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AN EXTREME EVENT BETWEEN THE LITTLE ICE AGE AND THE 20TH CENTURY: THE SNOW AVALANCHE CYCLE OF 1888 IN THE ASTURIAN MASSIF (NORTHERN SPAIN)

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ABSTRACT. *Between the late Little Ice Age (LIA) cold stage and the early 20th century warmer scenario, a transitional regime characterized by an unstable climatic pattern generated a series of climate extremes affecting mid-latitude mountainous areas, as the Asturian Massif. There, the 1888 snow avalanche cycle appears as the most significant event, standing out among the rest of avalanche cycles recorded in this area during the 1800-2015 period both in terms of the number of damaging avalanches and damages caused by them. Among the factors that explain this event stands out the orographic precipitation phenomenon; the interaction of a cold and wet air mass originating from the North Atlantic with the relief of the Massif, which led to extraordinary snow thicknesses (>2 m) at very low altitudes (500 m a.s.l.), especially in the north-facing, Asturian versant of the Cantabrian Mountains. This allowed the triggering of avalanches in slopes gentler and in lower altitudes than usual, covering longer distances; consequently, avalanches reached more easily the settlements, generally placed at the bottom of the valley or in middle slope positions. The greater impact on the settlements, which suffered 84% of the damages, was the cause of this episode's high socioeconomic impact (29 people dead, 34 injured, 123 heads of cattle dead, 124 buildings destroyed). These events occurred at a time when the mountain villages were highly populated and subjected to intense exploitation, coinciding with the development of new communication infrastructures in the upper parts of the Massif. Therefore, the 1888 episode constitutes a good example of both the impact of hydrometeorological events in mountain environments under high demographic pressure, and of climate extremes involved in a transition period from cold to warmer weather conditions.*

Un evento extremo entre la Pequeña Edad de Hielo y el siglo XX: el ciclo de avalanchas de 1888 en el Macizo Asturiano (norte de España)

RESUMEN. *Entre la Pequeña Edad de Hielo (PEH) y las primeras décadas del siglo XX, un régimen de transición climática caracterizado por su inestabilidad generó una serie de eventos extremos que afectaron a las zonas montañosas de latitudes medias, como el Macizo Asturiano. Allí, el ciclo de aludes de 1888 fue el acontecimiento más significativo, destacando entre el resto de ciclos de avalanchas registrados en esta área entre 1800 y 2015 tanto por el número de avalanchas dañinas que se registraron como por los daños que estas causaron. Entre los factores que explican este acontecimiento destaca el fenómeno de las precipitaciones orográficas; la interacción de una masa de aire frío y húmedo (procedente del Atlántico Norte) con el relieve del Macizo, condujo a espesores de nieve extraordinarios (> 2 m) a muy bajas altitudes (500 m s.n.m.), especialmente en la vertiente asturiana (orientada al norte). Esto permitió el desencadenamiento de avalanchas en pendientes más suaves y a altitudes más bajas de lo habitual, cubriendo distancias más largas que en otros episodios. En consecuencia, estas avalanchas alcanzaron más fácilmente los asentamientos, tradicionalmente situados en el fondo del valle o en posiciones de media ladera. El mayor impacto en los asentamientos, que sufrieron el 84% de los daños, fue la causa del alto coste socioeconómico de este episodio (29 personas muertas, 34 heridas, 123 cabezas de ganado muertas, 124 edificios destruidos). Estos acontecimientos ocurrieron en un momento en que los núcleos de montaña estaban muy poblados y sometidos a una intensa explotación, coincidiendo además con el desarrollo de nuevas infraestructuras de comunicación en las partes altas del Macizo. Por lo tanto, el episodio de 1888 constituye un buen ejemplo tanto del impacto de los eventos hidrometeorológicos en ambientes montañosos bajo alta presión demográfica, como de los eventos extremos propios de un período de transición de condiciones climáticas frías a más cálidas.*

Key words: avalanche cycle, climate extremes, great blizzard, Little Ice Age, orographic precipitation, Cantabrian Mountains.

Palabras clave: episodio de avalanchas, extremos climáticos, gran nevada, Pequeña Edad de Hielo, precipitación orográfica Cordillera Cantábrica.

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1. Introduction

The study of past climate-related natural disasters is of great importance, allowing us to measure the magnitude of extreme future climatic events, as well as plan our response to them (Brázdil *et al*., 2005). The 1888 snowfall episode was undoubtedly the most extreme climatic event of the last 200 years experienced in the Cantabrian Mountains, with a great impact also on places such as the Northeast Coast of the United States (Kocin, 1983; Fisher *et al*., 2013; Michaelis and Lackmann, 2013, among others). Nonetheless, little is known about its impact on Europe, where the literature on the event is sparse (Hächler, 1987; Roveyaz *et al*., 2013) and, until the last decade, even less was known about its impact on the Iberian Peninsula (García-Hernández *et al*., 2014, 2016 and in press).

The Little Ice Age (LIA) includes the period spanning from the 14th to the late 19th centuries characterized by enhanced climate variability with respect to present-day conditions (Mann *et al*., 2009). Severe cold spells, snowstorms, floods and droughts affected the European continent causing substantial socioeconomic damages (Fagan, 2002). Within this context, cold-climate hazards were more frequent and intense than today, particularly those related to frost and snow (Lockwood *et al*., 2017). Of all the events that can be triggered during a snowstorm, snow avalanches stand out as one of the most dangerous phenomenon. Accordingly, the study of avalanches from a risk perspective is necessary in mountain regions characterised by the presence of a number of villages and communication infrastructures, particularly with the increased use of these areas as a result of the practice of mountain sports (Haegeli *et al*., 2010; Techel *et al*., 2016; Höller, 2017). Widespread avalanche cycles, while concentrated in only a few days, have the potential to cause damages over an entire region (Birkeland and Mock, 2001), and the comprehension of both their links with climatic factors and their spatial extent and severity, can facilitate avalanche forecasting and risk mitigation (Fitzharris and Bakkehøi, 1986; Höller, 2009; García *et al*., 2009; Eckert *et al*., 2011; Oller *et al.,* 2015). Thus, the study of avalanche cycles must be a priority for medium and high altitude mountainous areas, which have previously witnessed extreme events, since the recurring risk is high and their socioeconomic consequences can be huge.

Despite the current absence of research studies in steep slopes of the main European mountain ranges, densely populated and particularly prone to avalanches (Fuchs *et al.,* 2017), it is unlikely that severe avalanches did not occur during the 1888 snowstorms. The Asturian Massif, situated in the northwest of the Iberian Peninsula, inside the Cantabrian Mountains, is a mountainous area largely exceeding 2000 m a.s.l. in many places, covering a wide area in altitudes between 1000 and 1500 m a.s.l. In such altitudes, annual snowfall is significant and, combined with steep terrains characterised by prominent unevenness, very deep valleys and slopes of considerable inclination, can lead to the triggering of large avalanches. This poses a significant risk nowadays, but it certainly posed a greater risk in the late 19th century, a period when the rural mountain areas were densely populated (López, 1981), while communications in the area were affected by an impulse (Rodríguez, 1984).

This study aims to fill the current existing gap in the knowledge relating to the most extraordinary snowfall and avalanche episode experienced by the Cantabrian Mountains during their recent history. Hence, the specific objectives of this study are the following: i) to define the weather, topographic and social factors involved in the triggering of these snow avalanches; ii) to describe the physical parameters of the avalanches; iii) to establish their socioeconomic impact; iv) to map the spatial distribution of events and the damages caused.

2. Methods

Essentially, data was collected from three sources: i) news from sixteen regional and national newspapers, published between 10 February and 30 May 1888; ii) obituary books from 23 mountain parishes in the Asturian Massif; iii) daily temperature and rainfall data obtained from a total of 82 personal interviews conducted in 42 different villages affected by avalanches during the episode.

Other contemporary sources, such as cartography and old pictures and prints, were used to support the fieldwork in which the trajectory of some of the avalanches was reconstructed, based on oral testimonies and geomorphological evidences. All relevant information was subsequently entered into a database, statistically processed and introduced in a GIS. These data allowed us to determine the location and damages caused by 69 avalanches, as well as the starting point, aspect, release angle (θ), average angle over the run of the avalanche (α), and horizontal distance covered by 27 avalanches from the original study.

In order to determine the unique nature of this episode, it was compared to other episodes that have occurred in the Asturian Massif (Fig. 1). In order to do this, data was obtained and used from a database containing information on the location and damage caused by 291 avalanches that affected the area between 1800 and 2015. Such database also provided information about the path of 126 of these avalanches. The sourcing of this information, contained in the database, has been expanded upon in a previous study (García-Hernández *et al*., 2017a). The following criterion was applied so that we could define the existence of a damaging episode: the occurrence of at least four avalanches causing material or personal damages, with a time-frame of no greater than six days.

For statistical processing, we used the R software to create a classic descriptive analysis, applying robust statistical methods and winsorized means. Using the Tukey method (Tukey, 1977), where the extreme values of distribution are characterized as "high" (Eq. 1) or "far-high" (Eq. 2), we detected extreme, as to their damages, avalanches. A damage index (DI) that allows us to quantify the impact caused, by making it comparable and fit for charting and mapping, was created to assess the evolution of the damages caused by the avalanches. The DI was configured following the method used by García-Hernández *et al*. (2017), in which the total damage (TD) results from the synthesis of the personal and material components of the damage, giving more weight to the former (Eq. 3).

Eq. 1: High = 75th percentile (P75) + 1.5*Intercuartile Range (IQR)

Eq. 2: Far-high = P75+3*IQR

Eq. 3: TD= 0.8*PD+0.2*MD

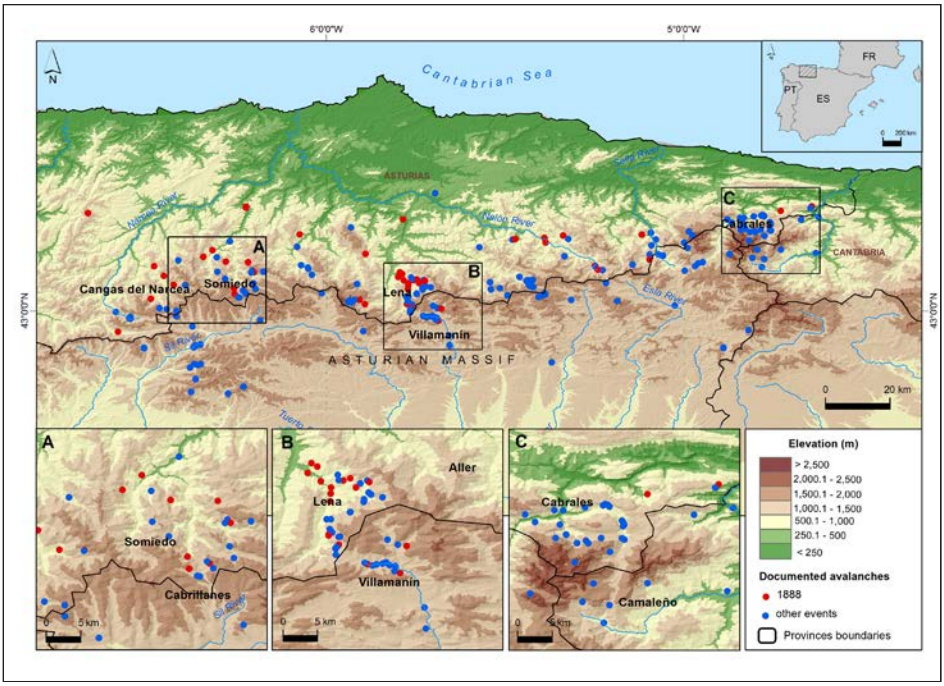

Figure 1. Location of events which occurred during the 1888 episode, and the rest of the documented avalanches in the study area between 1800 and 2015.

Lastly, the synoptic situations at 500 and 850 hPa corresponding to the 1888 episode have been analyzed using the data shown in the repository www.wetterzentrale.de (obtained through the NOAA 20th Century Reanalysis project), for the period between 13 February and 9 April 1888.

3. Results

3.1. Snow weather conditions and synoptic situation

The episode occurred in the context of a series of snowstorms that took place from 14 February to 8 April 1888. The first snowstorm started on 14 February in towns located at altitudes over 600 m a.s.l., where the snow thickness exceeded 5 m. The storm subsided between 21 and 23 February, even though the average temperatures did not increase significantly, remaining under 3.5°C in Oviedo (231 m a.s.l.). From 24 to 29 February the intense snowfalls returned, especially on 27 (when the average temperature reached its lowest, -0.9°C) and on 28 February, when the snow accumulated at a rate of 10 cm per hour in areas located over 500 m a.s.l., resulting in a snow accumulation of over 50 cm in a single night. During this second snowfall, the snow thickness exceeded 5 m in villages such as Pajares (970 m a.s.l.), located in the Massif's central area. These initial two storms were caused by a depression that moved diagonally from the British Isles towards the Mediterranean and Northern Africa (Fig. 2A and 2B). The passage of this depression pushed northbound winds that were humid, and consisted of temperatures lower than -5°C at 1500 m a.s.l., i.e. the sort of winds that encourages low altitude snowfalls. Such conditions of low-pressure areas concentrated in the Iberian Peninsula, with a lot of cold air and instability, persisted during the second fortnight of February (Fig. 2C). Later on, until mid-March, high pressures associated with the Azores anticyclone created the conditions for atmospheric stabilization, spreading to the Mediterranean basin in an elongated arrangement W-E (Fig. 2D). The synoptic situation in question fostered a gradual increase in temperatures, to an average of about 10°C between the days 7 and 14, as well as sunshine.

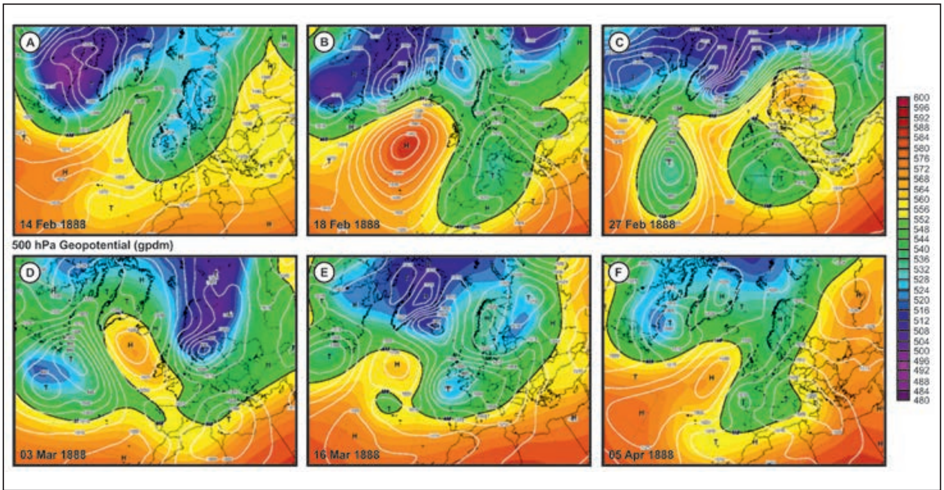

Figure 2. Synoptic situation of days 14, 16 and 27 February; 3 and 16 March; and 5 April 1888. Images contained in the Wetterzentrale archive, obtained from the project NOAA 20th Century Reanalysis.

From approximately 14 March, however, conditions started to progressively change with a low-pressure area that moved from the British Isles towards central Europe and Italy. Ultimately, when this very cold north-northeast air reached the Cantabrian Sea, it was very humid, thus prompting a new episode of snowfalls in the mountain range (Fig. 2E), which lasted until 21 March. At first, the snow began falling intermittently at over 500 m a.s.l. (precipitation fall in the form of rain and hail in lower altitude areas). Snow precipitation became widespread and more intense from 18 to 21 March, with a significant decrease in average temperature, which were at their lowest on 20 March (0.7°C). Throughout this second snowstorm, in areas over 500 m a.s.l., recently fallen snow was more than one metre deep, reaching 2.6 m depth in areas over 1000 m a.s.l., where thicknesses as deep as 8 m (accumulated from the previous three storms) were recorded on 22 March. From 23 March onwards, temperature began to increase again (generally remaining above 6°C average in Oviedo), due to the high pressures associated with the Azores anticyclone. The situation started to switch once more on 4 April with the entrance of a squall descending from the North, bringing cold and humid air and causing one last snowstorm episode (Fig. 2F), which was particularly intense between 4 and 6 April. It was not until 7 April that the atmosphere became stable and the depression displaced northwards. On 8 April, snow thickness exceeded 3 m in areas over 500 m a.s.l., and reached 5 m in some Picos de Europa villages such as Sotres (1050 m a.s.l.).

During the storms, there was a clear connection between the gain in altitude and the increase in the snow depth. This phenomenon can be observed in Table 1, which links altitude with maximum thicknesses achieved during the episode of snowstorms in 1888 in the cores of the Pajares valley (Lena municipality). Moreover, during the first three snowstorms, in particular, strong blizzards resulted in the formation of big snow cornices and snowdrifts of more than 10 m high.

Table 1. Villages in Pajares valley, altitudes and maximum accumulated snow depth.

Municipality	Altitude (m a.s.l.)	Snow depth (m)
Pola de Lena	322	0.84
Campomanes	390	1
Puente de los Fierros	500	1
Malvedo	550	1.1
Congostinas	675	3
Linares	900	3.2
Navidiello	950	4
Pajares	1000	8

3.2. Damaging avalanche episodes in the Asturian Massif

Applying the criteria for defining the existence of a damaging episode, established in the methodology section, we have detected 14 episodes from 1800 to 2015. The duration, number of events and total rate of accumulated damage of each of those episodes are shown in Table 2. There, we can see that the 1888 episode lasted for 53 days during which 69 damaging avalanches occurred and the maximum snow depth was recorded (8 m accumulated after the third storm).

Table 2. Damaging episodes detected between 1800 and 2015.

Starting date	End date	Number of days	DI Value	Number of events	Max. Snow depth (m)
15/02/1888	07/04/1888	53	410.6	69	8
07/01/1895	04/02/1895	29	92.0	20	7
02/04/1910	06/04/1910	5	105.2	4	6
20/02/1931	26/02/1931	7	0.4	6	2.5
27/02/1934	07/03/1934	9	45.4	7	1.5
03/03/1936	09/03/1936	7	10.6	5	4
09/01/1945	20/01/1945	12	93.0	15	1.5
02/02/1954	20/02/1954	19	3.6	7	6
09/12/1990	12/12/1990	4	17.8	7	7
01/03/1993	15/03/1993	15	3.4	4	1.5
19/02/1996	25/02/1996	7	2.4	5	1.6
26/02/2005	07/03/2005	10	2.4	16	3.7
04/12/2008	16/12/2008	13	1.2	6	1
31/01/2015	01/03/2015	30	2.4	25	2.25

In order to define and compare the importance of these episodes, we have created a ranking by changing the scale (from 1 to 10) allowing us to homogenize the range of values taking into account the duration (Fig. 3A), the number of events (Fig. 3B) and the damage they caused (Fig. 3C). Finally, for the elaboration of the average ranking (Fig. 3D) we only considered the last two factors, given the high correlation coefficient between duration and number of events (0.836). Ultimately, it can be observed that the 1888 episode is the most significant of those having occurred in the Asturian Massif between 1800 and 2015, both in terms of the number of avalanches and the damage it caused. In the same ranking, this episode is 1.7 points away from the second most important episode (which occurred in January 1895), but comprised twice the number of events and caused four times the amount of damage.

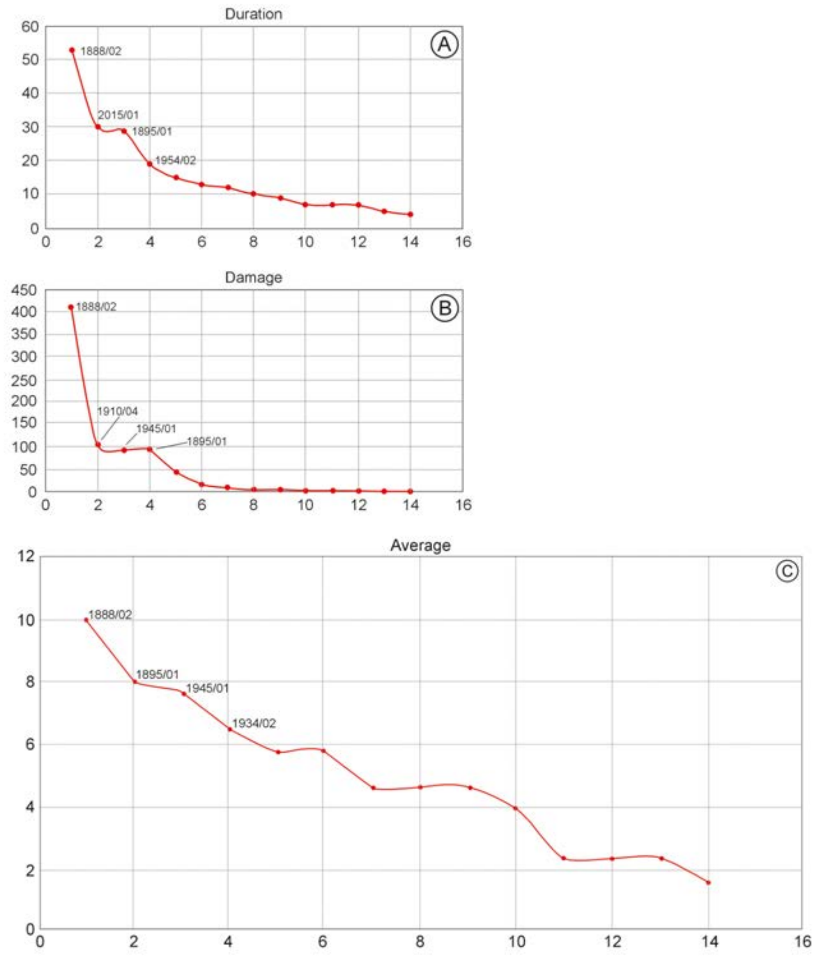

Figure 3. Duration ranking (A), ranking of damage caused (B) and average ranking of episodes (C).

If we evaluate the damage caused by the avalanches as individual events (apart from the episodes during which they occurred), applying the Tukey (1977) criteria we can detect 36 atypical or extreme avalanches (in terms of damage caused), between 1800 and 2015: 16 high avalanches and 20 far-high avalanches (Fig. 4). 24 of them happened in the 19th century. Of these avalanches, 50% of high and 40% of far-high belong to the 1888 episode, which resulted in 35% of the damage caused by this kind of avalanches.

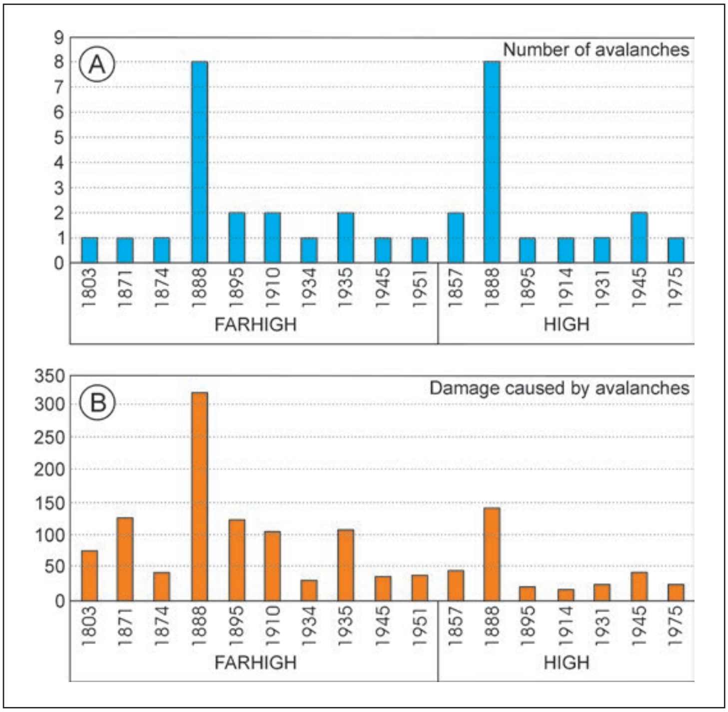

Figure 4. Annual distribution of avalanche number in the Asturian Massif between 1800 and 2015 (A) and the damage caused by them (B).

3.3. The geographic distribution of the 1888 episode

Taking into account the geographic distribution of the phenomenon of avalanches in this area from 1888 to 2015 (Fig. 1), during the 1888 episode few damaging events can be observed in the León, south-facing versant of the Asturian Massif. We also observe a minor concentration of events in the eastern sector (which was only hit by two damaging avalanches in 1888), and a major concentration in the central and western sectors of the Massif. These two sectors of the Massif's Asturian slope (north-facing) concentrated practically every extreme avalanche of the 1888 episode. The western sector, in particular, was hit by eight high and far-high avalanches. Nonetheless, the eastern sector, which concentrated numerous high and far-high damaging avalanches in other episodes, only experienced three in 1888 (Fig. 5).

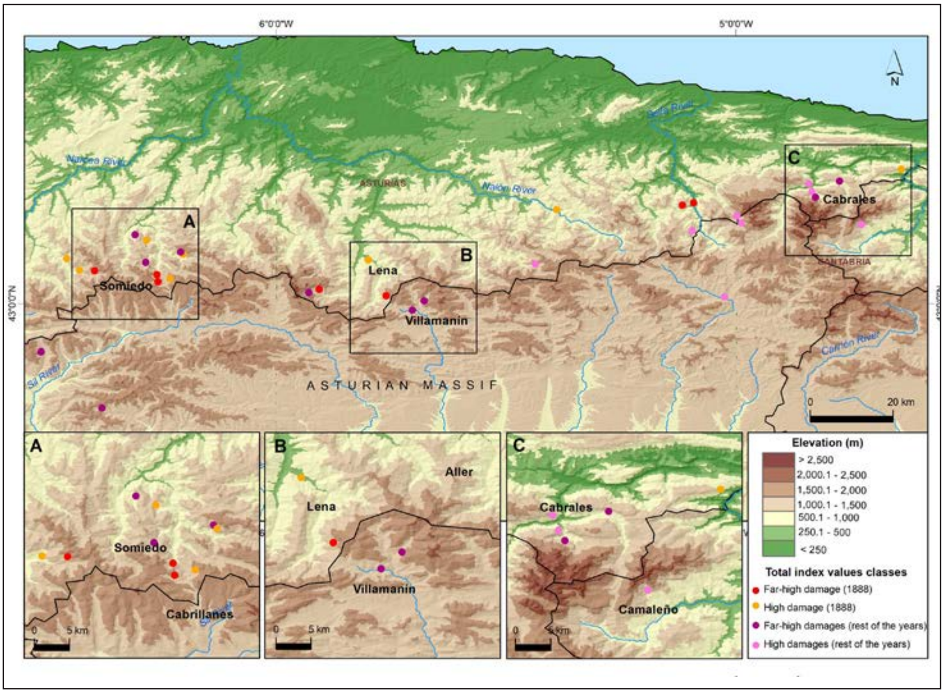

Figure 5. Chart showing the location of the avalanches which have caused extreme damage in the Asturian Massif, differentiating those belonging to the 1888 episode from those occurring in different years.

3.4. Physical parameters: comparison with other episodes and relationship with climate conditions

With regard to differences in physical parameters in terms of the rest of the episodes, it is found that the avalanches relative to the 1888 episode tended to generally occur in south- and east-facing areas (7% more for southwest, 3% more for south and 12% for east) (Fig. 6A). Thus, these orientations were those that suffered most of the damage (Fig. 6B). Furthermore, the avalanches were triggered at altitudes lower than the rest of the cases (average of 1381 m a.s.l. as opposed to 1490 m a.s.l.) and reached lower areas (848 m a.s.l. versus 974 m a.s.l.) since they covered, in general, longer runout distances (average distance of 1431 m a.s.l. versus 1190 m a.s.l.). Also, the slopes had lower angles, both average angles (a): 30° versus 32°, and release angles (θ): 32° versus 36° (Fig. 7).

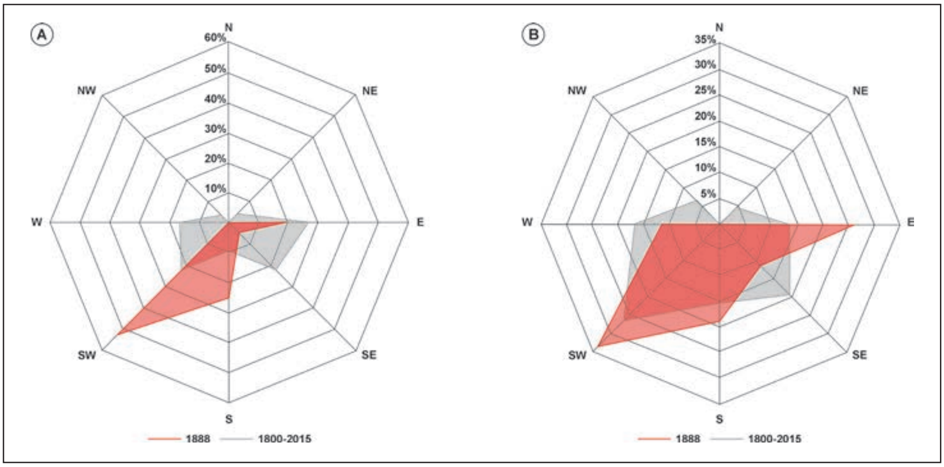

Figure 6. Number of events (A) and damage rate (B) for all events between 1800 and 2015, and only for 1888, in terms of orientation.

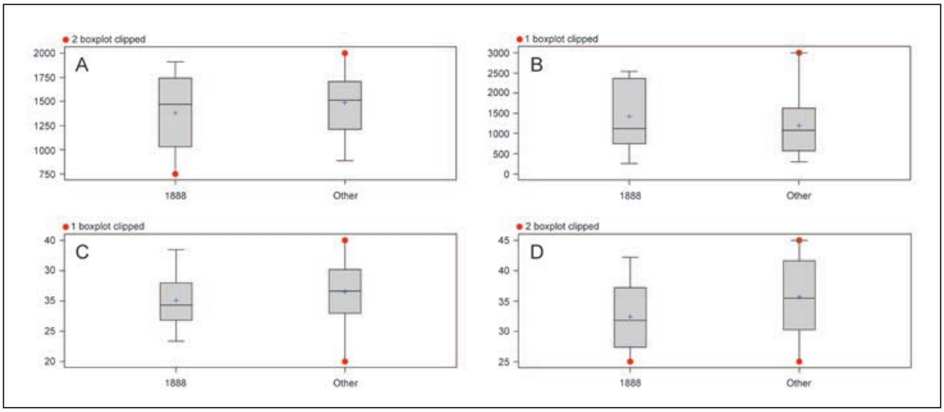

Figure 7. Distribution of (A) release altitudes; (B) horizontal distance; (C) angles α; and (D) angles θ, comparing 1888 with the rest of the 1800-2015 sample.

The avalanches tended to occur particularly in areas with maximum accumulated snow depth between 3 and 5 m (average of 2.3 avalanches per day; Fig. 8A). Essentially, the most serious damages were concentrated at altitudes with a snow depth between 1.5 and 2.9 m, with a daily average rate of 6.8 per avalanche (versus a rate of 4.5 between 2 and 2.9 m; and 0.5 between 3 and 3.9 m) (Fig. 8B). Regarding temperatures, avalanches were more damaging when the average temperature at 231 m a.s.l. was below 3°C (average rate per avalanche of 5.2 versus 2.6 when the temperatures were over 8°C) (Fig. 8C). Moreover, the avalanches covered longer runout distances when temperature remained in this range (average of 1727.2 m versus 1245.5 m when the temperature rose above 8°C) (Fig. 8D).

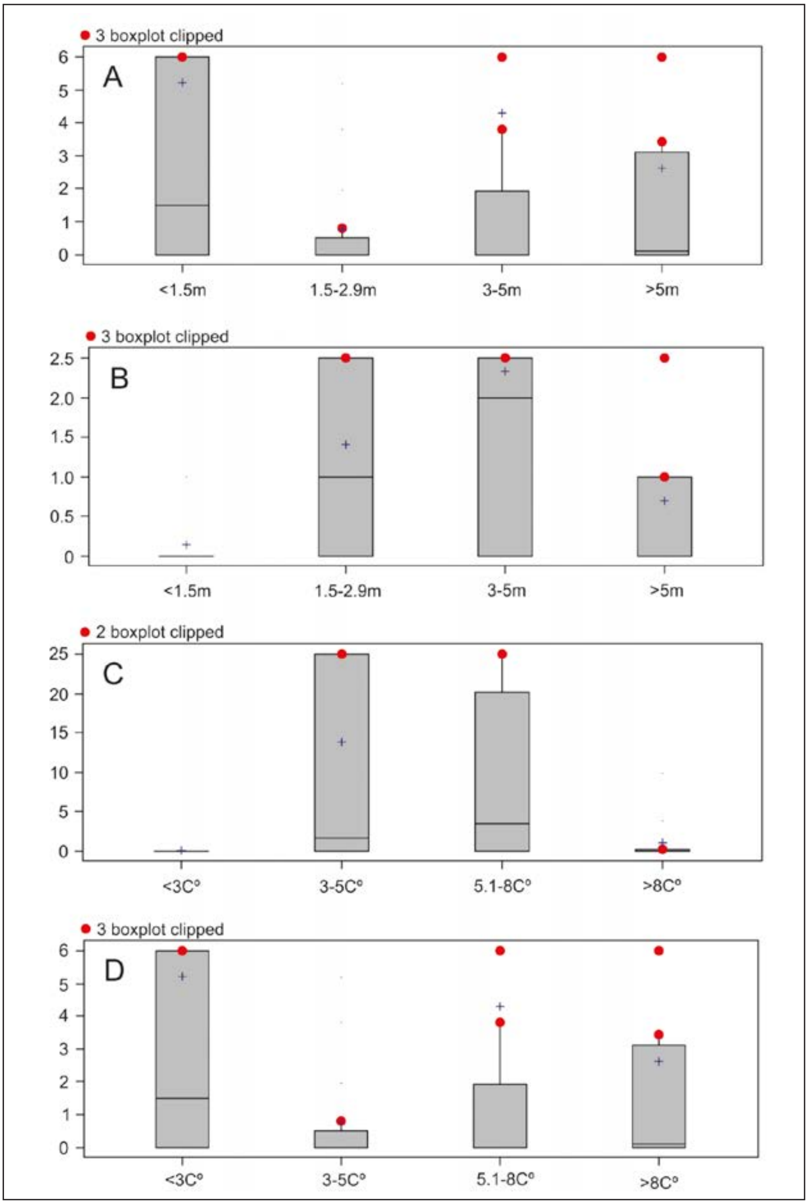

Figure 8. A) Number of avalanches per day in terms of maximum average thickness recorded per day; B) rate of accumulated damage per avalanche and day, in terms of maximum average thickness recorded per day; C) rate of accumulated damage per avalanche and day, in terms of average temperature at 231 m a.s.l.

In order to search for groups of days when the avalanches were highly frequent (above the standard rates which, in this case, is 48.1% of the days) we resorted to decision trees. In order to do this, we establish the limit in groups of, at least, five days. This allows us to identify the most decisive weather conditions for avalanche occurrence, taking into account daily precipitation and temperature data in Oviedo (231 m a.s.l.) and precipitation averages (six-day and three-day moving average) of days three and six prior to the triggering. We then established that the daily temperature appears to be the most determining condition (when it is <1.25 °C the probability increases to 83.3%). Increased temperature, however, is also linked to an increase of probability provided that precipitation is scarce (75% when the temperature was >1.25 °C and the daily precipitations <4.13 mm) (Fig. 9A). When the selected response variable is not the occurrence of daily avalanches, rather the occurrence of avalanches in a three-day span, the importance of precipitation is still insignificant (Fig. 9B). In fact, the highest increase of avalanche probability (from 84.6% to 96%) occurred when the moving average of precipitation for the six days previous was <0.68 mm.

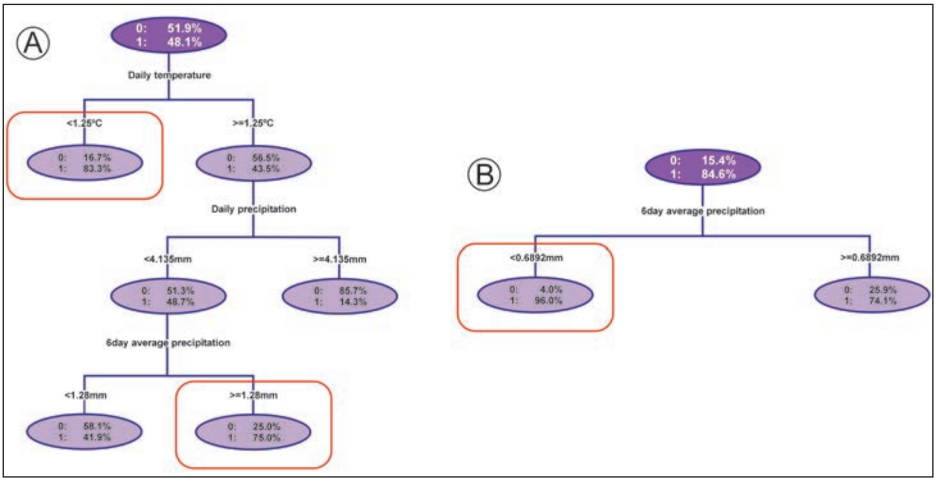

Figure 9. Decision trees showing the most decisive weather conditions; A) for avalanche daily occurrence; B) for the occurrence of avalanches in a three-day span.

3.5. The most damaging days during the 1888 episode

Seven of the 53 days of the snow avalanche episode concentrated 54% of the avalanches and 72% of the damages; 11 of the 1888 episode's far-high/high avalanches occurred during these days, as well as 30% of the total far-high/high avalanches which occurred from 1800 to 2015. The physical parameters and climate conditions of these days are summarized in Table 3. The highest number of damaging avalanches (9) occurred on 5 March, although the greatest total damage and greatest damage per avalanche accumulated occurred on 27 February. On that day, the average temperature was the lowest recorded in Oviedo (231 m a.s.l.) during the whole episode (-0.9°C). Also, the avalanches were triggered at higher altitudes and in slopes with lower angles, covering longer horizontal distances (Table 3).

Table 3. Extreme days in terms of number of snow avalanches and damages.

Date	Avalanches	DI value	Mean DI value	% Total DI	Mean starting point m a.s.l.	Mean distance (m)	Mean α angle	Mean θ angle	Prevailing Aspect	Mean T (ºC)	Max. Snow depth (m)
22/02	6	26.8	4.47	4	1738.4	403.4	34.5	42.2	E	2.2	4
27/02	7	172.8	24.69	29	1812.52	2445,05	28.57	28.35	SW	-0.9	4
05/03	9	134.6	14.96	22	1440.34	1778.66	31,08	34.54	E	5.8	3
09/03	5	17.2	3.44	3						13.8	2.4
22/03	5	9.8	1.96	2	833.95	648	31.55	33.75	SE	3.8	6
11/03	3	27.8	9.27	5	861.9	994.7	30.7	37	E	9.4	
26/02	3	41	13.67	7	1200.4	2008.1	28.6	31.8	S	1	2.5

Of the most damaging avalanches, the three which occurred in the Lena municipality on 27 February 1888 should be highlighted: (i) The first avalanche occurred at 2:00 a.m. near the village of Pajares; after being triggered in the source of the Matarredonda stream, it flowed through the valley and destroyed the railway viaduct (> 100 tons and 40 m width) (Fig. 10). From the point of impact, the avalanche descended more than 1 km until reaching the bottom of the valley where the remnants of the viaduct were deposited, though parts of it were found more than 3 km away from its original location. (ii) At noon, a second avalanche was triggered at the valley's highest point through which the Fayedo stream flows. The avalanche was canalized through this valley hitting the southern end of Pajares village; four houses were destroyed and 18 others suffered serious structural damages. Nine people died instantly and eight others were hurt, alongside the death of 60 cows. Eyewitnesses testified that the avalanche "…announced its arrival with loud noise and vibrations" (*El Carbayón* 02/03/1888), and one village's current inhabitant define the incident, as it was described by her ancestors, "…like a sort of sudden, hurricane-like wind, accompanied by great amounts of snow". (iii) Finally, moving on from Pajares yet remaining in the Lena municipality, a further avalanche occurred on the same day, 27 February, in Tuiza de Abajo village, causing serious personal and material damages. An entry in a document from the parish of Tuiza, describes the following:

> … an impressive and terrifying avalanche was triggered in the Siegalava crag which then, as an electric spark, spread out rapidly throughout the meadow of Tuiza de Abajo, and after having dragged along with it in a confusing frenzy the house of Carril in which it killed five cows, the houses of Veguellina and Villaquemada in which it killed 30 animals, some sheep and horses, it buried Tuiza de Abajo under huge amounts of snow and debris. This, combined with the fact that the houses in that village had already been covered with snow, being their roofs the only way out, the casualties were: First, the death of four women, may they be welcomed by God. Second, demolition of four houses. Three, demolition of a raised granary and two stables.

This information is available in the book *De nuestro corresponsal* (Rebustiello, 2007). The whereabouts of the obituary book of the San Cristóbal de Tuiza parish for 1888, from which this extract was taken, is currently unknown.

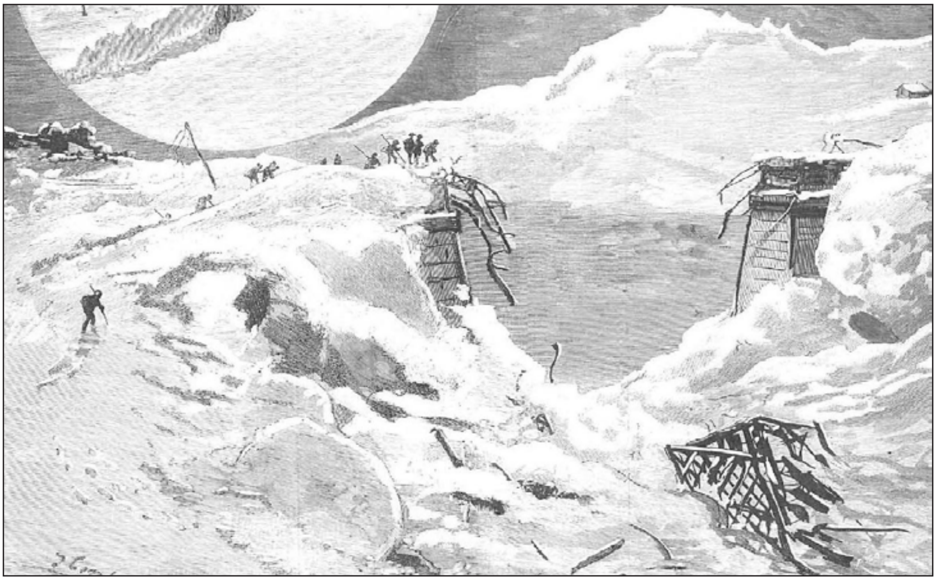

Figure 10. Xylograph published on 8 April 1888 by La Ilustración Española y Americana, *based on sketches made on site by engineer Eugenio Ribera. It shows the results of the avalanche which destroyed the Matarredonda viaduct on 27 February 1888.*

3.6. Social and environmental impact of the 1888 episode

A total of 69 events leading to the injury of 32 people and the deaths of a further 29 have been recorded. The specific damages caused by the avalanches are detailed in Table 4. The councils located in medium and high altitudes were affected the most, especially in the Asturian slope (Fig. 11A), where 65 of the recorded avalanches and 27 deaths occurred. From oral testimonies collected in Tonín de Arbás (León) we know that a big avalanche could have been triggered in such village in early March of 1888, causing at least 30 deaths. Nonetheless, this could not be confirmed by documentary sources since the documents of the village's parish are not currently available, hence, the decision not to include this event in the table, nor in the final tally of deaths and damages.

From 1800 to the present, avalanches have periodically affected 22 municipalities in the Asturian versant, 13 of which suffered a high percentage of the total damaging avalanches in the 1888 episode (Fig. 11A). Nevertheless, this was not the case with the south-facing versant (León province), which appears to have been more affected by other episodes, such as that of 1945 (Fig. 11). In the Asturian versant, virtually every avalanche to have hit eight of its municipalities belonged to the 1888 episode. The same for the damages caused: in five of the municipalities, the 1888 episode is responsible for more than 50% of the total damages, having also been responsible for all damages in other seven municipalities, distributed in the next quartiles (Fig. 11B). During the 1888 episode, the damages were particularly intense in the Lena municipality, where 32 avalanches leading to 17 deaths occurred (Table 4).

Table 4. Socioeconomic impact of the 1888 cycle, for the Asturian Massif and only for the Lena municipality.

	Asturian Massif	**Lena**
Total avalanches	69	32
Avalanches causing personal damage	18	7
Dead people	29	17
Injuried people	32	12
Avalanches causing material damage	59	25
Buildings	124*	39**
Heads of cattle	123	95
Infrastructure damage and traffic interrupted	22***	14****
Avalanches causing short communication outage	5	3

**88 houses, 11 cattle barns, 16 cabins, 2 churches, 3 raised granaries, 2 mills, 2 walls, 2 forests, 1 cultivated field*
***33 houses, 5 cattle barns, 1 raised granary*
****10 railroad traffic interruption , 7 road traffic interruption, 1 bridge, 1 viaduct, 3 locomotives*
*****9 railroad traffic interruption, 1 bridge, 1 viaduct, 3 locomotives*

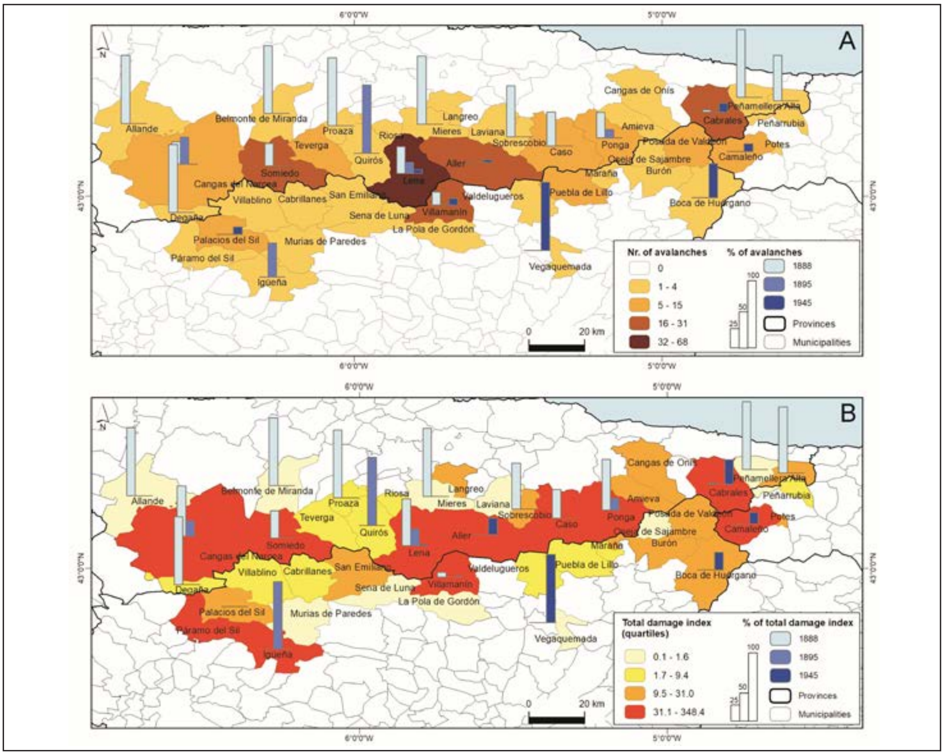

Figure 11. A) Map showing the number of avalanches per municipality between 1800 and 2015, and the percentage of avalanches resulting from one of the three main avalanche episodes of the same period in terms of number of events and damage caused (1888, 1895 and 1945); B) Map showing the distribution in quartiles of the damage caused by avalanches between 1800 and 2015 in each municipality, as well as the percentage of total damage resulting from one of the three main avalanche episodes of the same period (1888, 1895 and 1945).

Regarding the land use at the time of the incident, 67% of the avalanches affected settlements, which accounted for 80% of the damage (Fig. 12A and 12B). This result contrasts with the group formed by the rest of avalanches occurring in the Asturian Massif between 1800 and 2015, of which only 13% affected settlements, where approximately 60% of the damage was caused (Fig. 12C and 12D).

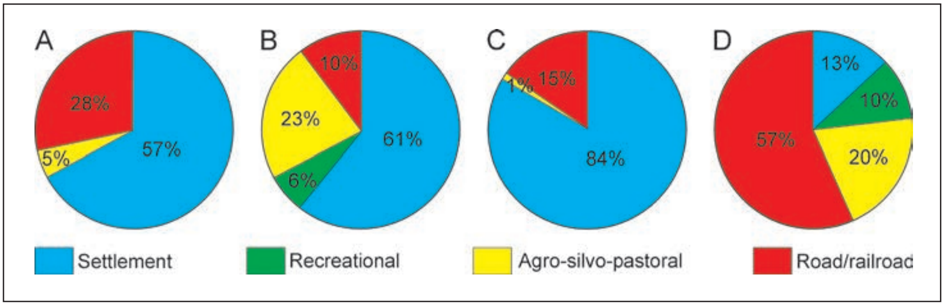

Figure 12. Percentage of avalanches according to the type of the land affected; A) for those belonging to the 1888 episode; B) for the rest of the avalanches of the 1800-2015 period. Percentage of damages caused according to the type of land affected; C) by avalanches produced in the 1888 episode; D) for the rest of the avalanches of the 1800-2015 period.

4. Discussion

4.1. Climate conditions and their interaction with relief

4.1.1. Snow depth

The occurrence of catastrophic avalanche cycles depends on the combination of several weather conditions: low temperatures, high snow precipitations combined with strong winds so that there is much drifting snow and, occasionally, a swift rise in temperature above de 0 °C **(**Fitzharris and Schaerer, 1980; Fitzharris and Bakkehøi, 1986**)**. Negative pressure anomalies, such as the one that affected the North of the Iberian Peninsula in February and March of 1888, have been linked to the occurrence of great avalanche cycles both in Europe and the USA (Föhn, 1975; Fitzharris, 1987; Birkeland *et al*. 2001; Birkeland and Mock, 2001; Höller, 2009). In the case of the 1888 episode in the Asturian Massif, the synoptic situation was determined by the entrance of a polar north flow that canalized a series of very cold frontal depressions, causing abundant precipitation and strong north winds in mountainous areas, as recorded by the newspapers.

Orographic precipitation usually defines the most important snowfalls in the Asturian versant, where altitude progressively increases from the Cantabrian Sea (Muñoz, 1982). This explains why the snow depths increased in parallel with the increase in altitude (Table 3). Snow depth is also a relevant factor for the triggering of catastrophic avalanches (de Quervain, 1972; Höller, 2007), because it reduces the role of the ground roughness and friction (McClung and Schaerer, 1993). Although the threshold for avalanche triggering changes according to the geographic area and its interaction with climate (Esteban *et al*., 2005), many authors consider that 30 cm of fresh snow is enough to develop an avalanche (Perla, 1970; McClung and Schaerer, 1993; Ancey and Charlier, 1998), particularly when combined with strong winds (Perla, 1970; McClung and Schaerer, 1993). Nevertheless, 1 m thick is considered the most adequate limit for the triggering of extreme avalanches (Schweizer *et al*., 2003). During the 1888 storms, snow thickness reached depths of over 3 m in altitudes as low as 500 m a.s.l., while 5 m snow depth (and locally up to 8 m depth in some places) were recorded in the highest parts of the Asturian Massif at altitudes over 1000 m a.s.l. (Table 2). In general, the higher the altitude, the more the snow depth. This, along with the presence of very steep slopes, explains why most of the avalanches and the resulting damage occurred in the north-facing municipalities of the Asturian Massif (Fig. 11A and 11B).

4.1.2. Characteristics of the avalanches

The extraordinary snow accumulation was the responsible for: (i) the triggering of the 1888 avalanches at altitudes lower than those occurred during other episodes of the 1800-2015 period; (ii) the exceptionally long horizontal distances recorded by the avalanches, because deep thickness do not only facilitated the triggering of avalanches, but also influenced the runout distances (McClung and Schaerer, 1993). This allowed the avalanches to reach lower areas than usual (average of 848 m a.s.l. as opposed to 974 m a.s.l.). Therefore, they affected settlements located in relatively flat areas (García-Fernández, 1980). In fact, during the 1888 episode, both the slopes affected by the avalanches and the triggering areas had angles slightly lower than the usual (30° as opposed to 32° and 32° versus 36°, respectively), i.e. at the limit of avalanche triggering (Schweizer *et al*., 2003). The higher quantities of snow accumulated before the avalanche event in these slopes, which were less inclined than usual, could increase their volume (McClung and Schaerer, 1993; Maggioni and Gruber, 2002) and damaging capacity. In fact, it is common for catastrophic avalanches to be triggered in angles lower than 30° (Ammann, 2000; García-Hernández *et al*., 2017).

Another particularity of the 1888 episode was the major occurrence of south-oriented avalanches (mainly south and south-west) (Fig. 6A). A possible explanation is the development of leeward snow cornices overhanging from ridges in the southern slopes due to the strong winds that, according to newspapers, blew predominantly from north. This might be the origin of many avalanches, since snow overload on the leeward ridges resulting from the combination of strong snowfalls and wind is usually the origin of the avalanche triggering (Burrows and McClung, 2006). In fact, cornice fall avalanches are very common and represent a high risk (Eckerstorfer and Christiansen, 2011; Vogel *et al*., 2012). The local inhabitants did not ignore that problem, and tried to eliminate some of the cornices during the lull days. This could explain, also, the higher concentration of damages in southern orientations (Fig. 6B), on which most settlements were also traditionally located (García-Fernández, 1980).

4.2. Importance of temperature and precipitation

Snow precipitation during the hours prior to an avalanche event is the most important weather condition in the formation of great, new snow avalanches (Poggi and Plas, 1969; Yanlong and Maoshuan, 1992; Jomelli *et al*., 2007; Baggi and Schweizer, 2009), even in wet snow avalanches (Jomelli *et al*., 2007; Baggi and Schweizer, 2009). According to regional newspapers, snowfalls appear to have been especially abundant in the hours prior to some of the most damaging events, such as the avalanches of 27 February (also with particularly low temperature). Some of these avalanches were described in such terms that lead us to think about a dry snow avalanche "like a whirlwind".

While the meteorological records at our disposal belong to a low altitude station, we can still use them as indirect indicators of what could have happened in higher altitudes, that is, more abundant precipitations and lower temperatures. Nevertheless, our results demonstrate a limited importance of precipitation when defining the occurrence of avalanches, the most determining factor having been the low temperature. As a matter of fact, when temperature is higher, an inverse relationship with precipitation is observed, even considering precipitation of the previous three and six days (Figs. 9A and 9B).

At this stage, we can establish two hypotheses: (i) either not all dates on the avalanche triggering are reliable, or (ii) there are significant errors in the precipitation data. The first hypothesis cannot be sustained by the analysis carried out; since the accumulation of avalanches in the third and sixth previous days shows that the relevance of precipitation is still scarce. The second hypothesis is supported by the important existing contradiction between data recorded in the Oviedo observatory and data provided by the press and eyewitnesses. It is striking that on the same day for which the press unanimously writes about the beginning of a lull and a break in precipitations, Oviedo records the episode's precipitation record (35.46 mm). For a number of days in which there are testimonies of high precipitation intensity (27 and 28 February, for example), the observatory records a zero mm precipitation.

Nonetheless, we cannot dismiss the possibility that in some of the avalanches the trigger was indeed the increase in temperatures, a decisive factor for the triggering due to its impact on snow stability (McClung and Schweizer, 1999), thus being a causation in some of the snow cornice failures (Burrows and McClung, 2006) and, especially, wet snow avalanches which require a rise in temperatures above 0°C in the hours before (Yanlong and Maoshuan, 1992; Jomelli *et al.*, 2007; Baggi and Schweizer, 2009). This factor could have been decisive especially between the second and third storm, when temperatures rose significantly, with a concentration of over 17 avalanches on days 5, 9 and 12 of March, which added up to 30% of the damage caused during this second lull and due to snow melting (García-Hernández *et al*., in press).

4.3. Socio-environmental factors and their influence on the 1888 cycle impact

Having previously expanded on factors such as snow thickness, the relief, the location of settlements and the characteristics of the triggered avalanches, it is easier to understand the occurrence of a high percentage of avalanches hitting the northern slope of the Asturian Massif, which belong to Asturias, and, more specifically, its settlements (Fig. 12A and 12C), resulting in much more serious damages (Fig. 12B and 12D). In fact, 35% of the total damage caused by avalanches which we can consider "extreme" (in terms of damage) was caused during this episode. Apart from the intense land use of the south-oriented slopes, one must also consider the possible interaction of other processes, such as the intense deforestation undergone by the Asturian Massif in the final decades of the 19th century which at that stage had an impact on the increase of damages in the settlement, especially in the western sector (García-Hernández *et al.*, 2017a, 2017b). Such dynamics of prior deforestation have been linked to the triggering of exceptionally damaging avalanches in other places in Europe during the same episode. This is the case of the avalanche that caused the death of eleven people in Avieil (Italian Alps) on 27 February 1888 in a slope where avalanches did not usually reach such proportions (Roveyaz *et al.*, 2013). This could explain the greater affectation of this sector compared to the eastern one where there were barely any high or far-high damage avalanches during this episode, despite the more prominent unevenness of its slopes.

On the other hand, the central sector concentrated most of the damage, since it was already the most populated area and supported a heavy transit of people and goods (Rodríguez, 1984). In fact, the railway line which connected Asturias to León, going through municipalities in high altitudes such as Lena and Villamanín, had been inaugurated four years previously. During the storms the track remained closed and its restoration was of utmost interest for both provinces, which could explain the increase in news from this area, since the press sent their correspondents to report from there (García-Hernández *et al.*, in press). However, municipalities such as Lena, also suffered avalanches which caused a high number of personal and material damages, a fact that cannot be explained as a geographical bias of the press. The presence of highly inhabited hubs in the highest areas, due to the role played by the Pajares mountain pass as a main connection point between Asturias and León (Rodríguez, 1984), along with the recent changes in topography and deforestation for the construction of the railway line, could explain some of the events which affected this municipality.

4.4. The 1888 event within the late LIA context

These events recorded in 1888 must be framed within the climate setting prevailing in southern Europe during the last decades of the 19th century. Increased solar radiation since ca. 1850 promoted a long-term temperature increase, despite large volcanic eruptions induced a decline of temperatures worldwide during the years following the volcanic events, such as the Krakatoa eruption in 1883 (Bradley, 1988). These oscillating temperatures associated to changing moisture conditions must be understood as a transitional regime between the colder LIA climate and the 20th century warmer scenario.

Natural and historical records in the Iberian Peninsula suggest that climate warming started ca. 1850; in other mountainous areas, as northern Europe and the Alps, the maximum in avalanche activity has been reconstructed around 1850, correlating with colder winters and glacier advances (McCaroll *et al.*, 1995; Corona *et al.*, 2012b, among others). The fact that two thirds of extreme avalanches occurring in the Asturian Massif between 1800 and 2015 happened in the 19th century, fits with that idea of a progressive warming affecting the triggering of avalanches. Notwithstanding, the last decades of the 19th century included periods of decreasing temperatures, intense climate variability and extreme hydroclimatic events; in Switzerland, for instance, the period 1886-1895 was one of the coldest in the last 500 years (Corona, 2012b); in Canada the 1880 decade was a period with a high precipitation and mountains experienced a glacial advance (Luckman, 2000); in Iberian Peninsula temperatures dropped by ca. 1ºC during the 1880-1890 decade, with more frequent and severe cold waves (Oliva *et al*., in revision) and in several sites across northern Iberia historical sources showed evidence of an increased frequency of catastrophic floods during the second half of the 19th century (Barriendos and Martín-Vide, 1998). Specifically, the 1880's coincided with a cold weather stage in which drought conditions could have dominated (Coll *et al.,* 2016), but with exceptionally wet years as 1885 and 1888 (Font-Tullot, 1988) in which snowstorms, hailstorms and heavy rain events, were more frequent than usual in Spain (Gonzalo de Andrés, 2004). In this context, winter precipitations were frequently associated to heavy snowfalls in the mountains, favoring avalanche activity in the Cantabrian Mountains but also in other mid-latitude mountain environments such as the Alps, as inferred from tree rings and historical sources (Corona *et al*., 2012a; Guillet *et al*., 2016).

5. Conclusions

The decades following the LIA cold stage were characterized by an unstable climatic pattern that generated a series of climate extremes affecting mid-latitude mountainous areas as the Asturian Massif, in which the 1888 avalanche cycle was the most remarkable. Both in terms of the number of damaging avalanches and damages caused by them, the 1888 episode stands out among the rest of avalanche cycles recorded in the Asturian Massif in the 1800-2015 period. The avalanches of 1888 cycle were not only more frequent, but also more damaging on average: of the most damaging avalanches occurring between 1800 and 2015, more than half of them belonged to the 1888 episode.

With respect to the factors that rendered the 1888 extraordinary, we should highlight the importance of orographic precipitations: the interaction of a cold and wet air mass originating from the North Atlantic with the relief of the Massif, led to snow thicknesses which were greater than those reached in other episodes, and in lower altitudes, especially in the North-oriented Asturian slope which, consequently, accounted for the majority of the events triggered. The thickness of the snow cover, as thick as 3 m in altitudes as low as 500 m a.s.l., allowed the triggering of avalanches in lower altitudes, covering also distances longer than usual. Thus, it was easier for those snow avalanches to reach the highly populated settlements, placed in middle slopes, which were particularly affected by this episode. On the other hand, these large snow accumulations facilitated the triggering of major avalanches in gentle slopes, which is where settlements are usually located. The triggering of cornice fall avalanches in the southern slopes, due to the predominance of strong northern winds, could also explain the high impact suffered by these, usually, southern-oriented settlements.

Despite the fact that the increase in temperatures appears to be the main trigger of the avalanches occurring during the periods of rest, the most damaging avalanches occurred in moments of intense precipitation and with very low temperatures. Some of these events have being described as consistent with avalanches of dry snow. However, the existing contradiction between instrumental data and those provided by testimonies of the press, and other historical sources along with the scarce correlation between precipitation and avalanche occurrence, suggests possible errors in the precipitation records.

The greater impact on the settlements, which suffered 84% of the damages, was the cause of this episode's high socioeconomic impact (29 people dead, 34 injured, 123 heads of cattle dead, 124 buildings destroyed). This impact was, however, uneven: in the villages located higher in the Asturian slope, especially in the central and western sections, the impact was much more important. Even though we cannot exclude the possible influence of a geographical bias in the information provided by the press, the severity of the damages caused by some of the avalanches that affected these areas suggests the involvement of other factors. Such factors would be the deforestation undergone by these areas (in particular the western) at the end of the 19th century, as well as the important population of the highest settlements in the central sector, due to the appeal of its new communication infrastructures.

Therefore, the 1888 events constitute an excellent example of the impact of extreme hydrometeorological events in mountain environments under high demographic pressure. But, as well, it constitutes a good example of processes involved in a climate transition period from cold to warmth weather conditions. Moreover, the accurate characterization of the spatio-temporal patterns and social consequences of this event can be used to assess the potential threat of avalanche phenomenon not only in the Asturian Massif, but in Iberian mountains in general.

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