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Floods in the Pyrenees: A global view through a regional database

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Abstract. This paper shows the results of the analysis on the first systematic dataset of flood episodes referred to the entire Pyrenees massif, named PIRAGUA_flood, which covers the period 1981-2015 (available at http://hdl.handle.net/10261/270351). First, the structure of the database is detailed, so that it can be reproduced anywhere else in the world adapting to the specific nature of each situation. Subsequently, the paper addresses the spatial and temporal distribution of flood episodes and events (including trends) that affected the Pyrenees regions of Spain (Catalonia, Aragon, Navarre, the Basque Country), France (Nouvelle Aquitaine, Occitanie) and Andorra, as well as the massif as a whole, for a given period of time. In the case of the Spanish regions, it was also possible to analyse the compensation paid out made by the Spanish Insurance Compensation Consortium, and the number of deceased. The weather types associated with flood episodes were also classified based on sea level pressure and 500 hPa geopotential height from ERA5. The results show 181 flood events and 154 fatalities, some of which affected more than one region. In the Spanish part of the Pyrenees, between 1996 and 2015, there were a total compensation payout amounting to €142.5 million$_{2015}$. The eastern part of the area records more flood events than the western one, being Catalonia the community that registered the highest number of events, followed by Andorra and Occitanie. Associated weather types are dominated by southern component flow over the Pyrenees region, with a thalweg on the Iberian Peninsula and a depression in the vicinity, either in the Atlantic or in the Mediterranean. In terms of the entire massif, there is a slight positive trend of 0.84 events/decade, driven by the evolution of ordinary and extraordinary floods, but not significant at 95%. At a regional level, flood behaviour is more heterogeneous, although not significant for the most part. Nouvelle Aquitanie is the only region that shows a positive and significant trend of 0.34 events/decade.

1 Introduction

It is well known that floods in the Mediterranean area are usually flash floods (Gaume et al., 2009; Braud et al., 2014; Llasat et al., 2016), associated with very heavy rains with a short duration, which generally go unnoticed in the databases. Most of these databases, such as the ones belonging to EM-DAT or Munich Reinsurance, also include other types of natural disasters and refer to what could be called very severe episodes. These databases, however, are often based on indirect information (for

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example, from the insurers that Munich Reinsurance reinsures) so many events are not included, either because the insurers are not aware of the events, or because they are not considered to have had sufficient impact (Llasat et al., 2013). More systematic and precise studies are therefore required. For example, there are very few such episodes that have affected the Pyrenees Mountain region on the databases. The high workload required to elaborate these studies means that they are only available for few regions. This is the case for FLOODHYMEX (Llasat et al., 2013), which currently includes all the catastrophic episodes (following the criteria of "catastrophic" introduced in Barriendos et al., 2003) that have affected Catalonia and the Balearic Islands, in Spain, the former Languedoc-Roussillon region, Midi-Pyrénées and PACA (Provence-Alpes-Côte d'Azur) in France, Calabria, in Italy, and Greece. This dataset can be found at https://mistrals.sedoo.fr/?editDatsId=1150&datsId=1150&project_name=HyMeX&q=flood.

The Pyrenees Mountain range has an area of 49,850 km² (W-E: 520 km; S-N: 150 km), and a maximum altitude of 3,404 m.a.s.l (Aneto), extending from the Atlantic Ocean to the Mediterranean Sea (Fig. 1). 43% of the Pyrenees is covered by forest, making it one of the richest regions in biodiversity in Europe. The number of inhabitants in the Pyrenean region is less than 1,200,000 people, but this figure can be doubled in summer. Although there is still notable agricultural and livestock activity, the service sector is the main source of income. Thus, in Andorra, the tourism sector constitutes more than 80% of the GDP. The Pyrenees are key in the generation of water resources in the surrounding regions, where more than 20 million people live, as well as in the production of hydroelectric energy, which exceeds 3,300 MW. In this context, floods, usually flash floods, can have a great direct impact on both the fixed and floating population, as well as on water services and energy resources. An example is the catastrophe at Camping las Nieves, in Biescas, on August 7, 1996, in which 87 people drowned. The recent death in September 2023 of two people who were canyoning when the flash floods occurred is another example of an increasingly frequent risk.

However, until now there is no database or flood catalogue that specifically covers the Pyrenean regions, and even less so, the Pyrenees massif as a whole. The aim of this article is to present the first systematic database of flood episodes covering the entire Pyrenees massif, for the period 1981-2015, that was created in the context of the Interreg POCTEFA project, PIRAGUA (https://www.opcc-ctp.org/en/piragua). This database is available at http://hdl.handle.net/10261/270351(Llasat et al., 2022). Following the introduction of the study area, the structure of the base is shown, the criteria followed for its construction, and the sources of information used. The spatial and temporal distribution of flood episodes, both in the massif and the administrative regions, as well as the weather types, are then analysed. The paper ends with conclusions and discussion.

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2 Area of study and sources of information

2.1 Area of study

The study area (Fig. 1) is exclusively comprised of the municipalities within the limits of the Pyrenees, as defined by the Pyrenees Climate Change Observatory (Observatorio Pirenaico del Cambio Climático - OPCC), a subsection of the Pyrenees Working Community (Comunidad de Trabajo de los Pirineos - CTP), and which includes part of the Nouvelle Aquitaine and Occitanie regions of France, part of the Basque Country, Navarre, Aragon and Catalonia in Spain, and Andorra as a whole. In total, 1803 municipalities are included, of which 609 are in Spain, 1187 are in France and 7 are in Andorra.

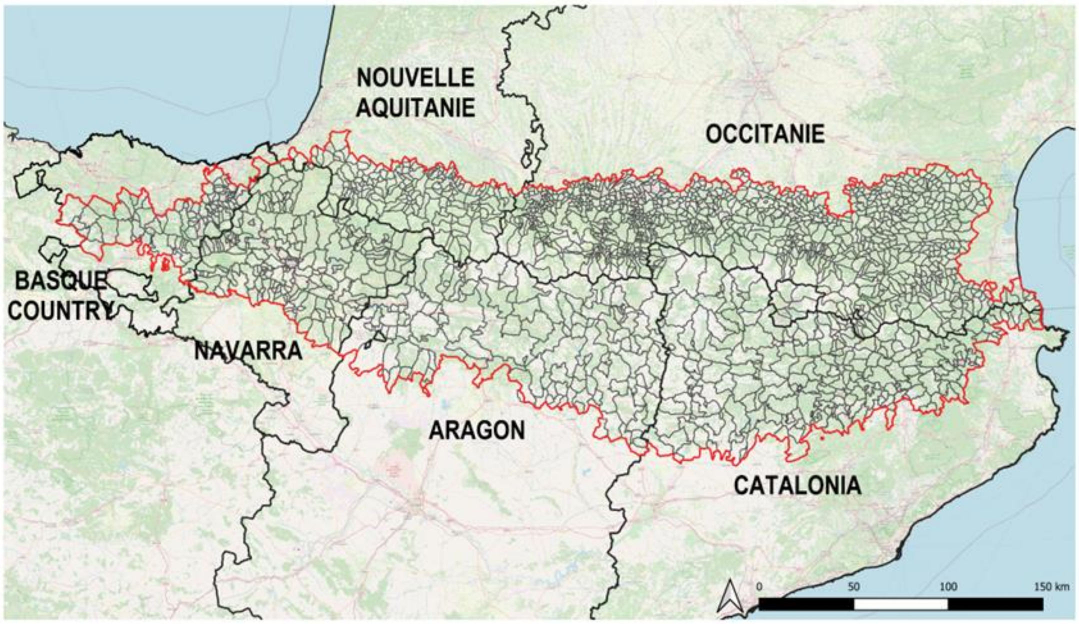

Figure 1: Map of the municipalities located within the area defined as the Pyrenees by the OPCC.

2.2 Sources of information and identification of flood events

FLOODHYMEX (Llasat et al, 2013) was used to recover the catastrophic events that have affected the Pyrenees in Catalonia and the part of Occitanie corresponding to the Languedoc-Roussillon. For the Spanish part of the Pyrenees, the National Catalogue of Historical Floods (Catálogo Nacional de Inundaciones Históricas - CNIH, DGPC, 2022) was also used. This catalogue is published by the General Directorate of Civil Protection in Spain and contains the most important flood events. The CNIH is divided into reports by drainage basin. It is possible, for example, to find the same event on two different dates for the same drainage basin, so it is necessary to compare the data with other information to verify the affected area and correct dates. For the Spanish part, some information is also available from the Spanish Insurance Compensation Consortium (CCS,

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2021), which provides a list of compensation paid out for floods in the Basque Country, Aragon, Navarre and Catalonia for the period 1996-2015. From this, it is necessary to extract the compensation paid to municipalities in the Pyrenees. There is also the added difficulty that the information provided by the CCS is organised by postal code rather than by municipality, and this database shows the date of the "claim", which may be different from the date of the flood. In order to resolve this, the postcode data was transformed to a municipality data (a municipality may have more than one postcode) and the damage caused is considered to be any between the initial day of the event and the final day, with an additional 7 days, as in Cortès et al. (2019). For events that were not known, it was even more time-consuming to identify new events on the CCS database. Finally, the information was completed based on news from the most representative newspapers in each region. This means that La Vanguardia was consulted for Catalonia; El Heraldo de Aragón was consulted in Aragon; and for Navarre, Diario de Navarra. In the case of the Basque Country, consultation was difficult as the sources were written in Basque. This was resolved thanks to the record of historical floods included in the Preliminary Flood Risk Assessment (Evaluación Preliminar del Riesgo de Inundación - EPRI) of the 2nd Cycle of the Eastern Cantabrian Hydrographic area (CHC and URA, 2018). The catalogue of historic floods that included the "Special emergency plan for the risk of flooding in the provincial community of Navarre", and press releases from the Government of Navarre, were also available for consultation.

For Nouvelle Aquitaine (AQ) and Occitanie (OC), the database of the Central Reinsurance Company (*Caisse Centrale de Réassurance* - CCR) was consulted, as well as the extreme rainfall records of Météo France, and information from the National Observatory of Natural Risks (*Observatoire National des Risks Naturels* - ONRN).

In the case of Andorra, the information was obtained from the Andorra Snow and Mountain Studies Centre-Andorra Studies Institute (*Centre d'Estudis de la Neu i de la Muntanya d'Andorra-Institut d'Estudis Andorrans* - CENMA-IEA) database, which includes press information on floods in the media in Andorra. As the information in this database ends in 2002, information was also obtained from a register of the impacts caused by overflows of rivers and secondary streams provided by the Ministry of Territorial Planning of the Government of Andorra.

In some specific cases, precipitation maps were created from rainfall reanalyses provided by SAFRAN (Quintana et al., 2016), which allowed us to detect some municipalities that suffered flood damage where there was no other record. This was the case for Navarre, where possible cases not included in the CNIH were detected, which were later corroborated by the press.

3 Database structure and methodology

3.1 Development of the database

The database was built in EXCEL and is made up of two tables: a) Events; b) Affected municipalities. The Events table aims to collect the most relevant data in as systematic a format as possible and contains the following fields: Identification of the

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event, meteorological and hydrological information indicators, impact indicators. In the second table, the municipalities affected by each event are entered. In case of victims, the information related to the victims is entered in the corresponding municipality. All fields are detailed in Appendix A.

The category of flood events is based on impacts, and is divided into Category 0 (ordinary), 1 (extraordinary), 2 (catastrophic) according to table 1, inspired by the criteria presented in previous publications (Barriendos et al., 2003; Llasat et al., 2013, 2016; Cortès et al., 2017). Category 3 is for major catastrophic events. Level 1 in each table refers to possible minor damage. Level 2 includes floods inside buildings and on communication routes that can cause interruptions to traffic, etc. Level 3 refers to partial or total destruction, supply cuts, etc. Fatalities are not included in table 1 since they can occur at any flood event category, although fatalities are more likely in cases of catastrophic floods. The same applies to vehicles, since they can be swept away if they are parked on a creek where there is normally little water flow, without the river breaking its banks. This is why additional categories have been included in the database, with the code “0.5” if the episode swept away cars and “5” if there were fatalities. Since the category of the episode may be different for each affected Pyrenees municipality, the highest occurring level represents the episode.

Table 1: Criteria for categorizing flood events based on impact (0: Ordinary: one or more indicators at level 1; 1: Extraordinary: most of the indicators at level 2, with up to two at level 3; 2: Catastrophic: three or more indicators at level 3; 3: Major Catastrophe: seven or more indicators at level 3).

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3.2 Spatial analysis

The number of flood events was represented at a municipal level using Geographic Information Systems (GIS), ArcGIS 10.4 and QGis 3.10. Spatial analysis was carried out for all categories of flood episodes. To do this, for Catalonia it has been used the database of municipalities in shapefile format provided by the Cartographic and Geological Institute of Catalonia (ICGC). For the other regions, the database of municipalities and regions in the Geographic Information System of the European Commission (GISCO) has been used, which is part of Eurostat. Regarding the study area, it has been used the defined delimitation in PIRAGUA (OPCC) in shapefile format (https://www.opcc-ctp.org/en/geoportal).

3.3 Temporal analysis

The temporal analysis includes a climatological aspect that makes it possible to characterise the seasonality of the events, and a study of the possible annual trends. A linear regression was used to obtain the trend, while Mann-Kendall test was used to check its significance (Mann, 1945; Kendall, 1975). The Mann-Kendall test states as a null hypothesis (H0) that there is no monotonic tendency in the series, while the alternative hypothesis (Ha) is that there is trend (positive or negative). This is a non-parametric test, and it can therefore be applied to all types of data regardless of the underlying probability density function. In the present study, it was established that a trend is significant when the p-value of the Mann-Kendall statistic is below 0.05 ($p < 0.05$).

These analyses were carried out for the Pyrenees as a whole, as well as for the subregions of Catalonia, Andorra, Aragon, the Basque Country, Navarre, Aquitaine and Occitanie. Likewise, for the severity of flood events, their evolution was studied by categories (0, ordinary; 1, extraordinary; and 2, catastrophic), as well as their total aggregate.

3.4 Weather types

The weather types associated with each flood episode have been classified using the mean sea level pressure (mslp) and the geopotential height at 500 hPa (z500), obtained from the ERA-5 reanalysis (Hersbach et al., 2020) in its native resolution (0.25°) for the geographical domain 20°W-20°E, 30°N-60°N, which was then averaged on a daily basis.

To synthesise all the dates that comprise the flood episodes, a principal component analysis (PCA) was applied to the mslp and z500 matrices in mode T. Mode T configures the data matrix to which the PCA is applied as follows: the variables (columns) of such matrices are the days in which flooding occurs, while the cases (rows) are the grid points of ERA-5. Once the PCA had been applied to the standardised data matrix, new variables were obtained: the principal components (PC), which are linear combinations of the original variables. Subsequently, the PCs that explain a greater variance of the original data were identified using a screen test (Cattell, 1966). Once the most explanatory PCs had been retained, a Varimax rotation was applied to them to readjust the orthogonal combination of each PC and obtain a greater variance explained by the initially less-explanatory PCs (Richman, 1986). Using the rotated PCs, the factor loads (i.e. the correlation matrix) were obtained, indicating the degree of correlation of each day with respect to each PC. In this sense, the allocation of each day to each of the PCs is based on the value of the maximum positive correlation and the minimum negative correlation. For example, day 1 is assigned to the absolute maximum correlation, but subsequently retains the correlation symbol. As a result, PC1 can be divided into two groups, one for days with the maximum positive correlation (PC1+) and another for days with the lowest negative correlation (PC1-). This means that, if 6 PCs are retained, up to 12 weather types can be obtained. This type of classification has already been widely used to classify extreme events (with few samples), such as tornadic events (Rodriguez & Lemus-Canovas, 2023), torrential precipitation events (Martin-Vide et al., 2008; Lemus-Canovas et al., 2021) and heat waves and cold waves (Serrano-Notivoli et al., 2022). To calculate the classification, the synoptReg R package was used (Lemus-Canovas et al., 2019a). This package is available at https://github.com/lemuscanovas/synoptReg.

4 Regional distribution of flood events and impacts

4.1 Distribution of floods on a scale of the entire Pyrenean massif

Table 2 has been provided in order to synthesise the information that will be analysed in this section. Municipalities listed in Table 2 are localised in figures 5 to 11. It should be noted that the same event can affect more than two regions. This is why we have calculated the total number of times that the different Pyrenees regions have been affected by floods, TOTAL, and the total number of episodes that have affected the massif, TOTAL ep (considering that an episode that affects more than one region is counted only once). In the period 1981-2015 there were 181 flood events throughout the Pyrenees area (Fig. 2). Of these events, 128 affected the Spanish part, 43 affected the French part, and 46 affected Andorra. Some of the events were common to two or all three countries, such as the events of November 1982 (which affected all three countries) and June 2013 (which affected France and Spain), or they affected different regions from the same country, with a total of 41 “transregional” episodes. It means that if the number of events that have affected each Pyrenean region is added, the result is 242 events. In this article, the criterion is to consider that those floods that occur on the same day are related to the same meteorological synoptic situation, and, therefore, it is the same episode that has produced floods in different points. This clarification is necessary because in other articles (Barriendos et al, 2019) the criterion used is based on the sum of all the locations where flooding has occurred. Pamplona (Aragón) and Llançà (Catalonia) have been the municipalities with the major number of flood events (17 and 16, respectively), although the economic impacts are very different (18 M€ and 1,1 M€, respectively), and in Catalonia the municipality with the major impact is Vielha (9,9 M€). This difference is consequence of the major exposure and vulnerability of Pamplona, with a population of 195,853 inhabitants, in front of the 5,450 inhabitants in Vielha and 4,985 inhabitants in Llançà (year 2015). In the case of Vielha, the PIB is 170.2 M €, practically double that the PIB of Llança, with 91.9 M € that partially explains the different impacts between both Catalan villages, added to the fact that the 2013 flood in the Garonne River was catastrophic.

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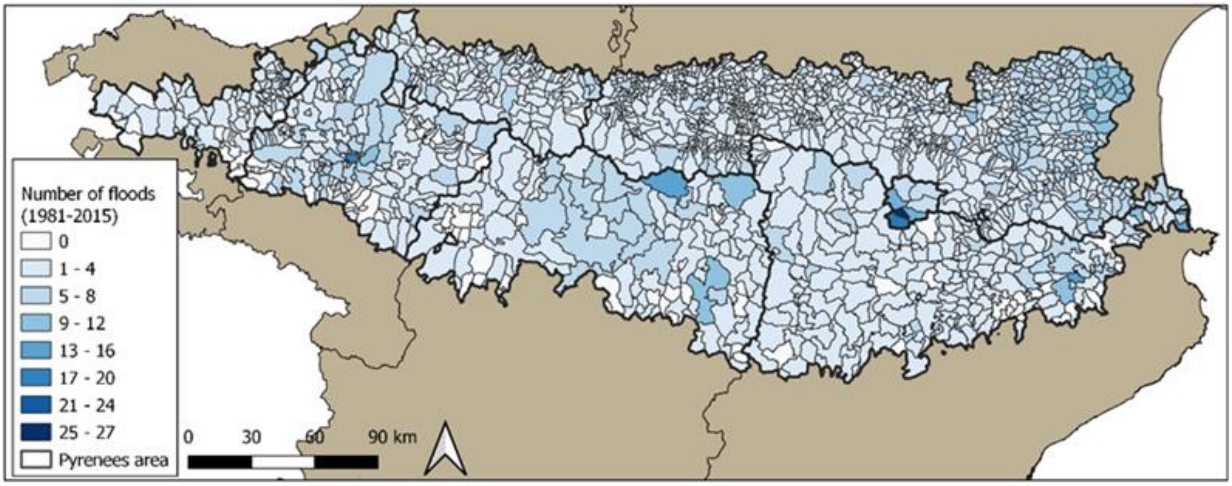

Figure 2: Number of flood events that affected each municipality in the Pyrenees.

Figure 2 shows an apparently uniform distribution throughout the region, highlighting only a greater frequency in some municipalities, which is why Fig. 3 has been constructed, which also allows us to distinguish the category of flood episodes. It shows that the region with the highest number of flood events was Catalonia, with 66 flood events, followed by Andorra, with 46, while the region with the lowest number of flood events is the Basque Country, with 16 flood events. This difference may be related to both the orography and the meteorological disturbances causing intense rains, which will be discussed later. But it should also be considered that for Andorra and Catalonia there is more systematized information available, which allows all ordinary floods to be included. In fact, Andorra is the region that records the highest percentage of ordinary floods (67.4%). Figure 4 shows the distribution by municipality of flood events with notable damage (that is, they were extraordinary or catastrophic). Of the 181 flood events, 52% produced notable damages in one or more of the Pyrenean regions. The highest number of catastrophic flood events was recorded in Nouvelle Aquitaine, followed by Occitanie and Aragón. It is observed that notable flooding events are concentrated above all in the municipalities of the Pyrenees closest to the Mediterranean, both on the Spanish and French sides. The central part of the Spanish Pyrenees also stands out, located at the foot of the highest mountains.

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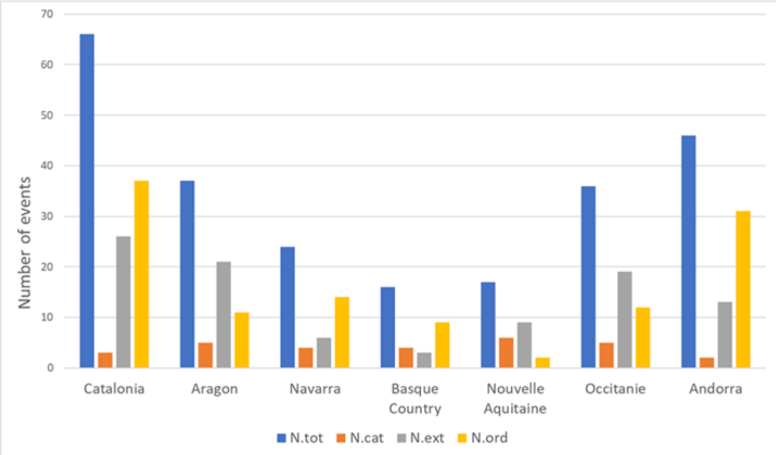

Figure 3: Distribution of the total number of flood events (blue) and the number of flood events by categories (catastrophic, orange; extraordinary, grey; and ordinary, yellow) in the different communities that make up the POCTEFA Pyrenees region, for the period 1981-2015.

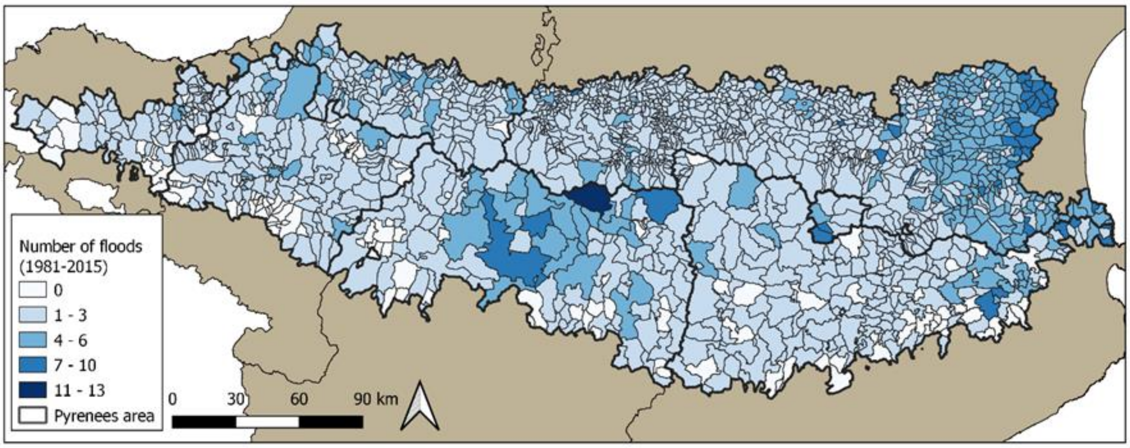

Figure 4: Number of events of catastrophic and extraordinary floods (non-ordinary episodes) that affected each municipality in the Pyrenees.

Table 2 also shows the number of fatalities per region. Of the 154 victims, 97 died in floods in August, 87 of which correspond to the flash flood that destroyed Las Nieves campsite of Biescas on August 7, 1996. This makes Aragon the region with the highest number of deaths, with a total of 97. The remaining ten deaths, as well as the other victims, were recorded in July or September and are associated with mountain sports or ravine crossings. In contrast, the 39 victims recorded in November were mostly a result of more organised and extensive episodes of heavy rainfall, and a major part of them died at home or they were in a car that was swept away by the flood.

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	N.tot	N.cat	N.ext	N.ord	Munic. max	N.tot munic. max	N.vict	CCS (M€) tot	Munic max CCS	CCS (M€) munic. max	Period. max.	Trend
Catalonia	66	3	26	37	Llançà	16	21	33.4	Vielha	9.9	SON	0.15
Aragon	37	5	21	11	Bielsa	15	97	15.2	Biescas	3.4	ASON	-0.01
Navarra	24	4	6	14	Pamplona	17	1	65.8	Pamplona	18	JFD	0.03
Basque country	16	4	3	9	Oiartzun/ Oyarzun	8	2	28.1	Tolosa	3.1	JnJlA	-0.08
Nouvelle Aquitaine	17	6	9	2	Mauleon-Licharre	7	6	no data			JMyJn	0.34*
Occitanie	36	5	19	12	Montgaillard	13	14	no data			JnON	0.32
Andorra	46	2	13	31	Andorra-la Vella	27	13	no data			JnJlA	0.05
TOTAL	242	29	97	116			154	142.5			JnJlA	0.74
TOTAL ep	181	16	78	87			154	142.5				0.84

Table 2: Synthesis of information on flood events that have affected the Pyrenees-POCTEFA region in the period 1981-2015. It indicates total number of events (N.tot); number of catastrophic episodes (N.cat.); number of extraordinary episodes (N.ext.); number of ordinary episodes (N.ord); the municipality most affected (munic. max) and the number of cases it recorded (N.tot munic. max); the total number of fatalities (N.vict.), the compensation paid by the CCS to the municipalities in the Spanish Pyrenees for floods that took place between 1996 and 2015, adjusted to 2015 (CCS tot); the municipality that received the most amount (munic. max CCS) and the amount (CCS munic. max); the three months that recorded the greatest number of events; and the trend of the number of events per decade (* means a significant trend at 95%). The sum of episodes that affected the various study regions (TOTAL) and the number of episodes that affected the Pyrenees region (TOTAL ep) is indicated. In the latter addition, events common to two or more regions have been included only once.

4.2 Regional flood events distribution

In the study period (1981-2015) there were 66 episodes in the Catalan Pyrenees in which the number of victims amounted to 21. Three episodes were catastrophic and 26 were extraordinary (Table 2). Figure 5a shows that the highest number of floods took place in the coastal foothills of the Pyrenees (16 episodes in the municipality of Llançà, of which 62% were extraordinary). The episodes of November 1982 and June 2013, category 3 and 2, respectively, were the most serious in the period analysed. The CCS paid a total of €33.4 million$_{2015}$ in flood compensation in the period 1996-2015, with the Val d'Aran being the most compensated region, mainly due to the June 2013 event (Fig. 5b).

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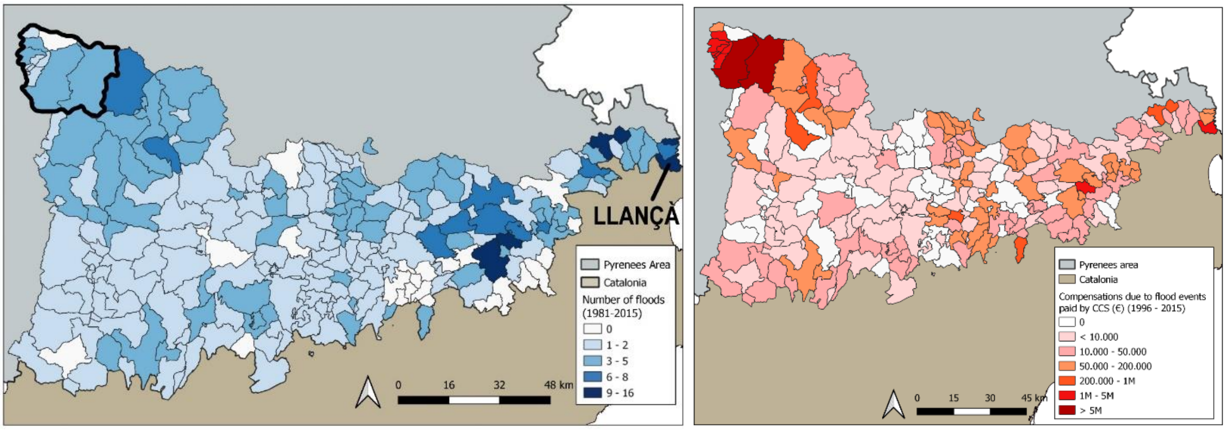
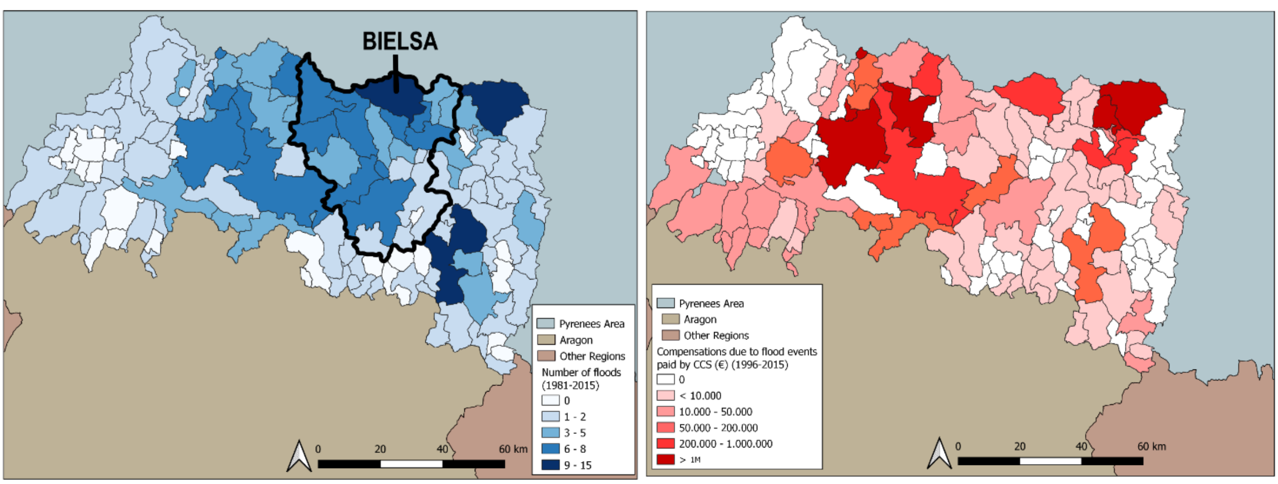


a b

Figure 5: a) Number of flood episodes that affected each municipality in the Catalan Pyrenees between 1981 and 2015. The location of Val d'Aran (marked with a black line) and Llançà is shown; b) Compensation paid by the CCS for floods between 1996 and 2015.

In Aragon there were a total of 37 flood events, of which 13.5% were catastrophic. In 4 of them there were flash floods that led to the evacuation or death of several people who were canyoning. The number of victims amounts to 97, 87 of whom died at the Las Nieves campsite (Biescas) in August 1996 (Ayala Carcedo, 2002). Aragon has the county with the highest number of floods in the Pyrenees and it is Sobrarbe, where 26 events have taken place in 35 years (Fig. 6a). Its capital, Bielsa, recorded 15 flood events. The CCS paid a total of €15.2 million$_{2015}$ in the period 1996-2015 (Fig. 6b), mainly due to the flood events of August 1996 and June 2013 that also affected Catalonia, Occitanie and Nouvelle-Aquitaine.



a b

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Figure 6: (a) Number of flood episodes that affected each municipality in the Aragon Pyrenees between 1981 and 2015. The location of Bielsa and the Sobrarbe region is shown (marked in black); b) Compensation paid by the CCS for floods between 1996 and 2015.

24 events affected the Navarre Pyrenees in total, in which there was one victim. About 17% were catastrophic. The capital of the autonomous region of Navarre, Pamplona (203,418 inhabitants) is included in the Pyrenees area and is the city in which the largest number of events was recorded, at 17. However, the largest number of catastrophic events in the Pyrenees area took place in the Baztan valley (Fig. 7a). The CCS paid a total of €65.8 million$_{2015}$ in compensation, of which about €18 million$_{2015}$ went to Pamplona and €5.5 million$_{2015}$ went to Baztan (Fig. 7b).

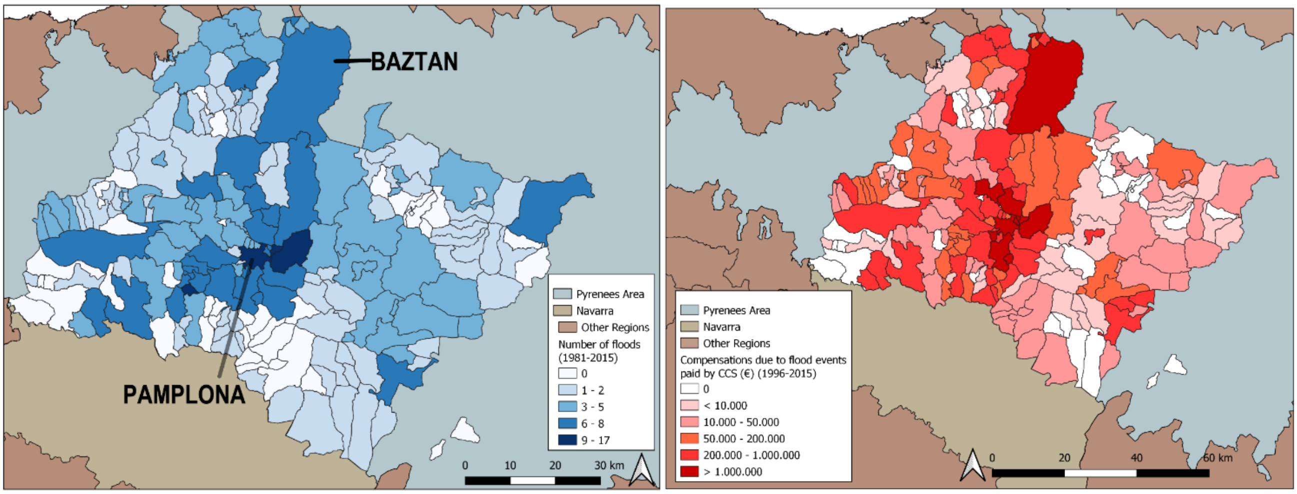

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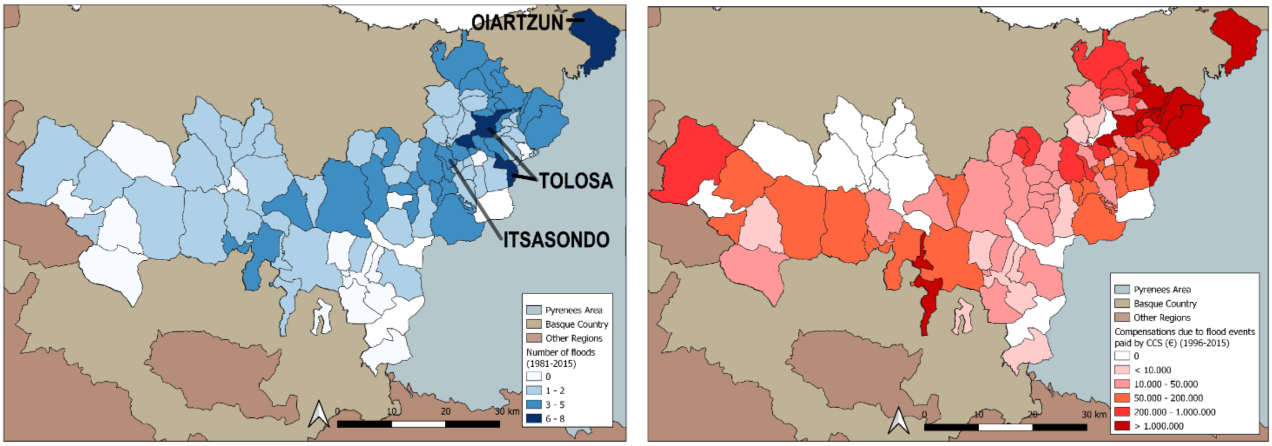
Figure 7: (a) Number of flood episodes that affected each municipality in the Navarre Pyrenees between 1981 and 2015. The location of Pamplona and Baztan is shown; b) Compensation paid by the CCS for floods between 1996 and 2015.

During the study period, there were a total of 16 episodes of flooding (25% catastrophic) in the Basque Pyrenees, with two victims. Most flood events are concentrated in the eastern part of the Basque Pyrenees, with a maximum of 8 events in Oiartzun (Fig. 8a), although the municipality with the highest number of catastrophic events is Itsasondo, with three events. The CCS paid a total of €28.1 million$_{2015}$ in compensation, of which the largest amounts went to Toulouse and Oiartzun, which received €3.1 million$_{2015}$ and €3 million$_{2015}$ respectively (Fig. 8b).



a b

Figure 8: (a) Number of flood episodes that affected each municipality in the Basque Pyrenees between 1981 and 2015. The location of Oiartzun, Toulouse and Itsasondo is shown; b) Compensation paid by the CCS for floods between 1996 and 2015.

In total, 43 episodes of floods affected the French side of the Pyrenees, of which Nouvelle Aquitaine recorded 17 events (Fig. 9) and Occitanie recorded a total of 36 events, with a percentage of catastrophic episodes of 35.3% and 13.9%, respectively. Ten of these episodes were common to the two regions. In Occitanie, the municipality with the most flood episodes was Montgaillard, with 13 (Fig. 10), while in Nouvelle Aquitaine the maximum was lower, with 7 events in Mauleon-Licharre. It is noteworthy that all the municipalities in the French Pyrenees have recorded at least one catastrophic flood event, with the maximum recorded in the northeastern part, close to the Mediterranean.

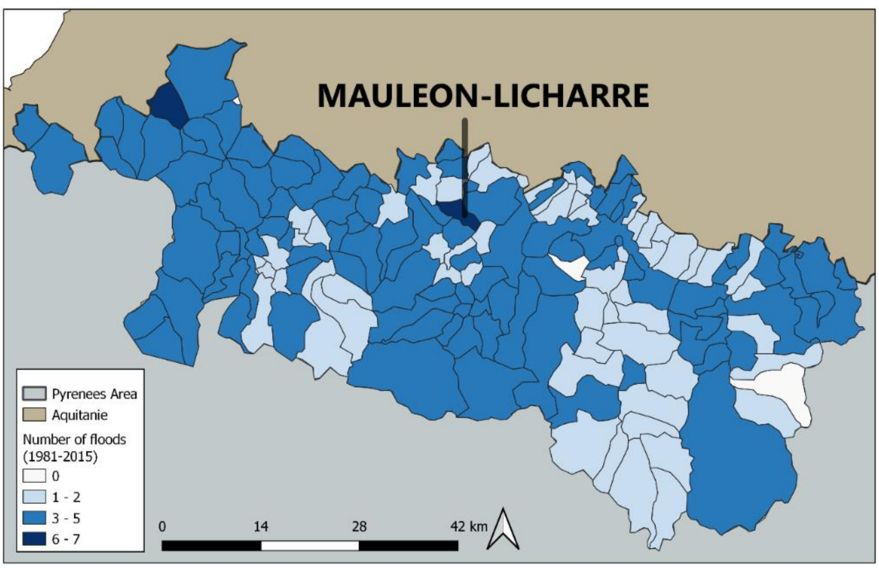


Figure 9: Number of flood episodes affecting each municipality in the Nouvelle Aquitaine Pyrenees between 1981 and 2015. The location of Mauleon-Licharre is shown.

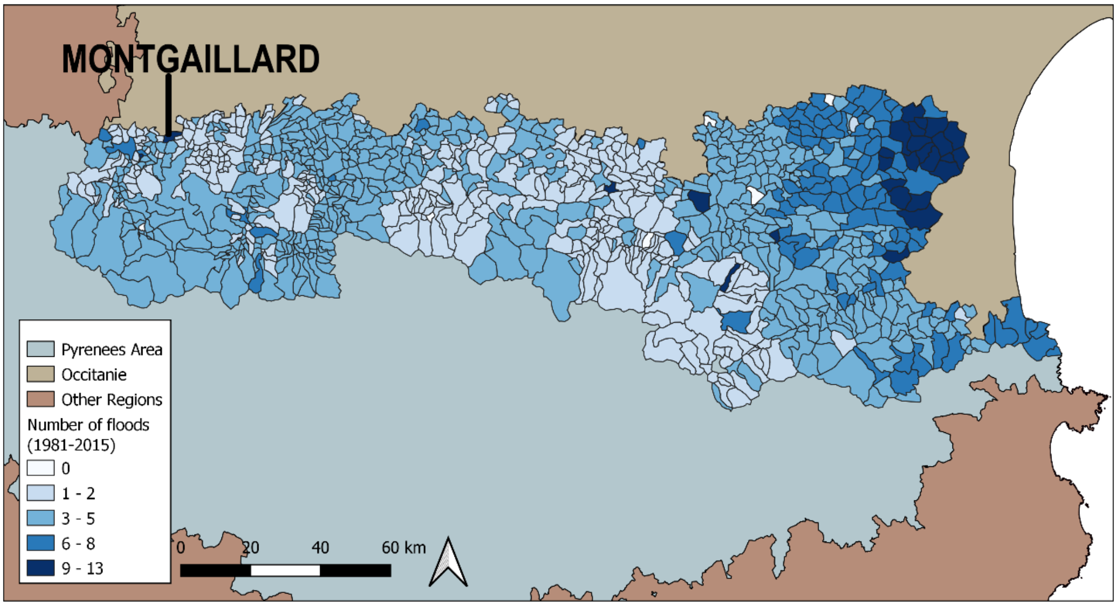


Figure 10: Number of flood episodes affecting each municipality in the Occitanie Pyrenees. The location of Montgaillard is shown.

A total of 46 flood events were recorded in Andorra in the period 1981-2015, of which only 4.55% were catastrophic. This percentage is very similar to that of Catalonia, which may be due not only to the proximity of both regions, but also to the fact that more information is available on flood episodes. The maximum number occurred in the municipality of Andorra la Vella, with 27 flood episodes, followed by Sant Julià de Lòria, with 18 floods (Fig. 11).

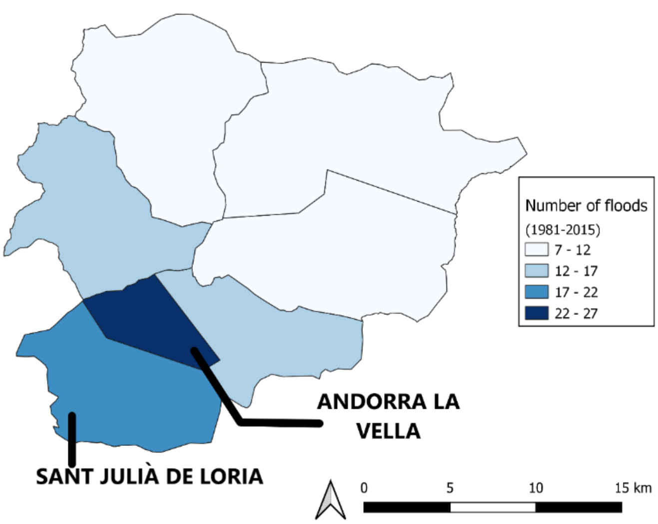


Figure 11: Number of flood episodes that affected each municipality in Andorra between 1981 and 2015. The location of Andorra la Vella and Sant Julià de Lòria is shown.

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5 Temporal analysis

Figure 12 summarises the monthly distribution of the number of flood events for each of the regions. In the case of the Catalan Pyrenees, most events are concentrated between September and November, while in Occitanie the October-November period stands out. In the Aragon Pyrenees, the August maximum stands out, extending the flood period until November. The summer season is also very significant in Andorra, with highs in July and August. In Navarre, the events they are distributed throughout the October-July period, with no remarkable month. This distribution differs from that of Aquitaine, with a greater concentration from May to June, and from that of the Basque Country, with two different periods: June-August and January-March. This distribution leads us to believe that the regions with maxima in autumn are due to Mediterranean disturbances, while the maxima in spring and winter are associated with cold fronts, and summer encompasses convective events. In the same figure the solid line shows how the monthly evolution in the total number of episodes (an episode that affects several regions is considered as a single episode) is unimodal, with a maximum in summer that would be associated with flooding by very intense and local convective rains. This is confirmed by the evolution of the number of flood episodes excluding ordinary ones (see the dashed line in Figure 12), in which the summer maximum disappears to give way to a bimodal distribution with maxima in June and October. The unimodal distribution bears a considerable resemblance to the distribution of the percentage of convective precipitation throughout the year obtained for the Spanish Mediterranean region (Llasat, 2001; Llasat et al., 2021).

The evolution of the flood events that have produced notable damages (extraordinary and catastrophic ones) in the different regions of the Pyrenees, shows high variability (Fig. 12). The trend analysis on a regional scale is only significant at 95% according to the Mann-Kendall test for Nouvelle-Aquitaine, which shows an increase of 0.34 events/dec., that is due to the increase of extraordinary events. For information purposes, although they are not significant at 95%, positive trends were also observed in Catalonia, Navarre, Occitanie and Andorra, although 0.1 ev./dec. is only exceeded in Catalonia and Occitanie. On the contrary, in Aragon and the Basque Country, the trend is negative, but it does not reach -0.1 ev/dec. Taking the Pyrenees massif in its entirety, the trend of notable flood events is positive and equal to 0.5 ev./dec., but it is not significant at 95% or 90% (Fig. 13). On the other hand, if ordinary episodes are also considered, the trend of flood events for the entire Pyrenees increases until 0.85 ev./dec. but if the confidence level is lowered to 90%, the trend is still not significant.

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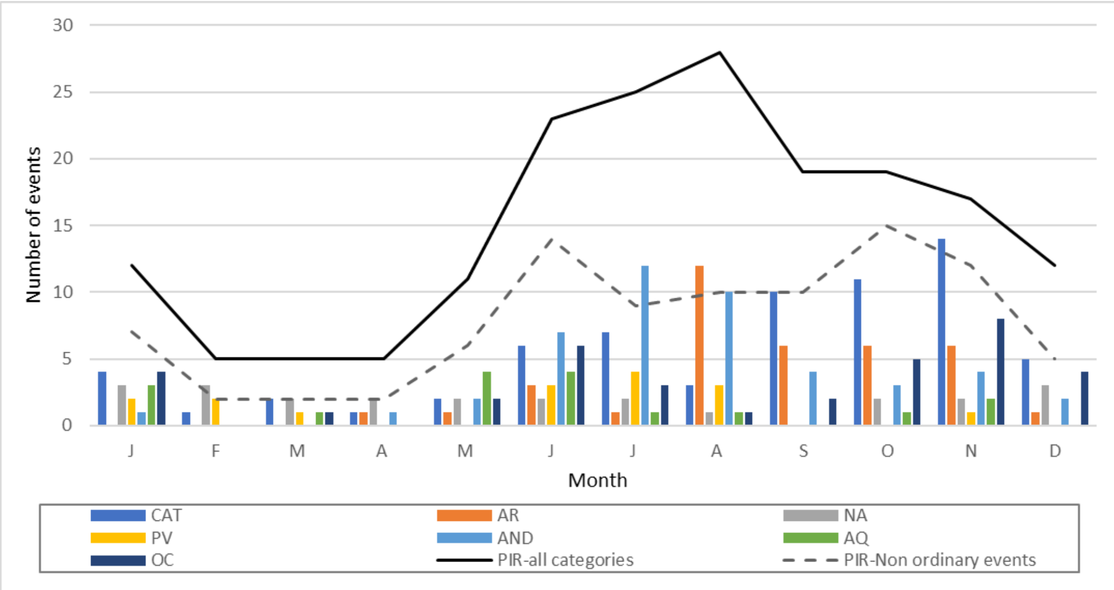

Figure 12: Monthly distribution of the total number of flood cases for the different regions. The solid line shows the entire Pyrenees-POCTEFA region, and the dashed line shows the number of significant events (period 1981-2015).

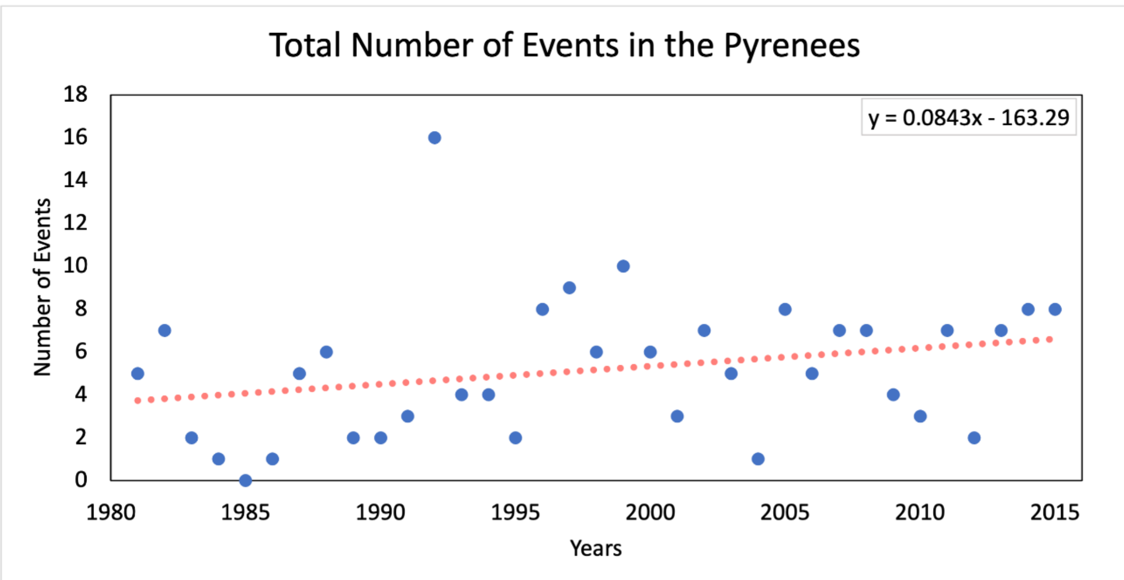

Figure 13: Evolution of the total number of flood events (including ordinary and non-repeated events in the different regions) for the period 1981-2015.

6 Cross-border flood episodes

Of all the recorded events, 41 affected two or more regions (Table 3). Of these, 34 were cross-border, 4 of which did not exceed the category of ordinary in any of the countries, 23 of which were extraordinary in at least one of the countries, and 7

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of which were classified in at least one of the countries as catastrophic. The episodes from 6-8 November 1982 and from 3-7 July 2001 affected the three countries, 8 affected Spain and Andorra and 24 affected Spain and France. Although the month of November recorded the most cross-border episodes, such episodes can occur at any time of the year (February is the only month with no cross-border episodes were recorded). It is important to note that, in general, in summer, such episodes do not usually last more than one day.

Month	Sp-Fr	Sp-And	Sp-And-Fr	Sp	Fr	And
January	2	0	0	6	3	1
February	0	0	0	5	0	0
March	2	0	0	3	0	0
April	0	0	0	4	0	1
May	1	0	0	4	4	2
June	3	0	0	9	4	7
July	1	1	1	11	1	10
August	1	1	0	16	1	9
September	3	1	0	12	0	3
October	4	1	0	12	0	2
November	6	3	1	6	1	0
December	1	1	0	6	3	1
TOTAL	24	8	2	94	17	36

Table 3: Monthly distribution of the number of episodes that affected the Pyrenees-POCTEFA region in the period 1981-2015, differentiating between the episodes that only affected one of the countries or, in the case of cross-border episodes, the countries affected. Sp: Spain, Fr: France, And: Andorra.

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Event dates	SP	FR	AND	Event dates	SP	FR	AND
4-10/11/1982	■	■	■	3-7/7/2001	■	■	■
25-28/8/1983	■	■		16/7/2002	■		■
8-11/11/1984	■		■	3-4/12/2003	■	■	
12-15/10/1986	■	■		12-15/11/2005	■	■	
28/9-5/101987	■	■		9-1/3/2006	■	■	
10-11/10/1987	■		■	3-4/5/2007	■	■	
14-18/11/1989	■	■		22-28/1/2009	■	■	
8-9/9/1992	■		■	10-13/10/2010	■	■	
26-28/9/1992	■	■		1-10/11/2011	■	■	
21-26/9/1993	■	■		19-22/11/2011	■	■	
18-20/10/1994	■	■		18-21/10/2012	■	■	
4/11/1994	■		■	12-16/1/2013	■	■	
2-3/8/1996	■		■	4-7/3/2013	■	■	
5-7/11/1997	■		■	17-20/6/2013	■	■	
16-20/12/1997	■		■	4/7/2014	■	■	
10-15/11/1999	■	■		27/11-1/12/2014	■	■	
10/6/2000	■	■		10/6/2015	■	■	

Table 4: Flood events that affected more than one of the countries of the Pyrenees-POCTEFA region in the period 1981-2015. Affected countries in blue.

Table 4 shows the list of cross-border flood events. As an example, Figure 14 shows the municipalities that were affected by the floods of November 1982. The heavy rains began on 6 November in Spain, and extended to Andorra and France on 7 November, ending the following day. They had a particular impact on the Eastern Pyrenees. The maximum total rainfall was 610 mm in Py (France), 556 mm in La Molina (Spain) and 203 mm in Soldeu (Andorra) (Figure 15). As a result of the floods, 14 fatalities were recorded in Catalonia, with damages valued at €994 $million_{2015}$ (Catalonia), €88 $million_{2015}$ (Aragon) and €132 $million_{2015}$ (Andorra). This flood event is one of the most extensive and intense of the 20th century in southwestern Europe. In it, the mountains played a very relevant role, favoring the orographic ascent and the release of instability (Trapero et al., 2013). The large amount of precipitation that occurred was due to the feeding of water vapor from remote sources, such as the subtropical Atlantic (Insua-Costa et al., 2019).

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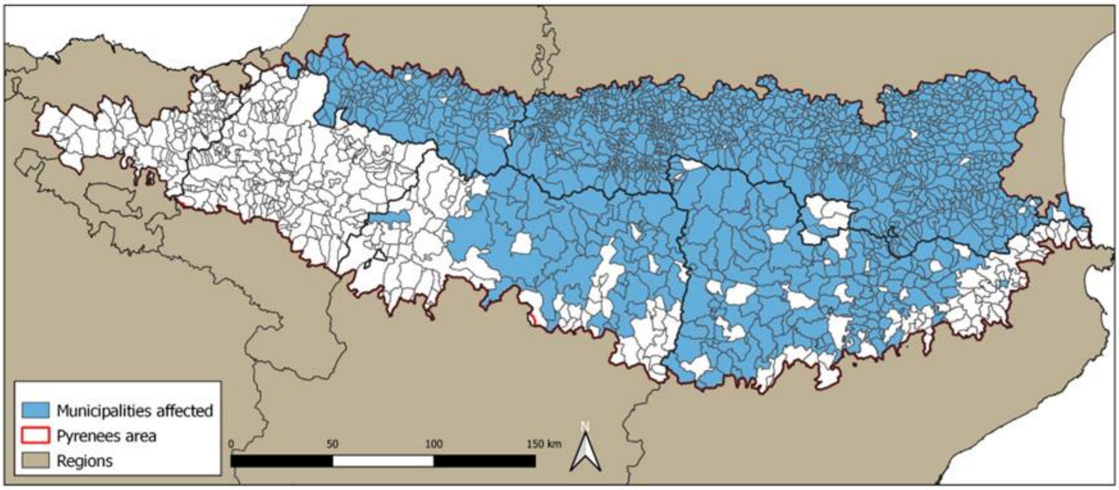
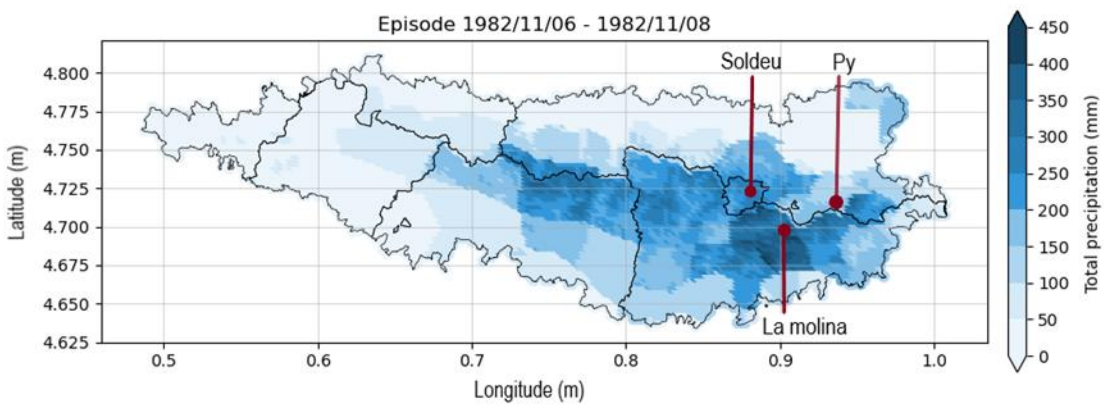


Figure 14: Municipalities of the Pyrenees affected by the floods of 6-8 November 1982.



365 **Figure 15: Precipitation collected between 6 November at 06:00 UTC and 9 November 1982 at 06:00 UTC from SAFRAN reanalysis.**

7 Weather types

Figure 16 shows the 12 weather types (WT) obtained from the combination of mslp and z500, and explaining practically 80% of the variance, corresponding to the flood episodes that affected the Pyrenees between 1981 and 2015. First of all, it should be noted that there is no significant trend in any of the WTs. The WT 1-, characterised by a marked depression to the NW of the Iberian Peninsula and a thalweg is the most characteristic of the episodes affecting the Eastern and Central Pyrenees in autumn (Fig. 17). This favours the advection of warm and humid air from the Mediterranean in low levels, and feeds humidity from remote sources. This was the case during the November 1982 episode (Llasat, 1987), and is the case in a large number of the episodes of intense rainfall that take place in the Western Mediterranean (Insua-Costa et al., 2022; Miró et al., 2022).

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Note in Figure 17 that this type of weather shows its maximum frequency in the month of October, the month with the most episodes of flooding in the Pyrenees.

The WT 3+ shows the formation of a mesoscale depression off the coast of Catalonia that results in instability and the E-SE air flow over the Eastern Pyrenees. The highest frequency is recorded in spring, specifically in June, a month that, as we have already seen, comes after October in terms of flood frequency. An example of this would be the floods of June 2014. These northern movements are usually associated with summer floods and can affect any area in the Pyrenees. The WT 1+ favours the entry of Atlantic air over the Western Pyrenees and, like the WT 1-, can lead to the passage of highly organised disturbances typical of winter or autumn, with notable rainfall accumulations in the western half of the Pyrenees (Lemus-Canovas et al., 2019b). In fact, the highest frequency is recorded in January (Fig. 17). On the other hand, the dominant weather type in summer is WT 2-, which shows in the slight wave over the Iberian Peninsula, while on the surface the situation relatively unclear. It would therefore be a situation favourable to isolated convection or poorly organised weather systems, typical of that time of year, but which can also result in some episodes of very intense rainfall, as also described in Lemus-Canovas et al. (2021). This is the situation that characterised the episode of Biescas (Aragon), which occurred on 7 August 1996, and the floods that affected the Basque Country and Aquitaine in August 1983. Finally, it can be observed that in November the WT 4+ and WT 5+ dominate, both with a very marked groove over the Iberian Peninsula that will favour the vorticity to the east and the contribution of air flow from the Atlantic that feeds intense rainfall, especially in the easternmost sector of the mountain range (Lemus-Canovas et al., 2018). An example is the episode of November 2005, which had a serious impact on Catalonia.

The types of weather associated with cross-border episodes depend on the time of year in which they occur. Of the eight cases recorded between June and August, seven have been characterized by WT 2-. In September, types 2- and 3- dominate. In October and November, which have recorded 16 common episodes, there is no dominant type of weather, and it is even the case that unusual types appear, such as 4-, characterised by a deep depression to the west of the British Isles that extends up to 500 hPa and even more, with a groove that crosses the Peninsula from northwest to southeast.

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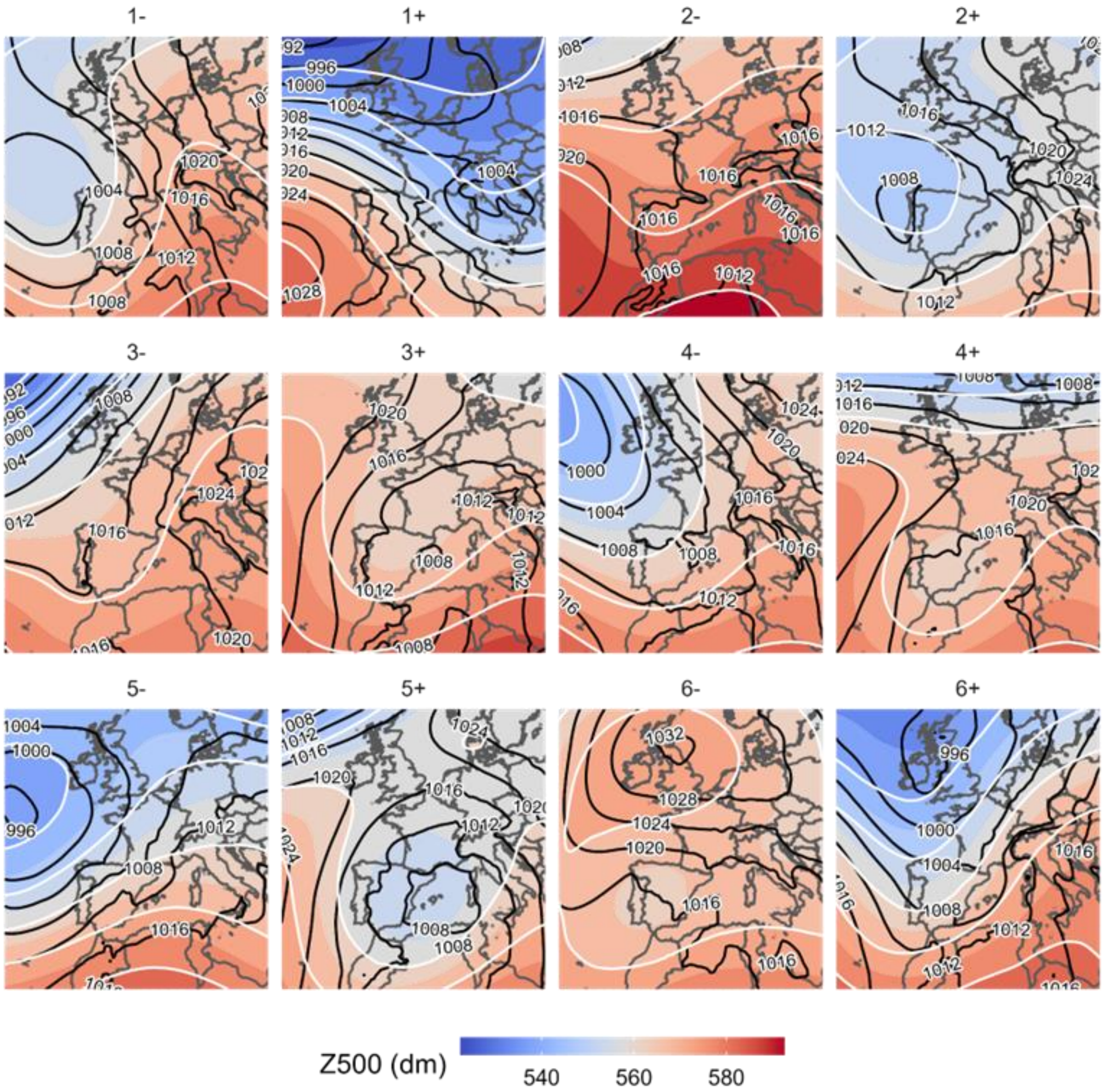

Figure 16: Types of weather that characterise flood episodes in the Pyrenees.

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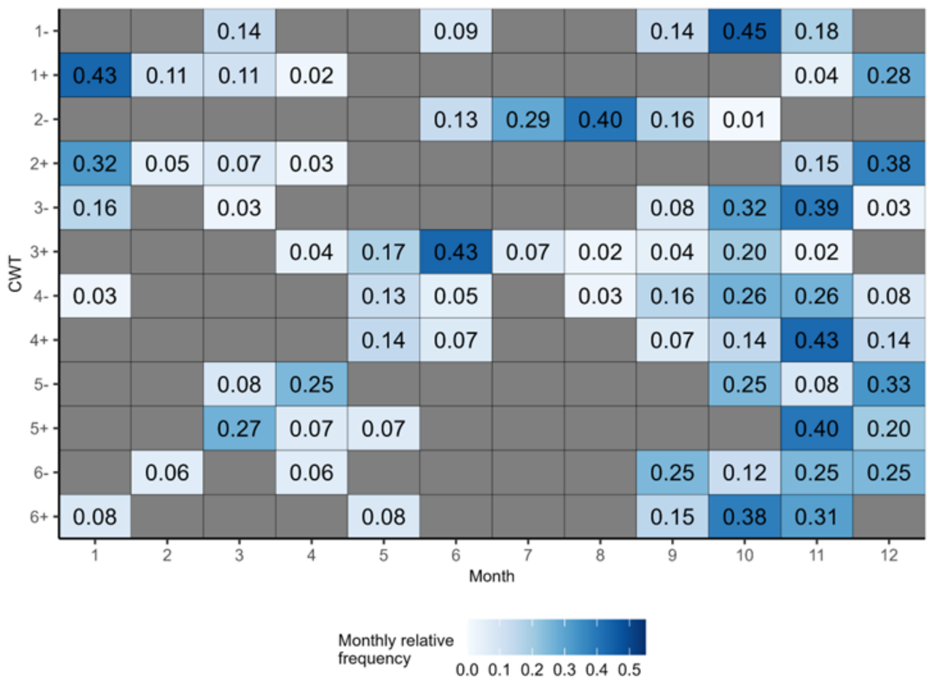

Figure 17: Monthly distribution of the frequency with which each weather type is recorded.

8 Discussion and conclusions

From the analysis of the flood episodes recorded in the Pyrenees massif between 1981 and 2015, it can be concluded that the region with the greatest number of episodes is Catalonia (66 episodes), although only 4.5% produced catastrophic damage to the massif. Andorra follows, with a total of 46 events, of which 4.3% were catastrophic. However, the one that records the most serious events in terms of percentage is Nouvelle Aquitaine, since, of the 17 events recorded, 35% were catastrophic. Note that, if the ordinary events are not taken into account, Catalonia is still the one with the most events (29), followed by Aragon (26) and Occitanie (24). It follows that the eastern part of the Pyrenees is the most affected by flood episodes, some which had catastrophic impacts. If we take into account that some events can affect more than one region, the number of events that produced floods in the Pyrenees is 181, of which 128 affected Spain, 43 affected France and 46 affected Andorra. Of these, 34 were cross-border. The November 1982 episode was the most extensive and in fact affected much of Spain and France, in addition to Andorra. The other very extensive episode took place in June 2013.

The economic impacts are not available in France and Andorra, and in the case of Spain, only the compensation paid by the Insurance Compensation Consortium between 1996 and 2015 are known. In total, the CCS paid €142.5 million$_{2015}$ for flood damage in the Spanish Pyrenees. For this period, and despite being in third position in terms of the number of events, Navarre is the region that received the most compensation in terms of damage for events, with a total of €65.8 million$_{2015}$. This high amount compared to Catalonia, which recorded more than twice as many events, is explained as Pamplona (the capital of Navarra) is within the Pyrenees region, and received payments worth €18 $million_{2015}$ in 2015. In this case, the risk of flooding is greater due to the high exposure and vulnerability, despite a moderate hazard compared to other Pyrenees regions. Something similar could take place in Catalonia on a regional and municipal scale. Although the Val d'Aran was not as affected by floods as other Catalan regions, it is a rich region, with a municipality, Vielha, to which the CCS paid more than €5 $million_{2015}$ for damage caused by floods from 17-20 June 2013. The latter was the most expensive episode since 1996, with an amount worth €27 $million_{2015}$ claimed in the Spanish Pyrenees. However, including the non-Pyrenees part of Aragon and Catalonia, this amount rose to €31 $million_{2015}$, and in France (mainly Occitanie) it rose to €240 $million_{2015}$ in insurance compensation alone (public works are considered to have exceeded this amount). The most expensive episode in Spain since 1981 however, if we take into account all of the autonomous communities affected, was 25-28 August 1983, which resulted in a total of €2.9 $billion_{2015}$ in compensation paid out in the Basque Country, Navarre and Cantabria. This high amount is a consequence of the serious damage suffered in the Basque Country, mainly in industrial areas.

The number of victims is closely linked to specific cases, such as the floods of August 1996 in Biescas and the flooding of November 1982, in which the majority of the deceased were swept away by water in their home or summer residence. Apart from these cases, fatalities are normally people who tried to cross a river, usually in a vehicle, or people doing adventure sports. The total number of victims in the Spanish Pyrenees was 121, with 13 in Andorra and 20 in the French Pyrenees.

The flood season starts in May in the Atlantic region and progresses to reach a maximum in autumn in the Mediterranean regions. Catalonia, Aragon, Navarre and Occitanie all share the month of October among the months that record the highest number of events. Basque Country and Nouvelle Aquitaine share the month of June in common, while in Andorra is summer. If we only take into account events that caused significant damage (extraordinary and catastrophic episodes according to the nomenclature agreed here), in order to unify the criteria—since it is possible that the information for all the ordinary episodes is not always available—a positive trend can be observed across the entire massif of 0.5 ev./dec., although it is not significant at 90%. However, if the ordinary episodes are included, the trend becomes 0.84 ev/dec., and it is significant at 95%. When analysing in terms of communities, Nouvelle Aquitaine is the only region with a significant positive trend (0.34 ev./dec.). It is striking that this level is not recorded in the Basque Country or in Navarre, which share an administrative—although not strictly geographical—border with Nouvelle Aquitaine.

From the classification of weather types, it can be concluded that most are dominated by southern component flow over the Pyrenees region, with a thalweg on the Iberian Peninsula. There is a frequent depression in the vicinity, either in the Atlantic or in the Mediterranean, which is in line with the studies carried out on intense rains in the Mediterranean region (according to the IPCC classification (2021), the Pyrenees massif would be included in the region) (Jansà et al., 2014). This type of configuration favours vorticity advection at the medium and upper part of the troposphere and the consequent instability at low levels, the advection of warm and humid air and, occasionally, the contribution of humidity from remote sources. No specific weather type is observed for cross-border episodes.

Apart from generating knowledge about floods in a mountainous region like the Pyrenees, this study also has an important social objective. The aim is to make the population living in the Pyrenees and who practice hiking or any other mountain sport aware that floods are also very important in this region and cause serious damage and even fatalities. This study was carried out in the context of the Interreg PIRAGUA project, and the meetings with the stakeholders showed that the awareness regarding floods in the Pyrenees was very low. Finally, Appendix A has been added detailing the fields of the database so that if desired it can be reproduced on another site.

Data availability. The dataset of flood episodes in the Pyrenees massif showed and analysed in this paper is available at http://hdl.handle.net/10261/270351.

Author contribution. MCLL contributed with the funding acquisition, conceptualized, and conducted the research, and prepared the manuscript with contributions from all co-authors; MLLB was responsible of data curation; RMM and MLC did de formal analysis and software; EP was responsible of the visualization.

Competing interests. One of the authors is members of the editorial board of journal NHESS.

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Appendix A

The database was built in EXCEL and is composed of two linked tables: a) Events; b) Affected municipalities.

a) Events

Identification of the episode:

- Integrated Event Code: the numerical code used to identify the global event, when episodes that have affected more than one region belong to an event. If the episode only affected one region, it will be the same as the corresponding event code.
- Event: Numeric field composed of the start and end dates of the event. In events that occurred across several municipalities, the dates are unified on the common basis of all regions (resulting in the integrated event code), but the original date is maintained on the individual basis of each region.
- Start date: Start date in date format. Indicates the beginning of the episode.
- End date: Date of the end of the episode in date format. Indicates the end of the episode.

  Criteria:
  - The event starts when the rain starts in the region.
  - The event ends when the flood or tangible damage ends.
  - The event lasts while heavy rain, damage or floods are occurring and ends when they cease to occur. A subsequent episode is considered a new episode when there is more than one day (at least) without any of these points occurring.
- Region: Indicates the administrative region affected by the event: SPAIN: Aragon (AR), Catalonia (CAT), Navarre (NA), Basque Country (PV); FRANCE: Aquitaine (AQ); Languedoc-Roussillon (LR); Midi-Pyrénées (MP); ANDORRA (AND)

- Location 1: List of affected counties or departments
- Location 2: List of affected municipalities
- Number of municipalities affected: number of municipalities that suffered damage
- Affected area (Km^2): Sum of the total area of the affected municipalities, in Km^2

Meteorological and hydrological information indicators for the episode:

- Precipitation: Data included when the information is available. Maximum total precipitation during the episode in mm and location of the rainfall station where it was recorded; maximum precipitation in 24h in mm and location of the rainfall station where it was recorded; maximum rainfall intensity in mm/h and duration of this, and location of the station where it was recorded.
- Other meteorological data: Optional field to add rainfall data from other sources, or other data, as deemed appropriate.
- Other weather phenomena: Field to indicate if other adverse natural phenomena occurred in addition to floods. The following are included:
    - Rock slide/landslide
    - Hail
    - Snow
    - Wind storm
    - Tornado
    - Thawing
- Affected drainage basins: List of affected river basins.
- Flow rate: Maximum instantaneous flow recorded in m^3/s indicating the river, rainfall station and date, in addition to the average annual flow in m^3/s. If information is available for more than one river, it is included.

Episode impact indicators:

- Category: The Category of the event according to the criteria described in section 3.1.

b) Municipalities

Fields:

- Integrated Event Code: this is the numerical code described above.
- Event: An event code that allows you to link this table with the “Events” table; the same code that identifies the event in the “Events” table must be used.
- Event category: the event category.

- MunicipalityID: Code (in NATCODE and/or equivalent, which allows you to locate it with GIS) of the municipality affected by the floods. Each row is for a municipality, which means an event can have more than one row.
- Location name: Name of the municipality.
- Deceased: Total number of fatalities in the municipality (if any).
- Gender and age of victims: When information is available, the gender and age of each victim is indicated.
- Causes: A brief description of the causes of death.
- Other information: Necessary information that is not covered in the other fields.
- Region: region to which the municipality belongs