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CURRENT GLACIER AREA IN THE PYRENEES: AN UPDATED ASSESSMENT 2016

Superficie glaciar actual en los Pirineos: Una actualización para 2016

Ibai Rico[1,2]*, Eñaut Izagirre[3]*, Enrique Serrano[4], Juan Ignacio López-Moreno[2]

[1] Dept. of Geography, Prehistory and Archaeology, University of the Basque Country, Vitoria-Gasteiz, Spain
[2] Dept. of Geoenvironmental Processes and Global Change, Pyrenean Institute of Ecology-CSIC, Jaca-Zaragoza, Spain
[3] Dirección de Programas Antárticos y Subantárticos, Universidad de Magallanes, Punta Arenas, Chile
[4] Dept. of Geography, University of Valladolid, Valladolid, Spain

Identificador ORCID de los autores y e-mail:
Ibai Rico: http://orcid.org/0000-0003-4615-0488. E-mail: ibai.rico@ehu.eus
Eñaut Izagirre: http://orcid.org/0000-0001-8502-7824. E-mail: izagirre.enaut@gmail.com
Enrique Serrano: http://orcid.org/0000-0001-9760-3876. E-mail: serranoe@fyl.uva.es
Juan Ignacio López-Moreno: http://orcid.org/0000-0002-7270-9313. E-mail: nlopez@ipe.csic.es
*Autores corresponsales.

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ABSTRACT: Glacier area studies in the Pyrenees reported over 2000 ha in 1850, 806.5 ha in the 1980s and 310.33 ha in 2008. In this work we carried out an updated (2016) estimation of the current glacier area of the Pyrenees, based on remote sensing and contrasted with in-situ observations of the most representative glaciers. Our results yield a glacier area of 242.06 ha for 2016. This implies a reduction of 88.25 % since 1850, and a rapid wastage since 1980s, confirming the accelerated shrinkage during the end of the 20th century and the first decade of the 21st century.

KEYWORDS: Glacier Area; Pyrenees; Global Change.

RESUMEN: Los estudios de superficie glaciar en los Pirineos han informado de más de 2000 ha en 1850, 806,5 ha en la década de 1980 y 310,33 ha en 2008. En este trabajo hemos llevado a cabo una estimación actualizada (2016) de la superficie de los glaciares actuales en los Pirineos, a partir de imágenes satelitales contrastadas con observaciones "in situ" de los glaciares más representativos. Nuestros resultados dan una superficie glaciar de 242,06 ha para el año 2016. Esto implica una reducción del 88,25% desde 1850 y una rápida disminución desde la década de 1980, lo que confirma el acelerado declive durante el final del siglo XX y la primera década del siglo XXI.

PALABRAS CLAVE: Superficie Glaciar; Pirineos; Cambio Global.

1. Introduction

Mountain glaciers are key indicators of global climate change (IPCC, 2014). Small glaciers (<0.5 km^2) account for more than 80% of the total number of glaciers in mid- to low-latitude mountain ranges; although their total area and volume is small compared to larger glaciers, they are a relevant component of the Cryosphere, contributing to landscape formation, local hydrology and sea-level rise (Huss & Fischer, 2016). The glaciers and ice-patches located in the southwestern European mountains, between 44º N and 41º N, are facing continuous negative mass-balance since several decades (Grove, 2004), and are being recognized as highly sensitive geo-indicators of climatic variations (Grunewald & Scheithauer, 2010).

In the Iberian Peninsula glaciers only remain in the Pyrenees (42º-43º N; 2º-3º E; Fig. 1). These glaciers have been studied mostly since the 1980's (Schrader, 1936; Martínez de Pisón & Arenillas, 1988; Tihay, 1992; Chueca & Lampre, 1994; Serrat & Ventura, 1993; Serrano *et al.,* 2002; González-Trueba *et al.,* 2008; Chueca *et al.,* 2005; René, 2016; Marti *et al.,* 2015a; López-Moreno *et al.,* 2016; Rico *et al.,* 2012, 2014, 2016). Glacier surface area was estimated in 2060 ha for 1850 (René, 2013), 810.33 ha in early 80s (Serrat &Ventura, 1993; Arenillas-Parra *et al.,* 2008) and 495 ha in 2008 (the latter using data from studies in the 80s and early 2000s; Gonzalez Trueba *et al.,* 2008). This was homogenized by René (2013) and others that estimated 321 ha of glacier surface area for 2008 based data from Arenillas Parra *et al.* (2008) and original measurements (this has been corrected in this work to 306.5 ha by cross-checking with other studies and disregarding ice-masses acknowledged as ice-patches). In a recent work, Marti *et al.* (2015b) yielded an overall estimation glacier area of 300 ha for 2011 but with no specific data about each glacial body.

At present, the latest detailed available glacier surface area calculation is nearly 9 years old and thus and updated appraisal of glacier change for the whole Pyrenees is long overdue. This work aims to better understand the current global state of the Pyrenean glaciers by carrying out a calculation of glacier area and the number or current glacier bodies in 2016. This will allow us to contextualize the present day glacier's behaviour compared with the previous periods 1850-1984, 1984-2008 and 2008-2016 (from the information published in Serrat & Ventura 1993, René 2013 & Arenillas-Parra *et al.,* 2008).

2. Material and Methods

Glacier surface area is a recognized method for glacier monitoring (Bahr *et al.,* 1997; WGMS, 2008), providing wide-scale estimates of glacier changes. In order to infer current glacier areas in the Pyrenees we have used a combination of remote sensing techniques with field observations in the most representative glaciers.

2.1. Remote Sensing Imagery

The Sentinel-2 (28th September 2016) images have been obtained from the Copernicus European Space Agency with a 10 m (Cloud-free) resolution. However, it's common to have shadowed areas in the accumulation part of the glacier, due to the steepness of the headwalls in the glacier cirques. Thus, glacier delineation has been combined with recent ortophotos to measure the glacier's outline in the accumulation area. We have used the available ortophotos from PNOA (Plan Nacional de Ortofotografía Aérea) for the Spanish side (2015), and the *Institute National de la Information Geographique* for the French side (2013), both of them at a spatial resolution of 5 m. We assume little impact of using two slightly different dates for Spanish and French glaciers, accounting that accumulation areas do not vary substantially in the short-term. All the images were overlaid on a mosaic of SRTM-3 (Shuttle Radar Topographic Mission) stereoscopic images of the USGS (United States Geological Service).

2.2. Glacier delineation and field observations

Delineation of the glacier outlines has been corroborated in a selection of the most representative glaciers. During the fieldwork campaigns from 2010 to 2016 we visited 12 bodies out of the 19 current glaciers of the Pyrenees in the massifs of Infiernos, Vignemale, Gavarnie-Monte Perdido, Posets and Maladeta-Aneto. The *in situ* observations and pictures have been essential to cross-check the state of the glaciers on these massifs, including observations about debris cover processes, rock falls, aparition of rock outcrops, glacier split-ups, crevasses development and extinction and glacier front retreat.

2.3. Glacier area errors

This error can be calculated according to Williams *et al.* (1997), whereby to pixel size, or image resolution, is multiplied by the perimeter of the digitized polygon. Area calculation errors (Ae) are based on pixel sizes (n), which multiplied by ice area perimeter length (p), results in maximum area errors below the calculated areas for each of the 19 major glaciers, following Eq. (1):

$$Ae = \pm n \cdot p$$

Dividing this area calculation error, , by the calculated glacier area and multiplying by 100 provides the percentage error for each measured ice body. Overall there is moderate variability throughout the database with averaged inaccuracy for the entire ice/glacier inventory calculated as ~5 %.

3. Results and Discussion

Delineation of glacier outlines based on 2016 imagery, cross-checked with in-situ visits to the glaciers has allowed an updated estimation of current glacier area in the Pyrenees (Table 1). The calculations yield a total glacier

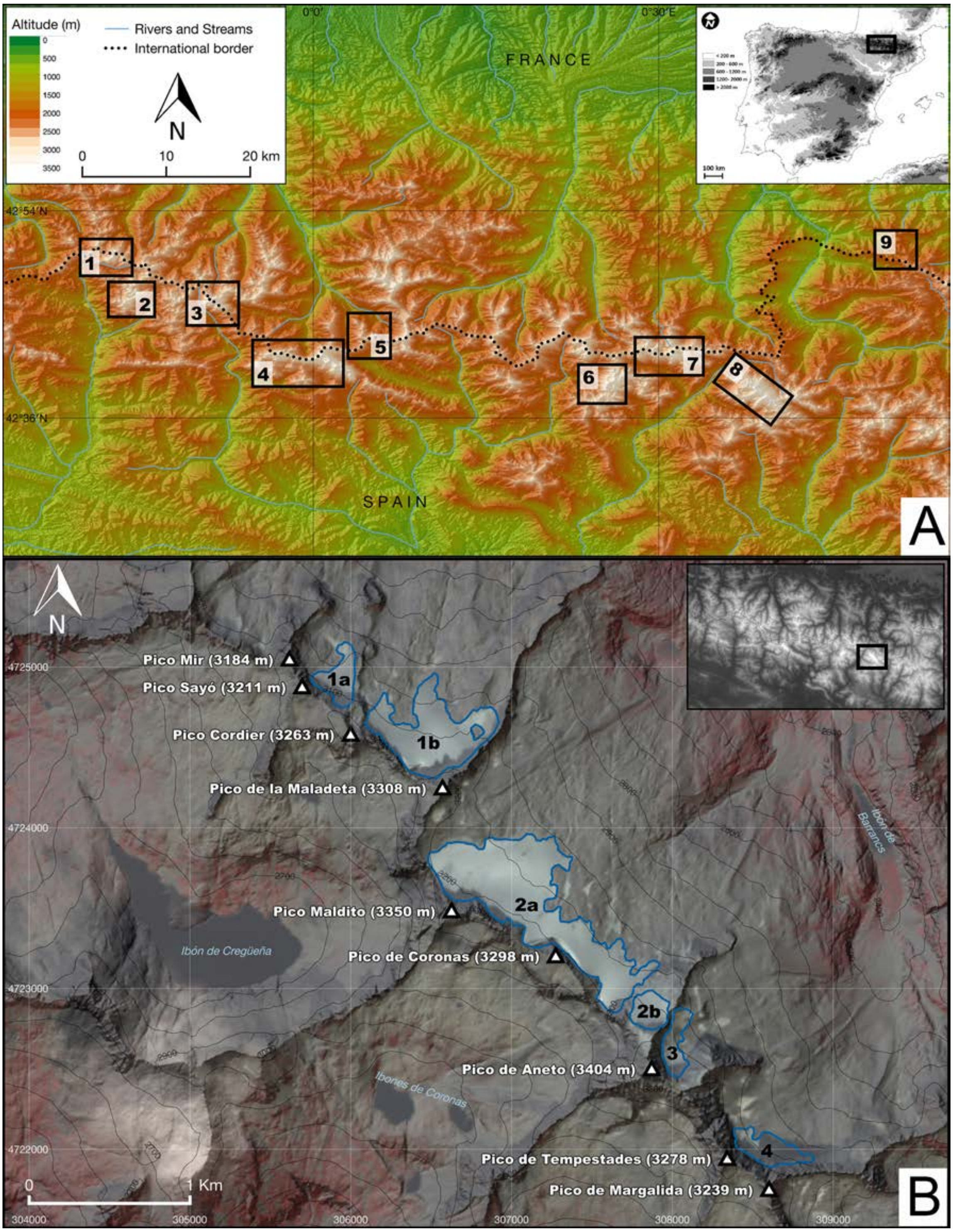


Figure 1: A. Location of the current glaciated massifs in the Pyrenees: Balaitous (1), Infiernos (2), Vignemale (3), Gavarnie-Monte Perdido (4), La Munia (5), Posets (6), Perdiguero (7), Maladeta-Aneto (8) and Mont Valier (9). Source: Elaborated from SRTM (USGS). B: An example of glacier delineation based on Sentinel-2 images from September 2016 for the Maladeta-Aneto massif, the most glaciated massif in the Pyrenees with 96.37 ha at present.

Figura 1: A. Ubicación de los macizos con glaciares actuales en los Pirineos: Balaitous (1), Infiernos (2), Vignemale (3), Gavarnie-Monte Perdido (4), La Munia (5), Posets (6), Perdiguero (7), Maladeta-Aneto (8) y Mont Valier (9). Fuente: Elaborado a partir de SRTM (USGS). B: Un ejemplo de delimitación glaciar a partir de imágenes Sentinel-2 de septiembre 2016 para el macizo de Maladeta-Aneto, que es el macizo que cuenta con la mayor superficie glaciar en los Pirineos con 96,37 ha en el presente.

Massif	Glacier Name	1850 (ha)	1984 (ha)		2008 (ha)		2016 (ha)	
		Massif	Glacier	Massif	Glacier	Massif	Glacier	Massif
Balaitous	Las Neus	**90**	28	**38**	8	**8**	3,8	**3,8**
	Pabat		10					
	Frondiellas							
	Brecha La Tour							
	Balaitous SE							
Infiernos	Infierno Central	**50**	9	**15**	6	**6**	5,73	**5,73**
	Infierno Oriental		6					
Vignemale	Ossoue	**180**	70	**106**	46	**62,5**	37,22	**46,21**
	Oulettes de Gaube		18		13		6,19	
	Petit Vignemale		12		3,5		2,8	
	Monferrat		6					
	Clot de la Hount							
Gavarnie-Monte Perdido	Gabietous	**455**	26	**165**	8	**62**	7,59	**53,9**
	Taillon		26		12		8,54	
	Pailla Oeste		15		3,5			
	Pailla Este							
	Astazous		8,5					
	Cascada		5,6					
	Marbore W		11,6					
	Brecha Roland		12,3					
	Marbore		7					
	Cilindro		5					
	Monte Perdido		48		38,5		37,77	
	Soum de Ramond SE							
	Soum de Ramond SW							
Pic-Long	Tourrat	**95**	7	**21**		**0**		**0**
	Pays Bache		14					
Munia	Munia	**45**	6,2	**11,2**	4	**4**	4	**4**
	Barroude							
	Robiñera		5					
Posets	La Llardana	**110**	23	**47,33**	9	**18**	7,56	**13,64**
	La Paul		11,33		7		6,08	
	Posets		13		2			
Perdiguero	Gourg Blancs	**420**	27	**133,5**		**23,5**		**16,41**
	Seil de la Baque Oeste		39		2			
	Seil de la Baque Este				11,5		8,86	
	Portillon dÓo		16,4		4		3,1	
	Boum		14		6		4,45	
	Cabrioles		17,5					
	Maupas		10,6					
	Graoues		9					
	Literola							
Maladeta-Aneto	Maladeta	**610**	60	**272**	33	**120**	29,38	**96,37**
	Aneto		132		69		56,1	
	Barrancs		28		8		4,48	
	Tempestades		34		10		6,41	
	Salenques		5					
	Coronas		13					
	Alba							
	Cregueña							
	Llosas							
Mont-Valier	Mont Valier	**5**	5	**5**	2	**2**	2	**2**
TOTAL AREA		**2060**		**810,33**		**306,5**		**242,06**
TOTAL Nº GLACIERS		**52**		**39**		**22**		**19**

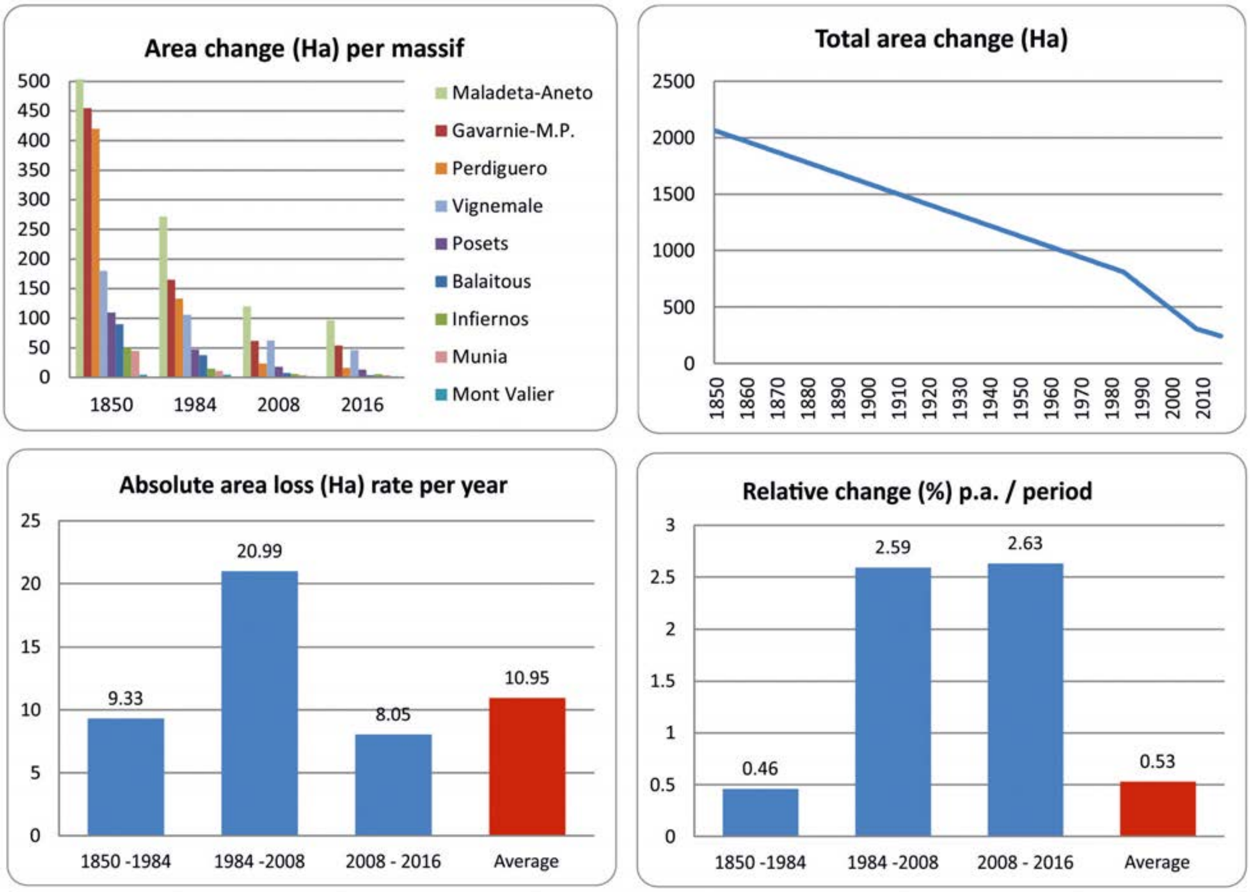
Table 1. Area changes and total number of glaciers for each massif and individual ice-mass in 1850 (René, 2013), 1984 (Serrat & Ventura, 1993; Arenillas Parra *et al.,* 2008, Rico *et al.,* 2016), 2008 (René, 2013; Arenillas Parra *et al.,* 2008) and 2016. The surface of glaciers that have been split up in different ice bodies during the last years have been accounted as a whole in order to facilitate the comparison with previous periods.

Tabla 1. Cambios de superficie y número total de glaciares para cada macizo y cuerpos individuales en 1850 (René, 2013), 1984 (Serrat & Ventura, 1993; Arenillas Parra et al.*, 2008, Rico* et al.*, 2016), 2008 (René, 2013; Arenillas Parra* et al.*, 2008) y 2016. La superficie de los glaciares que se han dividido en independientes cuerpos de hielo durante los últimos años han sido contabilizados como uno sólo con el fin de facilitar la comparación con los períodos anteriores.*

area of 242.6 ha for 2016 (Fig. 2). The current number of glaciers has been established in 19, distributed in 9 different mountain massifs holding substantially different glacier surface areas: Balaitous (3.8 ha); Infiernos (5.73 ha); Vignemale (46.24 ha); Gavarnie – Monte Perdido (53.9 ha); Munia (4 ha); Posets (13.64 ha); Perdiguero (16.41 ha); Maladeta-Aneto (96.37 ha) and Mont Valier (2 ha). The largest single glacier is Aneto glacier (42.6311° N, 0.6566° E) with 56.1 ha, and the smallest one is Mont Valier (2 ha).

Comparison of current (2016) glacier area data with previous studies referring to 1850, 1984 and 2008, allow us to carry out a primary estimation of absolute glacier area change for the 166 years, relative (%) change per period and per year (p.a.; absolute and relative) rate of change for the whole 1850-2016 time frame and its subsequent 1850-1984, 1984-2008 and 2008-2016 periods. We also provide the total glacier area waster for each main period (Table 1 and Figure 2).

Since 1850 to 2016 glaciers in the Pyrenees have lost 88.25 % of their area (-1817.94 ha), implying a substantial reduction in the number of glaciers: from 52 to 19. This means an average absolute area loss p.a. of 10.95 ha and 0.53 % reduction p.a. for the whole 166 year period.



Period	Absolute area change (ha)	Area % change relative to 1850	Area % change per period	Area change rate p.a. (ha)	Area % change rate p.a. / period	Area % change rate p.a relative to 1850
1850-2016	1817.94	88.25	88.27	10.95	0.53	0.53
1850-1984	1249.67	60.66	60.66	9.33	0.46	0.46
1984-2008	503.83	24.46	62.18	20.99	2.59	1.02
2008-2016	-64.44	3.13	21.02	8.06	2.63	0.39
1984-2016	568.27	27.59	70.13	17.76	2.19	0.86

Figure 2. Glacier area changes in the Pyrenees. From top-left to bottom; area changes per massif (ha); total area change (ha); absolute area loss rate per year (ha); relative area loss rate per year (%) / period and summary of key data.
Figura 2. Cambios de la superficie glaciar en los Pirineos. De arriba a la izquierda hacia abajo; cambios de superficie por macizo (ha); cambio de área total (ha); tasa de pérdida de área absoluta por año (ha); tasa de pérdida de superficie relativa por año (%) / períodos y resumen de los datos claves.

However, this area change has not been homogeneous and it is possible to infer significant differences. From 1850 to 1984 glacier area changed from 2060 ha to 810.33 ha (number of glaciers reduced from 52 to 39), meaning a 60.66 % of reduction (-1249.67ha) with an absolute area loss rate p.a. of 9.33 ha and a relative area loss rate of 0.46 % p.a. From 1984 to 2016 glacier area was reduced to 242.06 ha (19 glaciers in 2016), representing an area reduction of 70.13 %. Losses p.a. in 1984-2016 increased to 17.66 ha (absolute p.a.) and 2.19 % (relative p.a.).

A closer look to the 1984-2016 period reflects different glacier responses. From 1984 to 2008 glacier area reduced from 810.33 to 306.5 ha (-503.83 ha) and the number of glaciers was declined from 39 to 22. Glacier area (relative to 1984) was reduced 62.18 % in 24 years, with an absolute glacier area loss p.a. of 20.99 ha. This means that in this period (1984-2008), the glacier area in the Pyrenees reduced at a 2.59 % p.a. Also, a reduction of 64.44 ha in 8 years has been detected from 2008 to 2016, implying an area reduction of 21.08 % in 8 years (2.63 % p.a.) and an absolute area loss rate of 8.06 ha p.a. Total number of glaciers has decreased from 22 to 19 since 2008. The acceleration of glacier´s shrinkage during this period matches well with the tendency of majority of the glaciers in world. Thus, Marshall (2014) and Zemp *et al.* (2015) reported that loss of global glacier mass during the late nineties (20th century) and the first decade of the 21st century exceeded that of any other decade studied since the end of the LIA.

Glacier area losses after the 80's have therefore doubled the rates of the 20th century (from 9.33 ha p.a. to 17.76 ha p.a. in the 1984-2016 period). The absolute area losses were remarkably greater in the 1984-2008 period (20.99 ha), that in the last 8 years (8.06 ha). Relative losses per period (area %) do not differ substantially (2.58 % p.a. change for 1984-2008 and 2.63 % p.a. for 2008-2016) but observing the absolute are change p.a. relative to 1850 a clear acceleration is detected from the 80's and until the first decade of the 21th century (1.02 % p.a.) followed by a noticeable recent slowdown from 2008 until 2016 (0.39 % p.a.).

The reasons for this recent subtle change in the trend could be linked to the recent occurrence of wet and very wet winter episodes with negative NAO (North Atlantic Oscillation) anomalies (Añel *et al.,* 2014), or to the effect of the topoclimatic factors (cirque aspect, altitude and radiation among others). In this way, the remnant ice bodies tend to be confined in the most elevated and protected areas from solar radiation or benefited by large snow accumulations due to avalanches (López-Moreno *et al.,* 2006) which may slow down the current rate of ice losses. The ice loss can be by thinning more than surface loss, as have been seen in Infiernos, Monte Perdido, Vignemale or La Paul, where significant thickness loss has been measured (López-Moreno *et al.,* 2016; Marti *et al.,* 2015a; Rico *et al.,* 2012). The smaller sizes of today glaciers also explain the lower absolute area loss rates p.a. in the last 8-10 years as the relative area losses p.a. for each period do not differ so markedly. Out of the 19 current glaciers, 7 have now less than 5 ha, meaning that many of the Pyrenean glaciers are already housed within their original accumulation areas, protected by the cirque walls, being covered by debris and progressively reducing their motion and dynamic but not varying their area so markedly any more. Glaciers such as La Paul, Mont Valier, Gabietous, Portillon d'Oo or La Munia have not experienced very high glacier area losses in the last years compared to larger glaciers in the same range and close locations. Many of the smallest glaciers of the range are thus not reducing in area substantially but they are losing sings of dynamism and transitioning into motionless ice-patches.

4. Conclusions

The glaciers of the Pyrenees have shown accelerated area loss rates since the 1980's compared to general rates during the 20th century. Average glaciated area loss increased from 10.95 ha per year during the XX century to 17.66 ha per year in the 1984-2016 period. In absolute terms most of the glacier melting acceleration seems to have taken place from 1984 until 2008 (20.99 ha loss per year), whilst recent area losses have reduced to 8.06 ha per year in the 2008-2016 period. Relative changes (%) per year do not differ so significantly and remain around 2.5 % of the total glacier area melted every year in the 1984-2016 period – in any case substantially higher than the 0.46% loss per year value of the 1850-1984 period. The current 19 remaining glaciers are therefore showing severe loss in area and length, burials and several of them a progressive transformation into motionless ice patches. Disentangling the effect of climate variability from the incidence of topoclimatic factors will be critical to better understand the evolution of the Pyrenean glaciers in the context of global change.

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