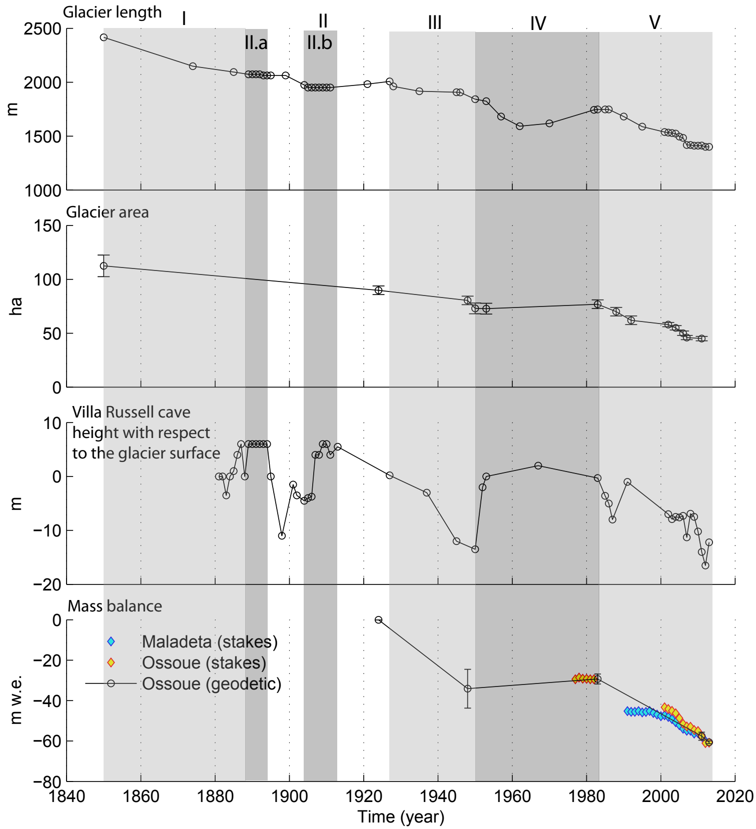

Figure 9. Length (m), area (ha) and thickness (m) at Villa Russell and mass changes (in m w.e.) of Ossoue Glacier. Glaciological mass balances of Ossoue (orange) and Maladeta (blue) Glaciers. The background color indicates the interpreted trend of the period, according to the metrics variations (see Sect. 5.1). In light gray, the ice depletion periods (I, III, V). In dark gray, the periods of accumulation or stability (II.a, II.b, IV).

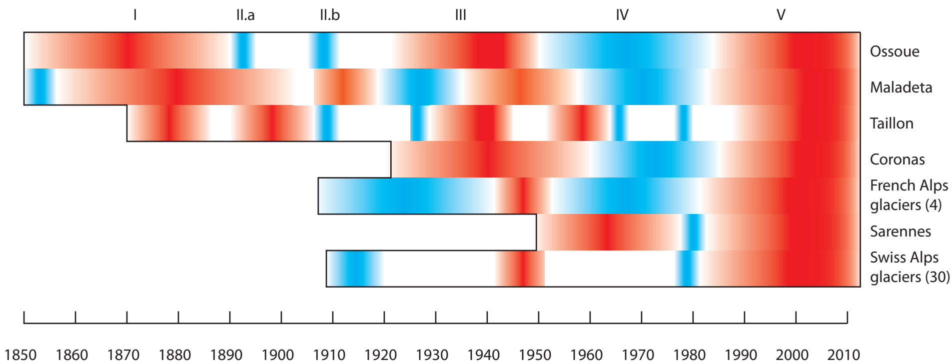

Figure 10. Comparison of Ossoue glacier fluctuations with others Pyrenean and Alps glaciers reconstructions. In red, the ice depletion periods. In blue, the accumulation or stable periods. In white, periods considered as "undertermined". The meta-data relative to the glaciers fluctuations are given in the table 4. For the localization of the glaciers, please refer to the figure 5. Roman numerals above Ossoue Glacier fluctuations refer to the mains periods of variation identified (Sect. 5.1).

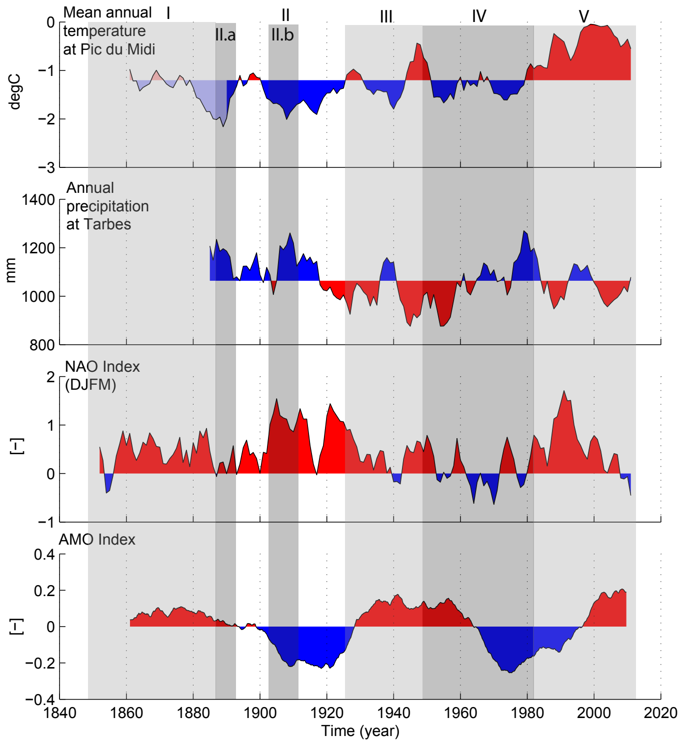

Figure 11. Climatic time series: mean annual temperature at Pic du Midi (beginning 1 October), annual precipitation at Tarbes, AMO mode and winter NAO (DJFM) anomalies. The background color indicates the interpreted trend of the period, according to the metrics variations (see Sect. 5.1 and Fig. 9). In light gray, the ice depletion periods (I, III, V). In dark gray, the periods of accumulation or stability (II.a, II.b, IV).

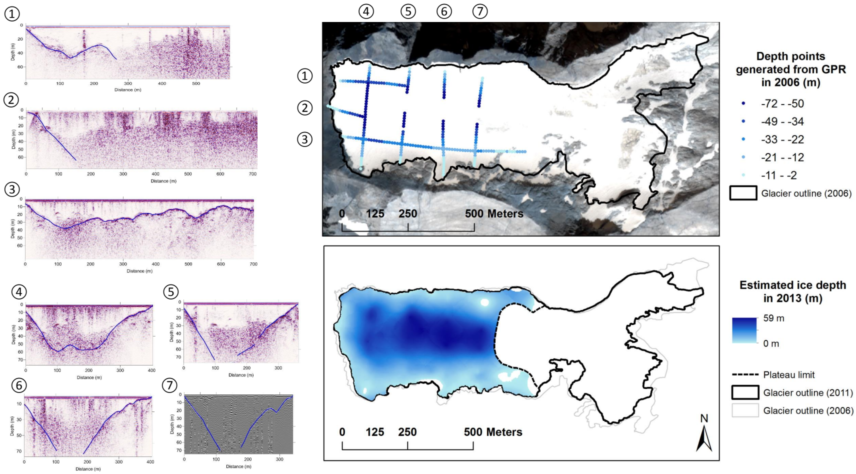

Figure 12. Map: Bedrock depth as interpreted from GPR radargrams plotted atop a 2013 XS Pléiades image. Numbers 1 to 3: interpretations of longitudinal radargram acquisitions. Numbers 4 to 7: interpretations of transverse radargram acquisitions.

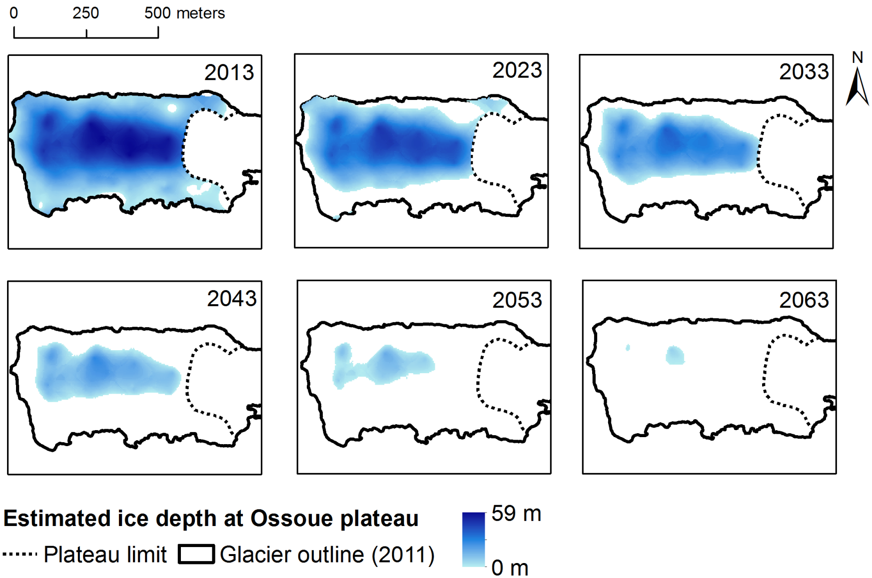

Figure 13. Map: Estimated ice depth at Ossoue plateau in the next decades. This projections are based on the sum of the ice depth estimation (measured by GPR, see Fig. 12) and of the cumulative mass balance over the period of projection. This later is based on the interpolation values of the averaged mass balance at stake location over 2001-2013 (data per year and stakes are given in figure 8). Spatial resolution is 4 m. Right from the plateau limit (dashed line), the ice depth was unknown in 2013.