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

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Abstract. This paper shows 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 talweg 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. In general, they cause local damage in coastal populations or mountainous regions, which can sometimes be very serious. Other times they can affect large regions, as happened with the Gard floods (France) in 2002 (Braud et al., 2010). Most of these episodes do not appear in the best-known flood databases such as EM-DAT (https://www.emdat.be/) or Munich Re's NatCatSERVICE (https://www.munichre.com/en/solutions/for-industry-clients/natcatservice.html), because these databases are often based on indirect information (i.e. 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., 2013a; Wirtz et al., 2014). For example, there are very few such episodes that have affected the Pyrenees Mountain region on these databases. More systematic and precise studies are therefore necessary, but the high workload required to elaborate these studies means that they are only available for few regions. This is the case of INUNGAMA (Llasat et al., 2014) that includes all the flood events that have affected Catalonia (NE Spain) between 1900 and 2020 (partial information available in the Flood Observatory of Catalonia, https://experience.arcgis.com/experience/484172e12fae4cbb934441203ee04e36/), and FLOODHYMEX (Llasat et al., 2013b), which currently includes all the catastrophic flood episodes (following the criteria of "catastrophic" introduced in Barriendos et al., 2003) that have affected Catalonia, Valencian Community 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 all Greece (available at https://mistrals.sedoo.fr/catalogue/).

On the other hand, concern about the impact of climate change in mountainous regions, including natural hazards, has grown significantly in recent decades. Proof of this is the increase in publications on this topic (i.e. Beniston, 2003; Beniston and Stoffel, 2014; Zimmermann and Keiler, 2015; Steiger et al., 2022) including a cross-chapter devoted to Mountains in the Sixth Assessment Report of IPCC (2022). There are, however, few studies that address mountain massifs in their entirety from a climatic or meteorological perspective. This is the case of the Pyrenees, a cross-border mountainous region between Spain, France and Andorra. To facilitate the international management of a massif distributed between three countries, the Pyrenees Working Community (CTP) was created, which in turn founded the Pyrenean Climate Change Observatory (OPCC, https://www.opcc-ctp.org/en) that promotes the observation and research on climate change from a multidisciplinary approach. Given that 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, the OPCC promoted the PIRAGUA project financed by the European call for projects POCTEFA (https://www.opcc-ctp.org/en/piragua) and whose results are available to the public in the OPCC Geoportal (https://www.opcc-ctp.org/en/geoportal) and the publications of Beguería et al. (2023a, 2023b). Among these results, noteworthy are those obtained from trend analysis. Clavera-Gispert et al. (2023) show that in autumn there is a predominance of significant negative trends throughout the mountain range, mainly in September, for low (P10) average (P50) and high flows (P90), for the period 1980-2013. A similar predominance is observed in summer, while only a relevant significant positive trend is observed in the western part (Basque Country, Spain), in the month of March. The decrease in flow throughout the mountain range is more clearly manifested when the period is reduced to 1990-2013. This negative trend becomes more pronounced, even on an annual scale, when analyzing projections of annual precipitation for the middle and end of the century, especially in the western part of the Pyrenees, while in the eastern part, especially in Catalonia (Spain), an increase is observed, which will also be reflected in the average annual flows (Beguería et al., 2023a). CLIMPY, another project from OPCC, concluded that the projections for the next seventy years do not showed a significant trend in the heavy precipitation index (CP95) at the mountain range scale; only a certain decrease could be detected in the south-eastern slope (Catalonia, Spain) and a certain increase in the northern and western parts (French basins, and Navarre and the Basque Country in Spain) (Amblar-Rancés et al., 2020). In this context arises the question about extremes, and specifically, about floods.

One of the objectives of PIRAGUA was the analysis of floods in the entire Pyrenean region, where flash floods, can have a great direct impact on both the fixed and floating population, as well as on water services and energy resources. Some examples are the catastrophe at Camping las Nieves, in Biescas (Aragón, Spain), on August 7, 1996, in which 87 people drowned (García-Ruiz et al., 1996); the June 2013 floods with catastrophic damages in Spain and France (https://hepex.org.au/flash-floods-in-the-french-western-and-central-pyrenees-17-19-june-2013/); or the floods produced on 7 November 1982 (Trapero et al., 2013) that affected the three Pyrenean countries. The recent death of two people who were canyoning in the Pyrenees of Aragón (Spain) on September 2, 2023, when a flash flood event occurred is another example of this type of event that most people are unaware of. 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. For this reason, in the same way that the final objective of FLOODHYMEX (Llasat et al., 2013) was to cover the entire Mediterranean region, it was decided to create a similar database for the Pyrenees, but that included all types of flood episodes. 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, analyze the trends in light of the most recent articles (Clavera-Gispert et al., 2023), and characterize the weather types favourable to these flood events. 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, the criteria followed for its construction, and the sources of information used are shown. 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, where some adaptation measures are also commented.

2 Area of study and sources of information

2.1 Area of study

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 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 (Table 1).

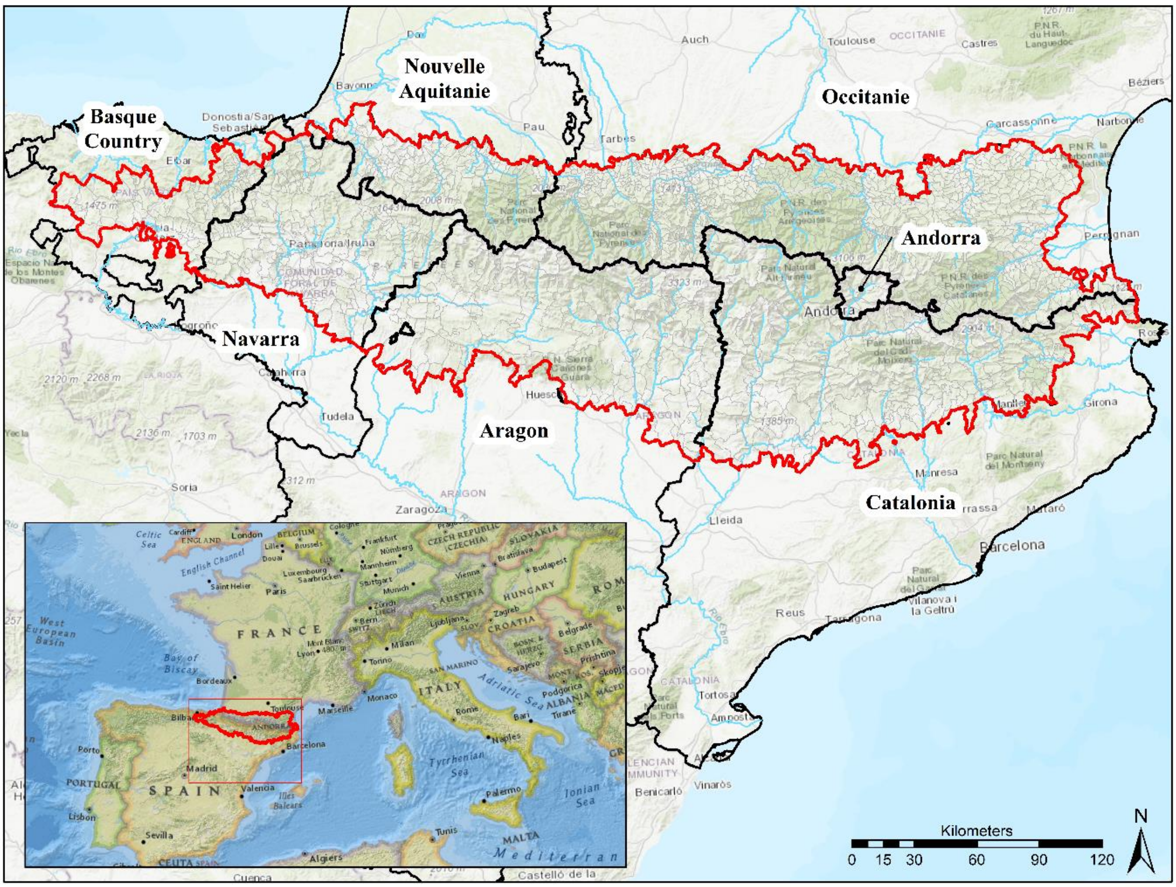

Figure 1: Map of the Pyrenean municipalities located within the area defined as the Pyrenees by the OPCC. The frontiers and names of the Pyrenean regions are also included.

2.2 Sources of information and identification of flood events

Table 1 shows the main physical and socioeconomic characteristics of the study area as well as the sources of information used to identify all the flood events that have affected de Pyrenean Region. 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) and the information from the Spanish Insurance Compensation Consortium (CCS, 2021) were also used. The CNHI catalogue was published by the General Directorate of Civil Protection in Spain and contains the most important flood events (DGPC, 2022). It is made up of reports made for the different river demarcations into which Spain is divided, observing some heterogeneities, such as the fact that the same event can be in two reports associated with different dates, which requires careful contrast with other sources. The CCS provided, for the period 1996-2015, the compensation paid to municipalities in the Pyrenees, organized by postal code and 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 by a flood event was considered to be the sum of the compensations due to floods between the initial day of the event and the final day, with an additional 7 days, as in Cortès et al. (2019). Data from CCS has been also useful to identify some minor flood events that haven't been found in the other sources of information. Finally, in the case of Catalonia, Aragón and Navarra, the information was completed based on news from La Vanguardia, El Heraldo de Aragón and Diario de Navarra, newspapers, respectively. La Vanguardia had already been systematically consulted, day by day, for the construction of the INUNGAMA database (Llasat et al, 2014), part of which was included in FLOODHYMEX (Llasat et al., 2013) and PIRAGUA_flood (Llasat et al., 2022). Given that day-to-day consultation of newspapers is extremely slow, in the case of Aragon and Navarra only the cases identified from the rest of the sources cited above were consulted plus the government press releases and the days of rain that exceeded 40 mm (threshold fixed following the criteria of Cortés et al., 2019). This information was obtained from the precipitation field provided by the SAFRAN analysis (Quintana-Seguí et al., 2016). In the case of the Basque Country and Andorra, the project partners, through whom we obtained the information, confirmed that it was complete, so it was not necessary to consult the newspapers, since the creators of the respective episode lists had done so.

For Nouvelle Aquitaine (AQ) and Occitanie (OC), the databases of the Central Reinsurance Company (*Caisse Centrale de Réassurance* – CCR) and the National Observatory of Natural Risks (*Observatoire National des Risks Naturels* - ONRN) were used to create PIRAGUA_flood. In this case the information was completed in basis to the extreme rainfall records of Météo France. This ensured that all episodes that produced notable damage were included, although it is possible that some minor flood events with little damage have gone unnoticed.

Table 1. Main characteristics of the study area. N.munic.: number of municipalities; Total pop.: total population; GDP: mean Gross Domestic Product for the region for the year indicated in the table ; *: value relative to the part of the region that belongs to the Pyrenees. CNIH: Catálogo Nacional de Inundaciones Históricas (National Catalog of Historical Floods); INE: Instituto Nacional de Estadística (National Institute of Statistics); PERICFN: Plan de Emergencia ante el Riesgo de Inundaciones en la Comunidad Foral de Navarra (Emergency Plan for the Risk of Floods in the Foral Community of Navarra) (https://gobiernoabierto.navarra.es/es/gobernanza/planes-y-programas-accion-gobierno/plan-emergencia-ante-riesgo-inundaciones-comunidad); EPRI: Evaluación Preliminar del Riesgo de Inundación (Preliminary Flood Risk Assessment of the

2nd Cycle of the Eastern Cantabrian Hydrographic Area); CCR: Caisse Centrale de Réassurance (Central Reinsurance Company) (https://catastrophes-naturelles.ccr.fr/); ONRN: Observatoire National des Risques Naturels (National Observatory of Natural Risks) (https://www.georisques.gouv.fr/articles-risques/onrn/acceder-aux-indicateurs-sinistralite#summary-target-1); INSEE: Institut national de la statistique et des études économiques (National Institute of Statistics and Economic Studies) (https://www.insee.fr); CENMA-IEA : Centre d'Estudis de la Neu i de la Muntanya d'Andorra-Institut d'Estudis Andorrans (Andorra Centre of Snow and Mountain Studies-Andorra Studies Institute). GDP data have been obtained from https://Datosmacro.Expansion.Com/Pib/Espana-Comunidades-Autonomas (Spanish regions), https://fr.statista.com/statistiques/479490/pib-par-habitant-selon-regions-france/ (French regions), https://datosmacro.expansion.com/pib/andorra (Andorra)

Region	**Country**	**N.Munic.***	**Area**(km^2)*	**Total pop.***	**GPD**(M€)	**Information sources**
Catalonia (CAT)	Spain	213	12,027.38	255,804	255,154 (2022)	INUNGAMA (Llasat et al, 2014); FLOODHYMEX (Llasat et al, 2013); CNIH (DGPC, 2022); CCS, 2021; La Vanguardia newspaper; INE.
Aragon (AR)	Spain	122	10,594.59	60,624	41,763 (2022)	CNIH (DGPC, 2022); CCS, 2021; El Heraldo de Aragón newspaper; INE.
Navarra (NA)	Spain	186	6,418.75	462,932	22,595 (2022)	CNIH (DGPC, 2022); CCS, 2021; PERICFN; Diario de Navarra newspaper; press releases from the Government of Navarre; SAFRAN (Quintana-Seguí et al., 2016), INE.
Basque Country (PV)	Spain	87	2,585.55	222,533	79,350 (2022)	CNIH (DGPC, 2022); CCS, 2021; EPRI (CHC and URA, 2018); INE.
Nouvelle Aquitaine (AQ)	France	162	3,697.2	104,568	189,300 (2021)	FLOODHYMEX (Llasat et al, 2013); CCR; Météo France; ONRN; INSEE.
Occitanie (OC)	France	1025	14,711.01	409,040	181,300 (2021)	FLOODHYMEX (Llasat et al, 2013); CCR; Météo France; ONRN; INSEE.
Andorra (AND)	Andorra	7	468	815,888	3,210 (2022)	CENMA-IEA; Database of the Ministeri d'Ordenament Territorial (Ministry of Territorial Planning) of the Government of Andorra.

3 Database structure and methodology

3.1 Development of the database

The database was built in ACCESS but to facilitate its use by any person interested in it, the public version is in EXCEL. It is made up of two tables: a) Events; b) Affected municipalities that are linked throughout the event code (Fig. 2). Tables 2 and 3 show the information and criteria used to create each one of these tables that follows the example of FLOODHYMEX and INUNGAMA databases.

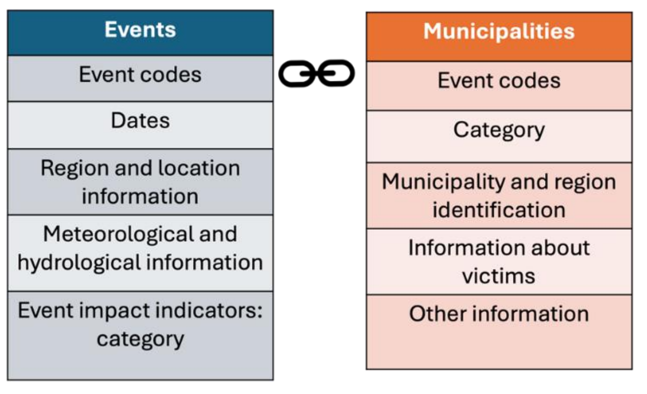

Figure 2. Structure of the PIRAGUA_flood database

Table 2. Information and criteria used to fill out the EVENTS table.

Event codes	**Integrated Event Code**: numerical code used to identify the event that have affected one or more regions. Indicates the first and last day on which the event has been registered in the entire Pyrenean region.
	Event: Numeric field composed of the start and end dates of the event in the specific region
Dates	**Start date**: Indicates the beginning of the episode in the specific region.
	End date: Indicates the end of the episode in the specific region. Criteria: -The event starts when the rain starts in the region. -The event ends when the flood ends.

	-A subsequent episode is considered a new episode when there is more than one day (at least) without any of the previous conditions occurring.
Location information	**Region**: Indicates the administrative region affected by the event: Aragon (AR), Catalonia (CAT), Navarre (NA), Basque Country (PV); Aquitaine (AQ); Languedoc-Roussillon (LR); Midi-Pyrénées (MP); Andorra (AND)
	Location 1: List of affected counties in the specific region
	Location 2: List of affected municipalities in the specific region
	Number of municipalities affected: number of municipalities that suffered damages in the specific region
	Affected area (Km^2): Sum of the total area of the affected municipalities, in Km^2
Meteorological and hydrological information	**Ptotal (Loc), Pmax (24 h) (Loc) o P (h) (Loc) (mm)**: It indicates the maximum cumulated precipitation in all the event or/and the maximum precipitation in 24h in mm or/and the maximum rainfall intensity in mm/h and its duration. In the three cases the station where the value was recorded is indicated.
	Other meteorological data: Optional field to add more hydrometeorological information.
	Other weather phenomena: Other adverse natural phenomena occurred in addition to floods: landslide, debris flow, hail, snow, windstorm, tornado, snow melting, lightning.
	Affected drainage basins: List of affected river basins
	Maximum flow (m^3/s): Maximum instantaneous flow recorded indicating the river, gauging station and date, in addition to the average annual flow. If information is available for more than one river, it is included.
Event impact indicators	**Category**: The category of the flood event in the region according to the criteria described in section 3.1. There is a column for each category and supplementary category

Table 3. Information and criteria used to fill out the MUNICIPALITIES table.

Event codes	**Integrated Event Code**: numerical code used to identify the event that have affected one or more regions. Indicates the first and last day on which the event has been registered in the entire Pyrenean region.
	Event: Numeric field composed of the start and end dates of the event in the specific region. The same code that identifies the event in the "Events" table must be used.
Category	**Event category**: Category: The category of the flood event in the region according to the criteria described in section 3.1. There is a column for each category and supplementary category
Municipality and region identification	**MunicipalityID**: Code (NATCODE, INSEE or equivalent) 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.
	Region: region to which the municipality belongs
Information about victims	**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	**Other information**: Supplementary information that is not covered in the other fields.

The category of flood events is based on the level of impacts and is divided into categories: 0 (ordinary), 1 (extraordinary), 2 (catastrophic), and 3 (major catastrophic), according to Fig. 3, inspired by the criteria presented in previous publications (Barriendos et al., 2003; Llasat et al., 2013, 2016; Barrera-Escoda and Llasat, 2015). However, in these publications, the distinction between categories was purely subjective. In order to facilitate its reproduction by other authors, a table has been designed to help decide in which category an event can be classified. Firstly, the "Damage indicators" have been selected based on literature (Petrucci, 2013; Boudou et al., 2016; Vinet et al., 2016). For each one of the indicators, the "Damage level" has been analyzed, where level 1 refers to possible minor damage (small floods in basements, breakdowns in traffic lights, etc.), level 2 refers to medium damages (it includes floods inside buildings and on communication routes which can cause traffic interruptions, partial damage to infrastructure, etc.), and level 3 refers to major impacts in the indicator (partial or total destruction of buildings, roads, bridges, long lasting supply cuts, etc.). To classify flood episodes into categories, the level of damage in each of the seven indicators is taken into account, as shown in Fig. 3. Fatalities are not included in Fig. 3 as they can occur in any flood event category, although they are more likely to occur in catastrophic floods. The same applies to vehicles, as 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 information has been included in the database, with the code of "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 determines the category of the episode.

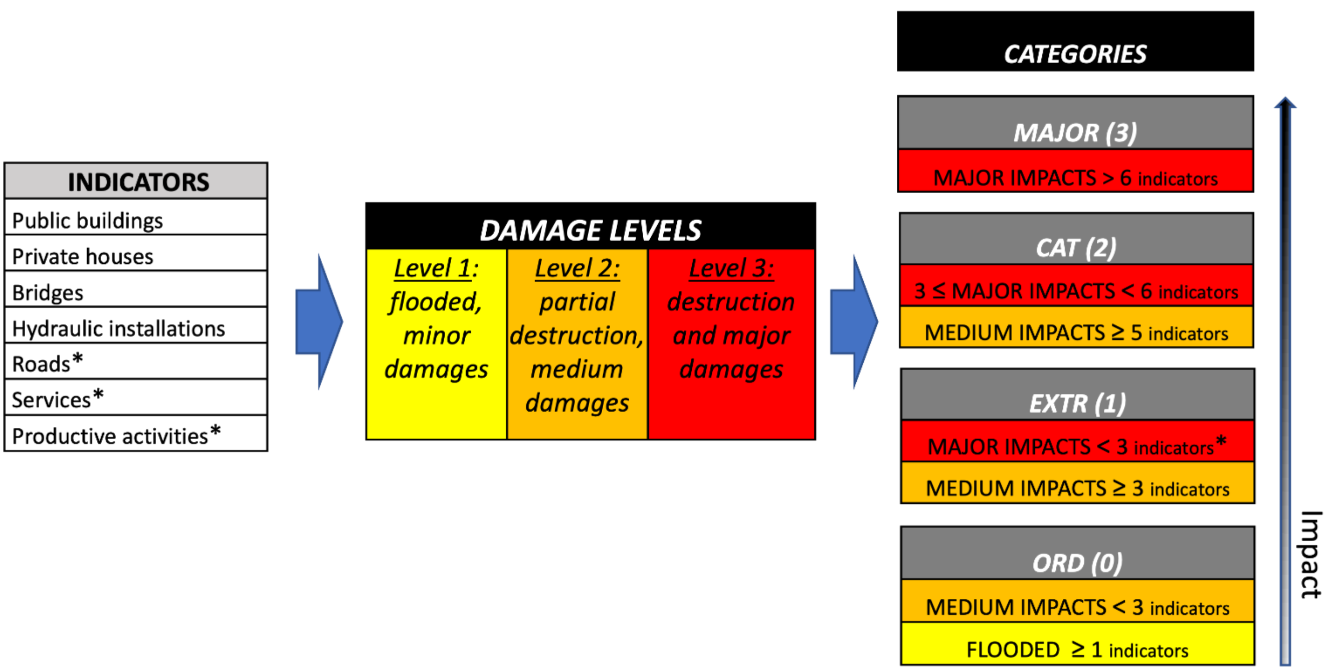

Figure 3. Criteria for categorizing flood events based on impacts. ORD (0): Ordinary flood event; EXTR (1): extraordinary flood event; CAT (2): catastrophic flood event; MAJOR (3): major catastrophic event. The level of damage is estimated from the direct impacts experienced, and a color scale is used (level 1: yellow; level 2: orange; level 3: red).

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) (https://www.icgc.cat/es/Administracion-y-empresa/Descargas/Capas-de-geoinformacion/Divisiones-administrativas). 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 (Eurostat https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/countries). 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 the monthly evolution of the events, in average, and the study of the possible annual trends. These analyses were carried out for the Pyrenees as a whole, as well as for the regions of Catalonia, Andorra, Aragon, the Basque Country, Navarre, Aquitaine and Occitanie. Likewise, for the severity of flood events, their evolution was studied considering the total number of events of each category per year (0, ordinary; 1, extraordinary; 2, catastrophic; or notable - combined number of extraordinary and catastrophic).

A linear regression was used to obtain the trend, while Mann-Kendall test was implemented 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 ($p < 0.05$).

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. The original hourly data spanning from 1981 to 2015 were averaged on a daily scale to compute the synoptic classification described below.

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 the Scree test plot (Cattell, 1966), shown in Fig. 4.

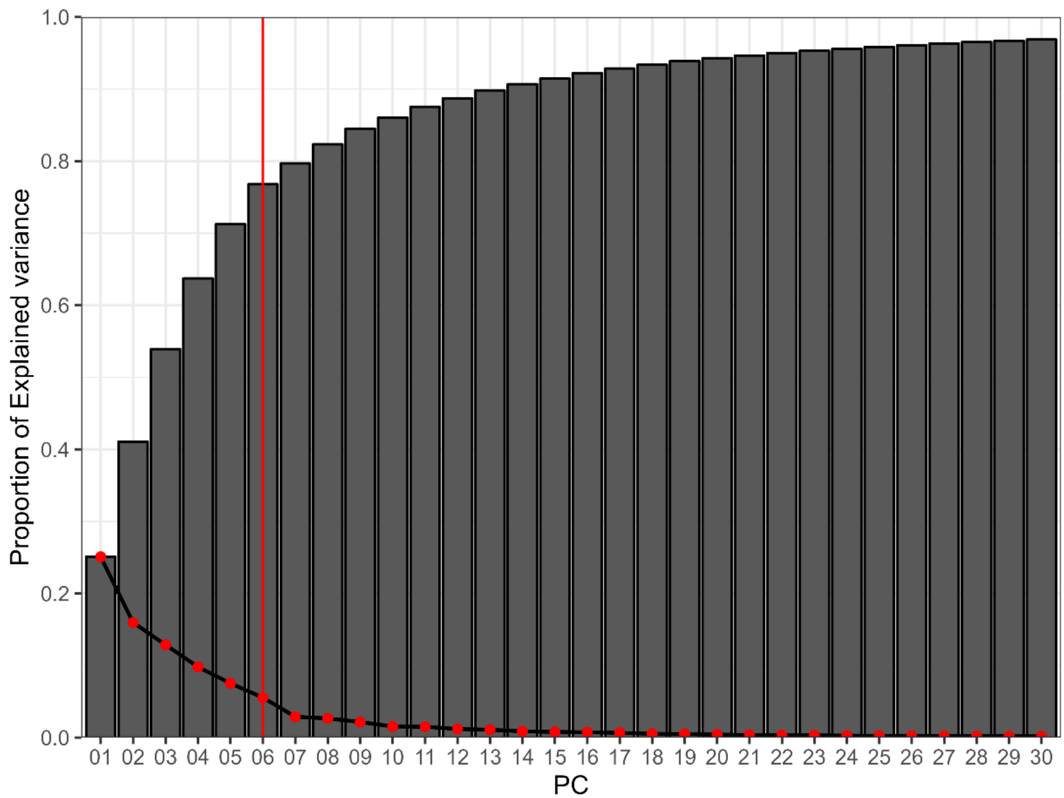

Figure 4. Scree test for the first 30 principal components (PCs). The red dots show the explained variance (%) for each principal component, while the grey bars show the cumulative explained variance. The red vertical line indicates the cut off PC. Thus, 6 PCs were retained accounting for the 78% of the total variance.

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 4 has been provided in order to summarise the information that will be analysed in this section. 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 this article, it is considered 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 places. This clarification is necessary because in other articles (i.e. Barriendos et al, 2019; Gil-Guirado et al., 2019) the criterion used is based on the sum of all the locations where flooding has occurred. If it would be considered the number of times the regions have been affected by flood events, the figure of 242 would be obtained, but if the criteria just explained is taken into account, it is concluded that the Pyrenees massif was affected by 181 flood episodes between 1981 and 2015. 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 or they affected different regions from the same country, with a total of 41 "transregional" episodes. One example was the flood event that occurred between June 17 and 19, 2013, that affected Spain and France. In Catalonia, the municipalities with the greatest damage due to the 2013 event were Salardú, Arties, Escunhau, Vielha, Bossòst, and Les; in Aragon, it was Cerler, Castejón de Sos and Benasque; in Aquitaine, there was catastrophic damage in Lourdes and Arreau (Hautes-Pyrénées), Nay (Pyrénées-Atlantiques) and Saint-Béat (Haute-Garonne). Some towns were isolated due to road damage, landslides or rock falls. Numerous bridges, some buildings and campsites were totally or partially destroyed by the violent floods that carried rocks and remains of vegetation. Numerous houses and crop lands were flooded, causing cuts in all types of supplies. It was, therefore, a flood event of category 3 (major).

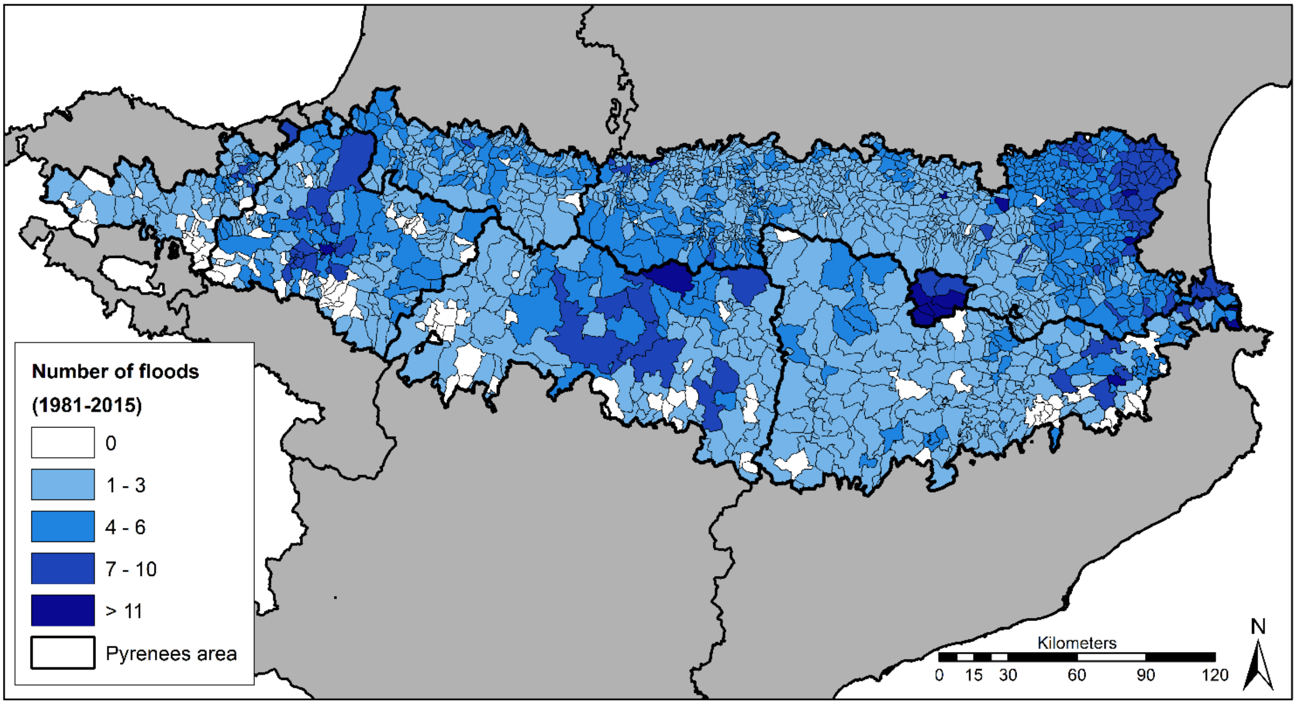

Figure 5: Number of flood events that affected each municipality in the Pyrenees between 1981 and 2015.

Figure 5 shows that the highest concentration of flood episodes occurs in Andorran municipalities and in the easternmost area of Occitanie and Catalonia. Some municipalities in Aragón and Navarra also stand out, while in the Basque Country and Nouvelle Aquitanie, no municipality have recorded more than 7 episodes of flooding. The region with the highest total number of flood events was Catalonia (66), followed by Andorra (46), while the lowest number was recorded in the Basque Country (16) (Fig. 6). Andorra is the region that records the highest percentage of ordinary floods (67.4%) although the absolute maximum corresponds to Catalonia. This regional difference may be related to both the orography and the meteorological disturbances causing intense rains, which will be discussed later. The highest number of catastrophic flood events was recorded in Nouvelle Aquitaine, followed by Occitanie and Aragón.

We cannot forget, however, that it is possible that some ordinary floods in France have gone unnoticed, as we have explained in section 2.2. This is why Fig. 7 has been constructed. It shows the distribution by municipality of flood events with notable damage (that is, they were extraordinary or catastrophic). The distribution hardly changes with respect to Fig. 5, and only the maxima of some municipalities are smoothed out. Of the 181 flood events, 52% produced notable damages in one or more of the Pyrenean regions. 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. Pamplona (Aragón) and Llançà (Catalonia) have been the municipalities with the major number of flood events (17 and 16, respectively). For the period 1996-2015, the number of flood episodes in both regions becomes 9 and 11, respectively, with a compensation paid by the CCS that amounts to €18 M_{2015} and €1.1M_{2015}, respectively. In the same period, Vielha (Catalonia), which after Pamplona is the municipality to which the CCS has paid the most, collected €9.9 M_{2015} in compensation for one episode. This difference is consequence of the major exposure 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 GDP is €170.2 M_{2015}, practically double that the GDP of Llançà, with €91.9 M_{2015} that partially explains the different impacts between both Catalan villages, added to the fact that the 2013 flood in the Garonne River was catastrophic in Catalonia and Occitanie.

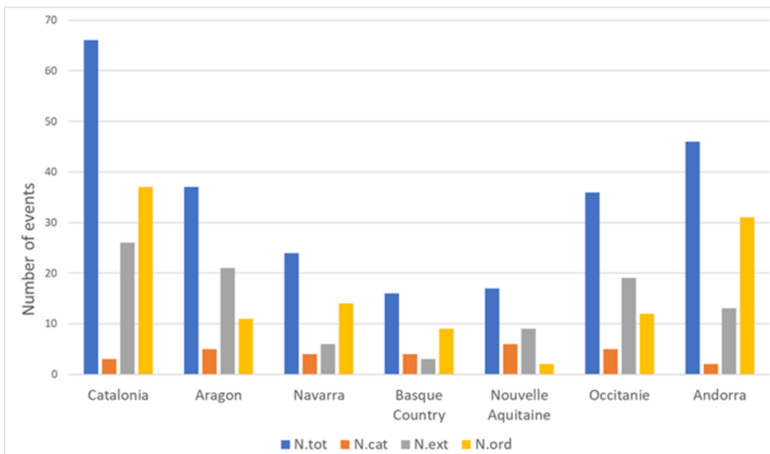

Figure 6: Distribution of the total number of flood events (blue) and the number of flood events by categories (catastrophic, orange; extraordinary, grey; and ordinary, yellow) in the different communities that make up the POCTEFA Pyrenees region, for the period 1981-2015.

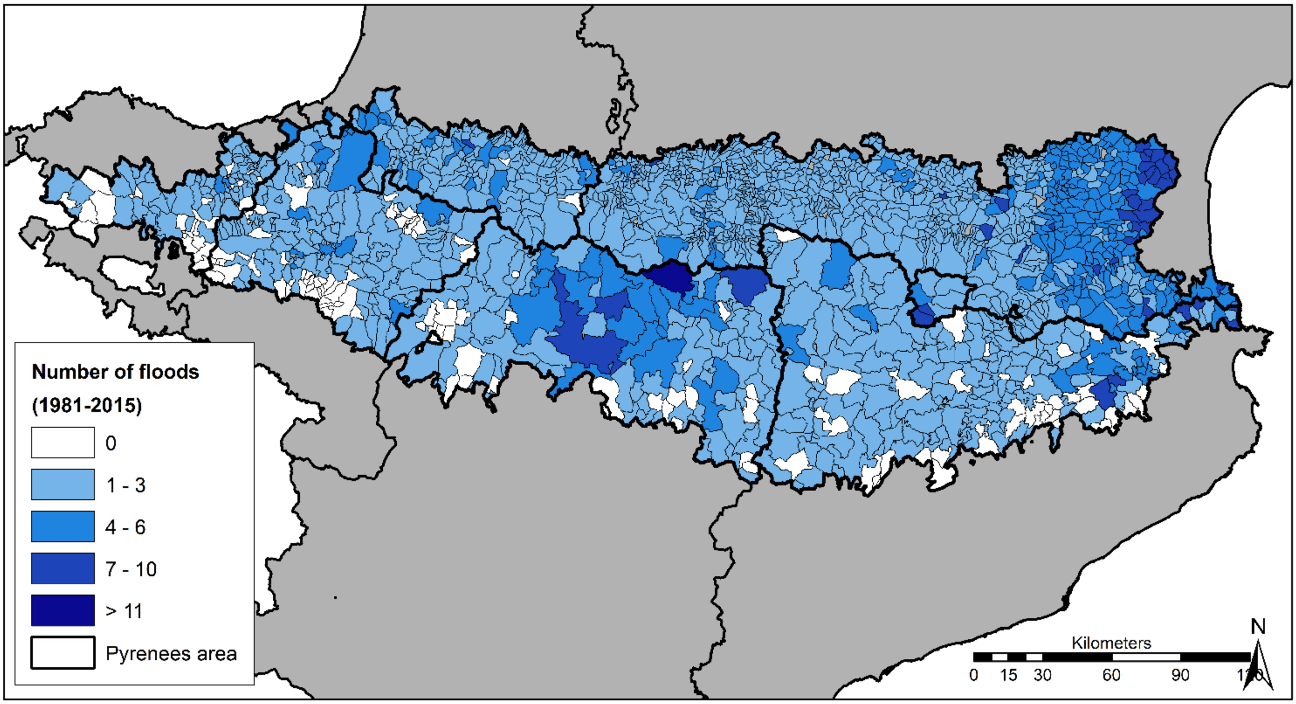

Figure 7: Number of notable flood events (catastrophic and extraordinary floods) that affected each municipality in the Pyrenees.

Table 4 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 (i.e. 6-8 November 1982), and a major part of them died at home or they were in a car that was swept away by the flood.

Table 4. 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.

	N.tot	N.cat	N.ext	N.ord	Munic. max	N.tot munic. max	N.vict	CCS (M€) tot	Period. max.	Trend
Catalonia	66	3	26	37	Llançà	16	21	33.4	SON	0.15
Aragon	37	5	21	11	Bielsa	15	97	15.2	ASON	-0.01
Navarra	24	4	6	14	Pamplona	17	1	65.8	JFD	0.03
Basque country	16	4	3	9	Oiartzun/ Oyarzun	8	2	28.1	JnJlA	-0.08
Nouvelle Aquitaine	17	6	9	2	Mauleon-Licharre	7	6	no data	JMJn	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

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 4). Figure 5 shows that the highest number of floods took place in the coastal foothills of the Pyrenees (16 episodes in the coastal municipality of Llançà, of which 62% were extraordinary) that confirms the strong role played by the entrance of Mediterranean air masses. 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 flash floods in the Pyrenees and it is Sobrarbe, where 26 events have taken place in 35 years. These are mainly events associated with thunderstorms in which the orography forces the rise and hinders the advance of convective systems, which can remain stationary in the same place (i.e. the Biescas case). The large number of torrents and dejection cones favors the production of flash floods. Given that these are very attractive mountain areas, it is possible that there are campsites, hikers or high-risk sportsmen and sportswomen, which increases vulnerability and exposure. The Navarre Pyrenees were affected by 24 events (17%, catastrophic) in which there was one victim. In this case, the damage is usually due to urban and peri-urban flooding, affecting its capital, Pamplona (203,418 inhabitants) that is the Pyrenean city with the largest number of recorded events (17). However, the most catastrophic episodes in Navarra have occurred in the Baztan valley, where numerous villages and small industries extend around the river. During the period 1981-2015 only 6 episodes of flooding (25% catastrophic) affected the Basque Pyrenees, with two victims. Most of them were concentrated in the eastern part of the region, near the Baztan valley. Although it is true that the costliest flood event recorded in Spain in that period took place in the Basque Country, in August 1983, the greatest damage occurred around the coastal estuaries, outside the Pyrenean region. Precisely, if the economic costs are taken into account, the CCS paid a total of €33.4 $million_{2015}$ (M_{2015}) in flood compensation in the Catalan Pyrenean Region in the period 1996-2015, with the Val d'Aran being the most compensated region (a recreation and ski area with luxurious urbanizations near the river), mainly due to the June 2013 event that also affected Aragón and the French Pyrenees (Table 5). For the same period, the CCS paid a total of €15.2 M_{2015} in flood compensations in Aragón, mainly due to the flood events of August 1996 (the Biescas case), that also affected Andorra, and the flood event of June 2013. The CCS paid a total of €65.8 M_{2015} in flood compensation in Navarra, of which about €18 M_{2015} went to Pamplona and €5.5 M_{2015} went to Baztan. The CCS paid a total of €28.1 M_{2015} in flood compensation in the Basque Pyrenees, of which the largest amounts went to Tolosa (19,525 inhabitants, the most important city in the region).

A total of 46 flood events were recorded in Andorra in the period 1981-2015, of which only 4.55% were catastrophic. It is a country of 79,824 inhabitants with a very high risk of flooding, especially because the most important towns and villages are surrounding the Valira River in a very narrow valley. The most important heavy rainfall events are usually due to Mediterranean perturbations that also affect Catalonia and/or Aragón (Table 5). The maximum number of flood events occurred in the municipality of Andorra la Vella (27), followed by Sant Julià de Lòria (18). In total, 43 episodes of floods affected the French side of the Pyrenees, of which Nouvelle Aquitaine recorded 17 events 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, while in Nouvelle Aquitaine the maximum was lower, with 7 events in Mauleon-Licharre. Both populations are located closer to the Atlantic than the Mediterranean, being exposed above all to disturbances from the west and northwest. As a whole, however, the municipalities located further east in Occitanie stand out, where floods are mainly associated with disturbances such as those affecting Catalonia and Andorra. 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.

5 Temporal analysis

Figure 8 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 maxima in July and August. In Navarra, the events 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 (42% of the total number of annual events) that would be associated with flooding by very intense and local convective rains. This is confirmed by the intra-annual evolution of the number of flood episodes excluding ordinary ones (see the dashed line in Fig. 8), 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). In these 36 years, the highest number of victims occurred in August. Generally, these are individuals who engage in risky sports, although the high number of deaths is due to the Biescas disaster. The number is also relatively high in November and is associated with longer-duration events.

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. 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% . On the other hand, if ordinary episodes are also considered, the trend of flood events for the entire Pyrenees increases until 0.84 ev./dec. but it is only significant at 90% (Fig. 9).

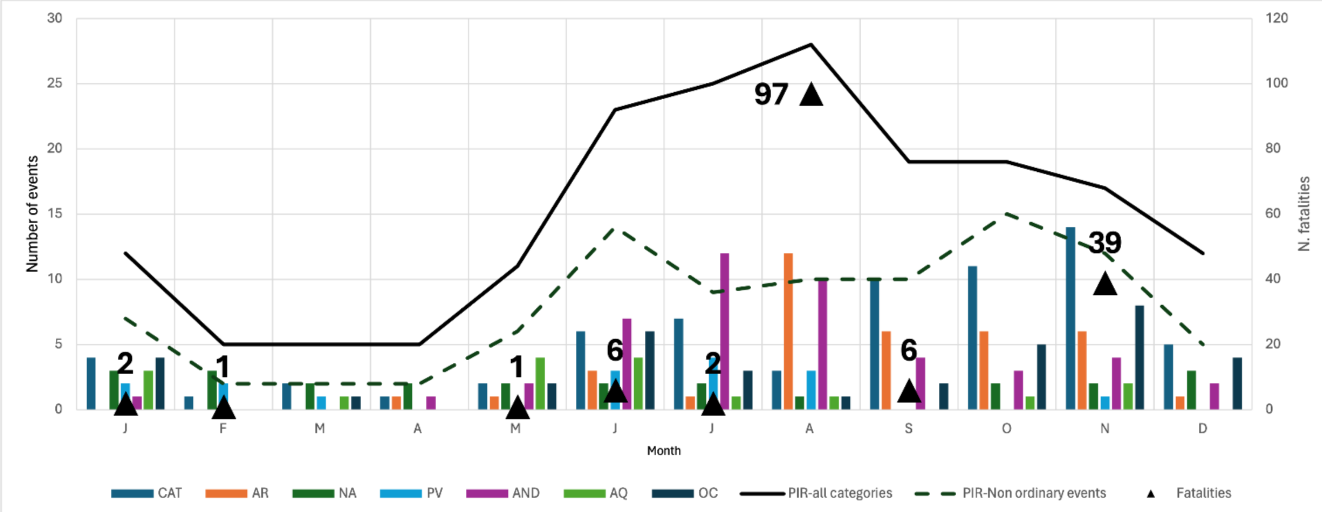

Figure 8: Monthly distribution of the total number of flood cases for the different regions. The solid line shows the entire Pyrenees-POCTEFA region, and the dashed line shows the number of notable events (period 1981-2015). The triangles indicate the total number of casualties in the entire study area for each month, the value is included next to the symbol.

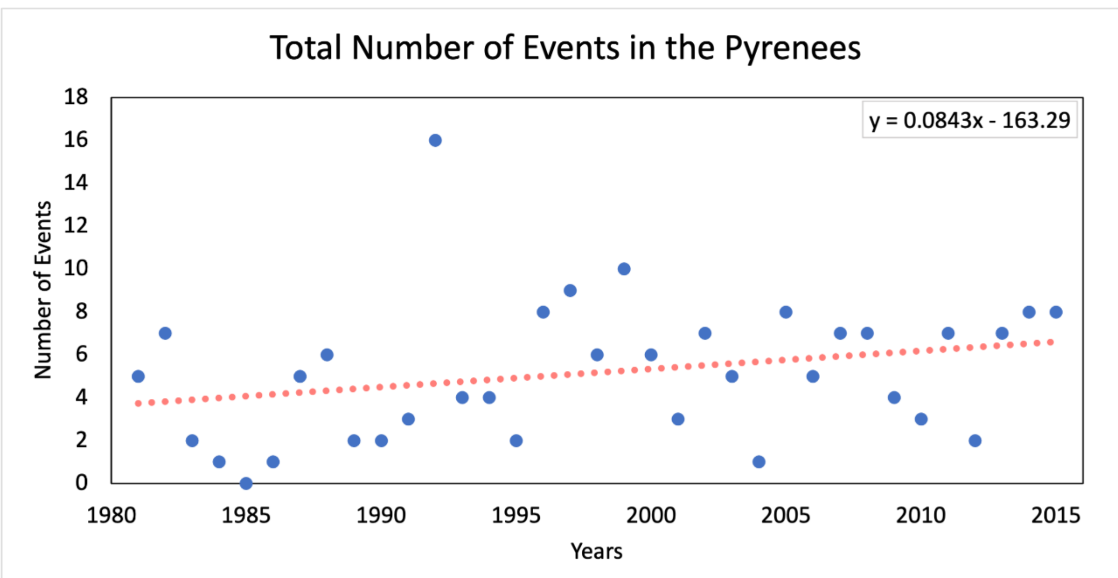

Figure 9. Evolution of the total number of flood events (including ordinary and non-repeated events in the different regions) for the period 1981-2015.

6 Cross-border flood episodes

Of all the recorded flood events, 41 affected two or more Pyrenean regions (Table 5). Of these, 34 were international cross-border, highlighting the episodes that affected Spain and France (71%), while 24% affected Spain and Andorra simultaneously, and 5% affected all three countries (Table 6). The most frequent are episodes that simultaneously affect two or more of the regions of Catalonia, Aragon, Occitanie and Andorra: 41% of the transregional episodes took place between Catalonia and Occitanie, while 24% were between Catalonia and Aragon and another equal percentage between Occitanie and Nouvelle Aquitaine (Table 5). They occur mainly in autumn (Fig. 10), which is consistent with the fact that it is in this season when the entry of organized Mediterranean disturbances is produced, usually associated with the presence of a depression in the Mediterranean and favored by a warm sea (Llasat, 2009). On the contrary, between January and April practically no transnational episodes are recorded, and none has been recorded in February, which points to more localized events.

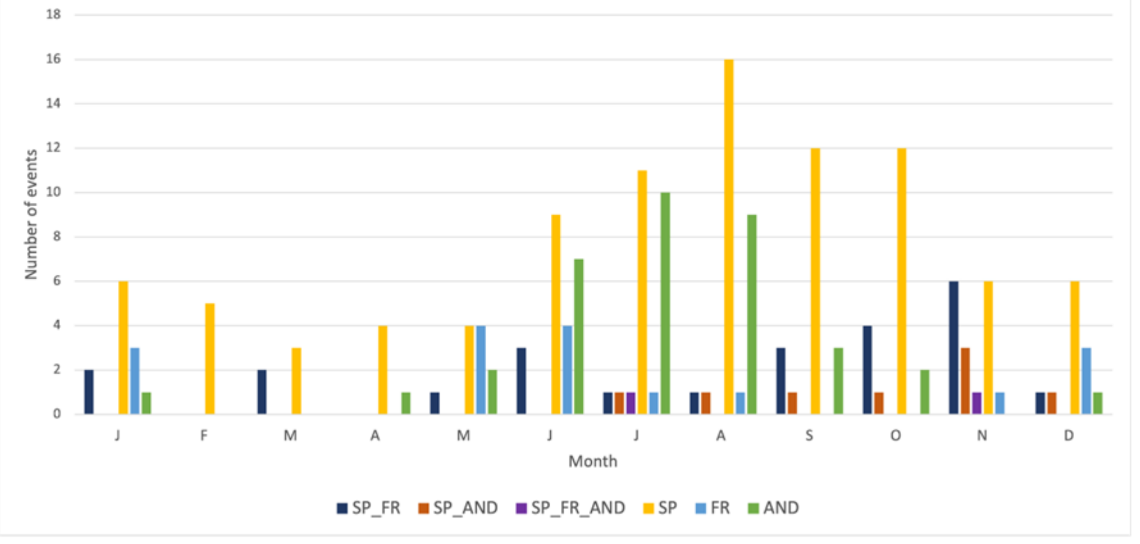

Figure 10. Monthly total number of flood events recorded in the Pyrenean Region (1981-2015), for each country (SP: Spain; FR: France; AND: Andorra) and for cross-border events.

Table 5. Number of events that have affected each Pyrenean region and number of events that have affected each pair of regions indicated by the intersection by them. The diagonal shows the total number of events in each region.

	CAT	AR	NA	PV	AND	OC	AQ
CAT	66						
AR	10	37					
NA	0	1	24				
PV	1	1	3	16			
AND	7	8	0	0	46		
OC	17	8	2	2	2	36	
AQ	3	4	5	4	1	10	17

Table 6. Flood events that affected more than one of the countries of the Pyrenees-POCTEFA region in the period 1981-2015. Affected countries in blue.

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 6 shows the list of cross-border flood events. As an example, Fig. 11 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) (Fig. 12). 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, favouring 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).

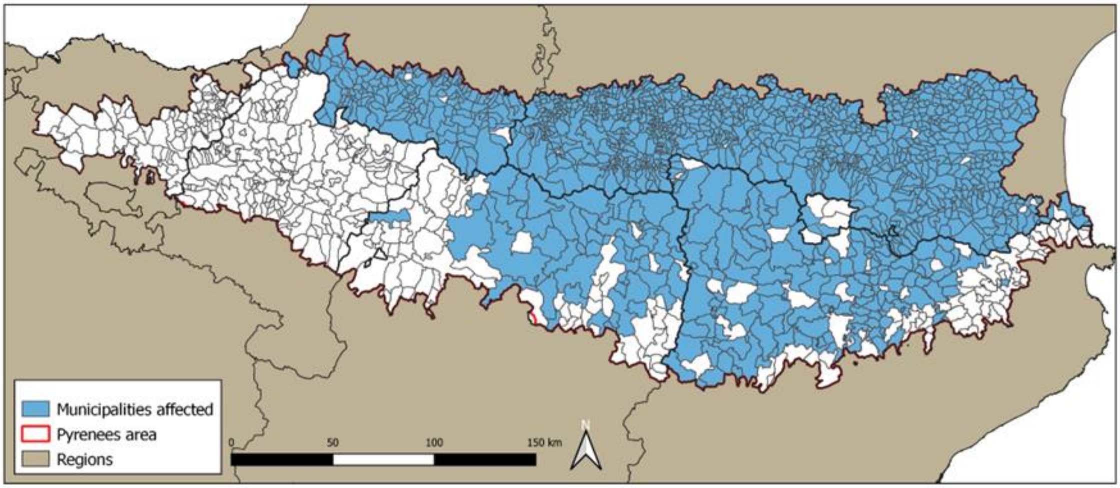

Figure 11: Municipalities of the Pyrenees affected by the floods of 6-8 November 1982.

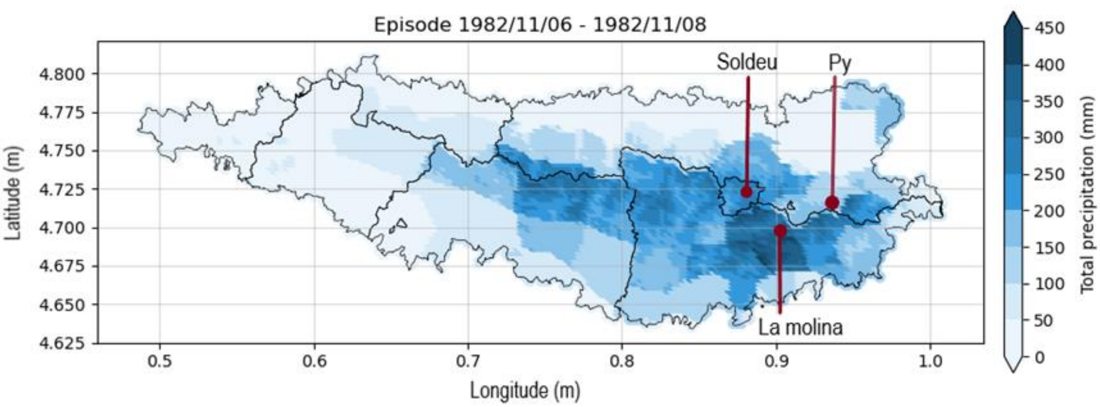

Figure 12. Precipitation collected between 6 November at 06:00 UTC and 9 November 1982 at 06:00 UTC from SAFRAN reanalysis.

7 Weather types

Figure 13 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 talweg is the most characteristic of the episodes affecting the Eastern and Central Pyrenees (Fig.

14a) in autumn (Fig. 14b). 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). Note in Figure 13b 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 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 (Fig. 14b), with notable rainfall accumulations in the western and northern part of the Pyrenees (Lemus-Canovas et al., 2019b) where most of the floods are recorded (Fig. 14a). In fact, the highest frequency is recorded in January (Fig. 14b). On the other hand, the dominant weather type in summer is WT 2- (Fig. 14b), which shows in the slight wave over the Iberian Peninsula, while on the surface the situation is 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, mainly concentrated in the southern half of the Pyrenees (Fig. 14a). 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 (Fig. 14a). 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 (Fig. 14b). An example of this would be the floods of June 2013. These northern movements are usually associated with summer floods and can affect any area in the Pyrenees. Finally, it can be observed that in November the WT 4+ and WT 5+ dominate (Fig. 14b), 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). These WT are mainly associated with floods in the Eastern part of the Pyrenees (Fig. 14a). 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 (Fig. 10), seven have been characterized by WT 2-. In September, types WT 2- and WT 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 WT 4-, characterised by a deep depression to the west of the British Isles that extends up to 500 hPa and even more, with a talweg that crosses the Peninsula from northwest to southeast.

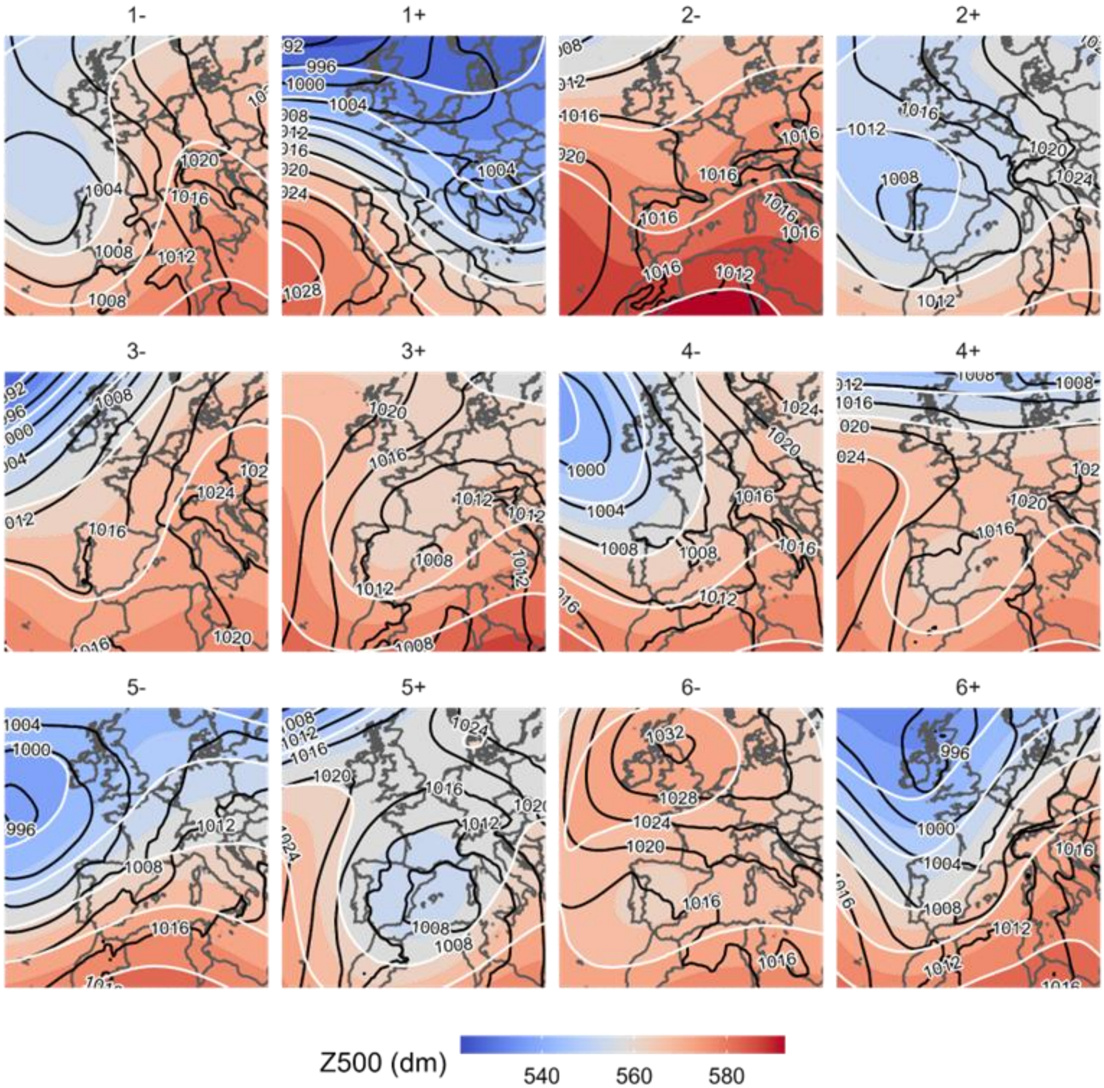

Figure 13. Weather types that characterise flood episodes in the Pyrenees.

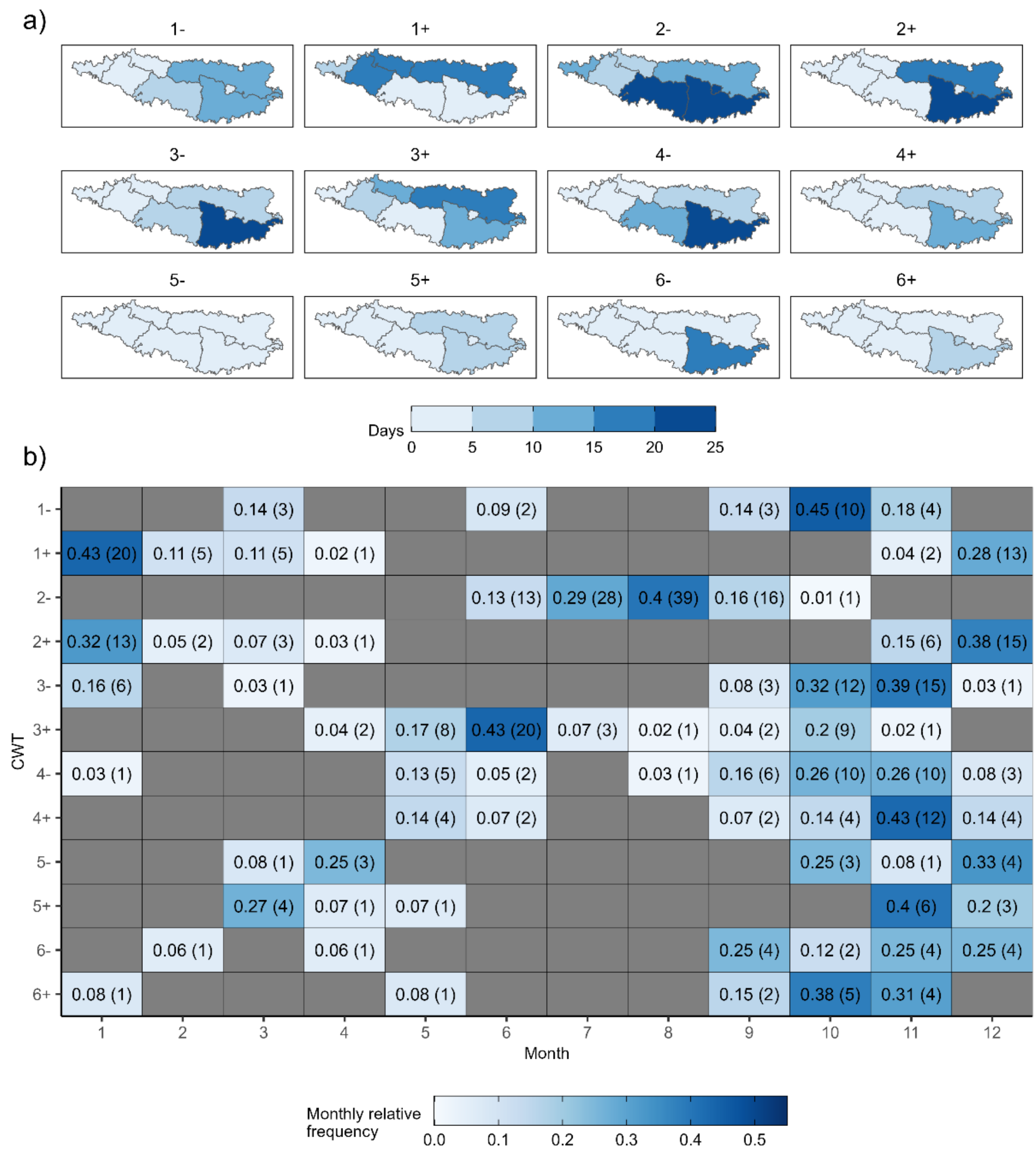

Figure 14. a) Number of flood days by weather type (WT) and Pyrenean region. b) Monthly relative frequencies of flood days by weather type and month. Between parenthesis absolute values are shown in flood days per month.

8 Discussion and conclusions

In this article, the first flood database integrating the entire Pyrenees massif and available to the public has been presented (http://hdl.handle.net/10261/270351). This database, PIRAGUA_flood, includes, at a municipal scale, all flood events that have affected each of the 1803 municipalities comprising this cross-border region between 1981 and 2015, of which 609 are Spanish, 1187 are French, and 7 are Andorran. Each event is characterized based on a scale that considers the impacts, providing information on these, including the number of victims, and in the Spanish case, compensations paid by the Insurance Compensation Consortium. Hydro-meteorological information is also included. The database has been constructed using information from press sources, official lists provided by various public agencies, scientific studies, and rainfall analyses. In the case of Catalonia and Andorra, systematic daily-scale information on all types of flood events, including those with lesser impact, has been available. For other regions, it is possible that some of these minor events may have gone unnoticed. However, since this information is typically difficult to obtain from any other source, it has been decided to maintain it. Additionally, these types of floods are becoming more common due to urbanization of the territory.

If we take into account that some events can affect more than one region, the number of events that have produced floods in the Pyrenees between 1981 and 2015 has been 181, of which 128 affected Spain, 43 affected France and 46 affected Andorra. Of these, 34 were cross-border. The November 1982 catastrophic flood event was the most extensive and affected the three countries. The other very extensive episode took place in June 2013 and affected Spain and France. The region with the greatest number of flood events has been 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 was the most affected by flood episodes, some which had catastrophic impacts.

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, Navarra 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, 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 very 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. The Biescas case is an example where all components contributing to the risk were high. It involved a camping site located in a debris cone at the foot of a dam in an area prone to storms (high hazard), with numerous people (high exposure) who took shelter in tents or trailers, and there was no early warning system (high vulnerability). 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, Navarra and Occitanie all share the month of October among the months that record the highest number of events. The 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 notable damage (extraordinary and catastrophic episodes according to the nomenclature agreed here), a positive trend can be observed across the entire massif of 0.5 ev./dec., although it is not significant. However, if the ordinary episodes are included, the trend becomes 0.84 ev/dec., and it is significant at 90%. When analysing in terms of communities, Nouvelle Aquitaine is the only region with a significant positive trend at 95% (0.34 ev./dec.). This positive trend in Nouvelle Aquitaine cannot be justified by the trend in the 90th percentile discharge, nor the lower percentiles, as shown in the study by Clavera-Gispert et al. (2023). To attribute this trend accurately, it would be necessary to conduct a study on more extreme discharge events and land use to associate it with an increase in vulnerability, exposure, or hazard. On average, projections also do not indicate an increase in intense precipitation in the Pyrenees (Amblar-Francés et al., 2020), but a recent study (Poncet et al., 2024) including the Mediterranean part of Occitania shows that the magnitude of the most intense floods will intensify.

From the classification of weather types, it can be concluded that most are dominated by southern component flow over the Pyrenees region, with a talweg 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 (2022), 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.

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. As it has been shown in the paper, many flood episodes are transnational, which calls for cooperation in the prevention and mitigation of flood risk between regions and countries. This is more relevant considering the United Nations call "Erly Warning for All" to ensure that everyone on Earth is protected from hydrometeorological hazard, including flood events through life-saving early warning systems by the end of 2027. Furthermore, in Europe there is a strong collaboration framework, both thanks to the ESA Copernicus observation program, Meteoalarm and within the Euromed Program of Prevention, Preparedness and Response to Natural and Man-made Disasters, in which all European Civil Protection agencies participate. However, it is necessary to land it in the interborder region of the Pyrenees.

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.

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10 References

Amblar-Francés, M.P., Ramos-Calzado, P., Sanchis-Lladó, J., Hernanz-Lázaro, A., Peral-García, M.C., Navascués, B., Dominguez-Alonso, M., Pastor-Saavedra, M.A., Rodríguez-Camino, E.: High resolution climate change projections for the Pyrenees region. Advances in Science and Research 17, 191-208. https://doi.org/10.5194/asr-17-191-2020, 2020.

Ayala Carcedo, F.J.: La inundación torrencial catastrófica del camping Las Nieves del 7 de agosto de 1996 en el cono de deyección del Arás (Biescas Pirineo Aragonés), in: Riesgos Naturales, coord. by Ayala Carcedo, F.J. and Olcina Cantos, J., Ariel, ISBN 84-344-8034-4, 889-912, 2002

Barnolas, M. and Llasat, M.C.: A flood geodatabase and its climatological applications: the case of Catalonia for the last century, Nat. Hazards Earth Syst. Sci., 7, 271-281, 2007.

Barriendos, M., Coeur, D., Lang, M., Llasat, M.C., Naulet, R., Lemaitre, F., Barrera, A.: Stationarity analysis of historical flood series in France and Spain (14th-20th centuries), Nat. Hazards Earth Syst. Sci., 3, 583-592, 2003.

Barriendos, M., Gil-Guirado, S., Pino, D., Tuset, J., Pérez-Morales, A., Alberola, A., Costa, J., Balasch, J.C., Castelltort, X., Mazón, J., Ruiz-Bellet, J. L.: Climatic and social factors behind the Spanish Mediterranean flood event chronologies from documentary sources (14th–20th centuries), Glob. Planet. Change, 182, 102997, https://doi.org/10.1016/j.gloplacha.2019.102997, 2019.

Beguería S. (coord.): Caracterización de los recursos hídricos de los Pirineos en la actualidad, y escenarios futuros. Memorias científicas del proyecto PIRAGUA, vol. 1. Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (EEADCSIC), Zaragoza, España, 124. DOI: https://doi.org/10.20350/digitalCSIC/14683, 2023a.

Beguería S. (ed.): Adaptación al cambio climático en la gestión de los recursos hídricos de los Pirineos. Memorias científicas del proyecto PIRAGUA, vol. 2. Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (EEADCSIC), Zaragoza, España (220pp.). DOI: https://doi.org/10.20350/digitalCSIC/14684, 2023b.

Beniston, M.: Climatic change in mountain regions: a review of possible impacts. Climatic change, 59(1), 5-31, https://doi.org/10.1023/A:1024458411589, 2003.

Beniston, M., and Stoffel, M.: Assessing the impacts of climatic change on mountain water resources. Science of the Total Environment, 493, 1129-1137. https://doi.org/10.1016/j.scitotenv.2013.11.122, 2014.

Boudou, M., Lang, M., Vinet, F., & Cœur, D. : Comparative hazard analysis of processes leading to remarkable flash floods (France, 1930–1999). Journal of Hydrology, 541, 533–552. https://doi.org/10.1016/j.jhydrol.2016.05.032, 2016.

Braud, I., Roux, H., Anquetin, S., Maubourguet, M.M., Manus, C., Viallet, P., Dartus, D. : The use of distributed hydrological models for the Gard 2002 flash flood event: analysis of associated hydrological processes. J. Hydrol. 394 (1–2), 162–181, 2010.

Cattell, R. B.: The screen test for the number of factors, Multivariate behavioral research, vol. 1, 2, 245-276, 1976.

Confederación Hidrográfica del Cantábrico (CHC) and Agencia Vasca del Agua (URA): Parte española de la Demarcación Hidrográfica del Cantábrico Oriental. Revisión y actualización de la evaluación preliminar del riesgo de inundación (EPRI). 2º ciclo. Anexo 1: Registro de eventos de inundación. Available at: https://www.chcantabrico.es/documents/20143/299434/epri_2ciclo_dhc_ori_anexo1_registro_inundaciones.pdf/a6203b3d-e2ca-58e9-f148-ca0be5eb063f, last access: 17 February 2023, 2018.

CCS (Consorcio de Compensación de Seguros): Estadística riesgos extraordinarios. Serie 1971-2020. Available at: https://www.consorseguros.es/web/documents/10184/44193/Estadistica_Riesgos_Extraordinarios_1971_2014/14ca6778-2081-4060-a86d-728d9a17c522, last access: 1 October 2022, 2021.

Clavera-Gispert, R., Quintana-Seguí, P., Palazón, L., Zabaleta, A., Cenobio, O., Barella-Ortiz, A., Beguería, S.: Streamflow trends of the Pyrenees using observations and multi-model approach (1980–2013). Journal of Hydrology-Regional Studies, 46, 101322, https://doi.org/10.1016/j.ejrh.2023.101322, 2023.

Cortès, M., Llasat, M.C., Gilabert, J., Llasat-Botija, M., Turco, M., Marcos, R., Martín Vide, J.P., Falcón, Ll.: Towards a better understanding of the evolution of the flood risk in Mediterranean urban areas: the case of Barcelona, Nat. Hazards, https://doi.org/1007/s11069-017-3014-0, 2017.

Cortès, M., Turco, M., Ward, Ph-. Sánchez-Espigares, J., Alfieri, J., Llasat, M.C.: Changes in flood damage with global warming in the east coast of Spain, Nat. Hazards Earth Syst. Sci., 19, 2855–2877, https://doi.org/10.5194/nhess-2019-253, 2019.

DGPC (Dirección General de Protección Civil): Catálogo Nacional de Inundaciones Históricas. Available at: http://www.proteccioncivil.es/, last access: 1 October 2022, 2022.

García Ruiz, J.M., White, S.M., Martí, C., Valero, B., Errea, M.P., Gómez Villar, A.: La catástrofe del barranco de Arás (Biescas, Pirineo Aragonés) y su contexto espacio-temporal, IPE-CSIC, Zaragoza, España, ISBN. 84-921 842-1-3, 1996.

Gil-Guirado, S., Pérez-Morales, A., and Lopez-Martinez, F.: SMC-Flood database: a high-resolution press database on flood cases for the Spanish Mediterranean coast (1960–2015), Nat. Hazards Earth Syst. Sci., 19, 1955–1971, https://doi.org/10.5194/nhess-19-1955-2019, 2019.

Hersbach, H. et al.: The ERA5 global reanalysis, Q. J. R. Meteorol. Soc., 146, n. 730, 1999-2049, 2020

Kendall, M.G.: Rank Correlation Measures. Charles Griffin, London, 1975.

Lemus-Canovas, M., Ninyerola, M., Lopez-Bustins, J. A., Manguan, S., and Garcia-Sellés, C.: A mixed application of an objective synoptic classification and spatial regression models for deriving winter precipitation regimes in the Eastern Pyrenees, Int. J. Climatol., 39(4), 2244-2259, 2019.

IPCC: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844, 2022.

Lemus-Canovas, M., Lopez-Bustins, J. A., Martin-Vide, J., and Royé, D.: synoptReg: An R package for computing a synoptic climate classification and a spatial regionalization of environmental data, Environ. Model. Softw., 118, 114-119, 2019a.

Lemus-Canovas, M., Lopez-Bustins, J. A., Trapero, L., and Martin-Vide, J.: Combining circulation weather types and daily precipitation modelling to derive climatic precipitation regions in the Pyrenees, Atmos. Res., 220, 181-193, 2019b.

Lemus-Canovas, M., Lopez-Bustins, J. A., Martín-Vide, J., Halifa-Marin, A., Insua-Costa, D., Martinez-Artigas, J., ... and Cuadrat, J. M.: Characterisation of extreme precipitation events in the Pyrenees: From the local to the synoptic scale, Atmosphere, 12, 6, 665, 2021.

Llasat, M.C.: Episodios de lluvias copiosas en Cataluña: génesis, evolución y factores coadyuvantes, Tesis Doctoral, Publicacions de la Universitat de Barcelona, 2, 448 pp., 1987.

Llasat, M.C.: An objective classification of rainfall events on the basis of their convective features. Application to rainfall intensity in the north-east of Spain, Int. J. Climatol., Vol. 21, nº11, 1385-1400, 2001.

Llasat, M.C.: Chapter 18: Storms and floods. In The Physical Geography of the Mediterranean basin. Edited by Jamie Woodward. Published by Oxford University Press, ISBN: 978-0-19-926803-0, pp. 504-531, 2009.

Llasat, M. C., M. Llasat-Botija, O. Petrucci, A.A. Pasqua, J. Rosselló, F.Vinet, L. Boissier: Floods in the North-Western Meditrerranean Region : presentation of the HYMEX database and comparison with pre-existing global databases. La Houille Blanche, January 2013, 1, 5-9, DOI 10.1051/lhb/2013001, 2013a.

Llasat, M. C., Llasat-Botija, M., Petrucci, O., Pasqua, A.A., Rosselló, J., Vinet, F., Boissier, L.: Towards a database on societal impact of Mediterranean floods in the framework of the HYMEX project, Nat. Hazards Earth Syst. Sci., 13, 1–14, https://doi.org/10.5194/nhess-13-1337-2013, 2013b.

Llasat, M.C., Marcos, R., Turco, M., Gilabert J., Llasat-Botija, M.: Trends in flash flood events versus convective precipitation in the Mediterranean region: The case of Catalonia, J. Hydrol., 541, 24-37, https://doi.org/10.1016/j.jhydrol.2016.05.040, 2016.

Llasat, M.C., del Moral, A., Cortès, M., Rigo, T.: Convective precipitation trends in the Spanish Mediterranean region, Atmos. Res., 257, 105581, https://doi.org/10.1016/j.atmosres.2021.105581, 2021.

Llasat M.C; Pardo E; Llasat-Botija M.: PIRAGUA_flood [Dataset]; Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (EEAD-CSIC); https://doi.org/10.20350/digitalCSIC/14650: http://hdl.handle.net/10261/270351, 2022.

Mann, H.B.: Nonparametric tests against trend, Econometrica, 13, 245–259, 1945.

Martin-Vide, J., Sanchez-Lorenzo, A., Lopez-Bustins, J. A., Cordobilla, M. J., Garcia-Manuel, A., and Raso, J. M.: Torrential rainfall in northeast of the Iberian Peninsula: synoptic patterns and WeMO influence, Advances in Science and Research, 2(1), 99-105, 2008.

Miró, J. J. et al.: A component-based approximation for trend detection of intense rainfall in the Spanish Mediterranean coast, Weather Clim. Extremes, 38, 100513, 2022.

Papagiannaki, K., Lagouvardos, K., and Kotroni, V.: A database of high-impact weather events in Greece: a descriptive impact analysis for the period 2001–2011, Nat. Hazards Earth Syst. Sci., 13, 727–736, https://doi.org/10.5194/nhess-13-727-2013, 2013.

Petrucci, O.: Brief communication "The assessment of damage caused by historical landslide events", Nat. Hazards Earth Syst. Sci., 13, 755–761, https://doi.org/10.5194/nhess-13-755-2013, 2013.

Poncet, N., Lucas-Picher, Ph., Tramblay, Y., Thirel, G. Vergara, H., Gourley, J., and Alias A.: Does a convection-permitting regional climate model bring new perspectives on the projection of Mediterranean floods? Nat. Hazards Earth Syst. Sci., 24, 1163–1183, https://doi.org/10.5194/nhess-24-1163-2024, 2024.

Quintana-Seguí, P., Peral, C., Turco, M., Llasat, M.C. and Martin, E.: Meteorological Analysis Systems in North-East Spain: Validation of SAFRAN and SPAN, J. Environ. Inform., 27 (2), 116-130, https://doi.org/10.3808/jei.201600335, 2016.

Richman, M. B.: Rotation of principal components, Journal of climatology, 6(3), 293-335, 1986.

Rodríguez, O., and Lemus-Canovas, M.: Synoptic patterns triggering tornadic storms on the Iberian Peninsula and the Balearic Islands, Atmos. Res., 285, 106634, 2023.

Serrano-Notivoli, R., Lemus-Canovas, M., Barrao, S., Sarricolea, P., Meseguer-Ruiz, O., and Tejedor, E.: Heat and cold waves in mainland Spain: Origins, characteristics, and trends, Weather Clim. Extremes, 37, 100471, 2022.

Steiger, R., Knowles, N., Pöll, K., & Rutty, M.: Impacts of climate change on mountain tourism: A review. Journal of Sustainable Tourism, 1-34, https://doi.org/10.1080/09669582.2022.2112204, 2022.

Soci, C., Bazile, E., Besson, F., Landelius, l. : High-resolution precipitation re-analysis system for climatological purposes, Tellus A 2016, 68, 29879, http://dx.doi.org/10.3402/tellusa.v68.29879, 2016.

Tramblay, Y., Somot, S.: Future evolution of extreme precipitation in the Mediterranean, Clim. Chang., 151, 289–302 https://doi.org/10.1007/s10584-018-2300-5, 2018.

Trapero, L., Bech, J., Duffourg, F., Esteban, P., and Lorente, J.: Mesoscale numerical analysis of the historical November 1982 heavy precipitation event over Andorra (Eastern Pyrenees), Nat. Hazards Earth Syst. Sci., 13(11), 2969-2990, 2021.

Vinet, F., Bigot, V., Petrucci, O., Papagiannaki, K., Llasat, M.C., Kotroni, V., Boissier, L., Aceto, L., Grimalt, M., Llasat-Botija, M., Pasqua, A.A., Rossello, J., Kılıç, Ö., Kahraman, A. and Tramblay, Y.: Mapping flood-related mortality in the mediterranean basin. Results from the MEFF v2.0 DB. Water (Switzerland), 11(10). https://doi.org/10.3390/w11102196, 2016.

Wirtz, A., Kron, W., Löw, P., and Steuer, M.: The need for data: Natural disasters and the challenges of database management. Natural Hazards, 70 (1), 135–157. https://doi.org/10.1007/s11069-012-0312-4, 2014.

Zêzere, J. L., Pereira, S., Tavares, A., Bateira, C., Trigo, R., Quaresma, I., Santos, P., Santos, M. and Verde, J.: - DISASTER: a GIS database on hydro-geomorphologic disasters in Portugal. Natural Hazards, 71: 1029-1050. DOI 10.1007/s11069-013-1018-y, 2014.

Zimmermann, M. and Keiler, M.: International frameworks for disaster risk reduction: useful guidance for sustainable mountain development? Mt. Res. Dev. , 35 (2), 195–202, doi:10.1659/MRD-JOURNAL-D-15-00006.1, 2015.