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Historical damaging flood records for 1871-2011 in Northern Portugal and underlying atmospheric forcings

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Abstract

A long time series of damaging flood records in Northern Portugal for 1871-2011, gathered from a large number of documentary sources, is analyzed. The relationships between damaging floods (DFs) and relevant circulation weather types (CWTs) are also assessed. The DFs database has 1861 records and CWTs are identified using the 20th century reanalysis dataset v2. A coefficient of effectiveness (CE) is calculated for each weather type in order to assess DF-CWT relationships. Furthermore, conditions in the 10 days preceding a DF outbreak, type of flood and season were taken into account in CE calculations. The DF occurrences were responsible for 186 killed people, 59 injured, 29 missing, 1873 displaced and 15924 homeless people. The monthly frequencies each CWT show that anticyclonic (A) and easterly wind (E) types are prevalent in winter, whereas R tends to prevail in the summer half of the year. However, the results show that the cyclonic (C) type has a positive frequency with DF occurrence (i.e. anomalously frequent), both on the DF day and on the nine previous days. The C type is commonly associated with southwesterly flow and unsettled weather conditions over Portugal, which are favorable to rain-generating mechanisms. The results also highlight some seasonal variation: in autumn, winter and spring, the C type is largely related to DFs, while the A and E types acquire higher preponderance in the summer. In effect, the latter two CWTs may trigger thunderstorms and heavy precipitation episodes in the Douro River catchment in summer.

Keywords: damaging floods, circulation weather types, Northern Portugal
1. Introduction

Floods are the natural hazards causing more damages worldwide. In 2012, it is estimated that floods affected 62,281,619 people and killed 3,401 (UNISDR, 2012). As an illustration, in the Madeira island (Portugal), a flash flood on 20 February 2010 resulted in 45 deaths (Fragoso et al., 2012). Other examples are the flash floods in the Lisbon region on 25 November 1967 that caused 700 deaths, or the river flooding in December 1909 that caused 25 reported deaths along the Douro River. Between 1865 and 2010, floods were responsible for 1,012 deaths, 478 injured, 13,372 displaced and 40,283 homeless people in Portugal (Zêzere et al., 2014). These numbers were assessed under the framework of a research project devoted to create, disseminate and exploit a GIS database (DISASTER database) on disastrous landslides and floods in Portugal for the period of 1865-2010 (Zêzere et al., 2014). This dataset was obtained from a systematic survey of news published in national and regional newspapers.

Flood damage databases, particularly high impact floods, are commonly based on insurance claim data, institutional reports, and media reports, especially news disseminated by newspapers with long and continuous periods of publication. The Portuguese DISASTER database on hydro-geomorphological disasters followed other recently produced historical repositories on catastrophes, such as the flood database for Catalonia (Spain) (Barnolas and Llasat, 2007), the SICI information system, concerning the occurrence of landslides and floods in Italy (Guzzetti and Tonelli, 2004), or the flood database for Athens (Greece) (Diakakis, 2013). These efforts also represent, to some extent, a strategy to improve the current knowledge on flood risks in Southern Europe, given the scarcity of instrumental data on river discharges. In fact, the longest and continuous river discharge data series for Northern Portugal is available only for the period from the 1950s onwards. Therefore, the analysis of the DISASTER flood occurrences under a climatological perspective allows an innovative and timely assessment of historical flood records in this region.
The combination of weather and hydrology commonly play a key role in flood processes (Llasat et al., 2005). In fact, the occurrence and intensity of floods depend on weather conditions prior to the event (Kron et al., 2012). Floods are extreme and temporary episodes, mainly triggered either by persistent and moderate precipitation or by abrupt heavy rains. Nevertheless, other conditions, such as soils, surface run-off characteristics, protection measures, land-use and seasonality in the hydrological regimes are also important.

Many works have been devoted to the relationships between atmospheric patterns and rainfall (Andrade et al., 2011; Burt and Ferranti, 2012; Casado et al., 2010; Espinoza et al., 2012; Goodess and Jones, 2002; Hidalgo-Muñoz et al., 2011; Lopez-Bustins et al., 2008; Raziei et al., 2013; Santos et al., 2005; Santos et al., 2007; Toreti et al., 2010; Trigo and DaCamara, 2000) or temperature (Andrade et al., 2012; Carril et al., 2008; Cassou et al., 2005; Cony M et al., 2008; Rodríguez-Puebla et al., 2010; Santos and Corte-Real, 2006) or both (Jacobeit et al., 2009; Pfahl, 2014). However, there is a lack of studies covering the links between atmospheric patterns and floods (Pattison and Lane, 2012). Most of studies were focused on the identification the circulation patterns responsible for flood occurrences in different areas, such as Arizona (Duckstein et al., 1993), France and Spain (Bárdossy and Filiz, 2005), the UK (Pattison and Lane, 2012; Wilby and Quinn, 2013), the Alpine–Carpathian range (Parajka et al., 2010), Germany (Petrow et al., 2007; Petrow et al., 2009) and central Europe (Jacobeit et al., 2006). Most of these studies have shown that cyclonic weather types are particularly important in flood concurrences.

The link between weather types and a long time series of damaging flood records in northern Portugal is investigated in the present study. The purposes of this work are twofold: 1) to investigate the atmospheric conditions leading to damaging floods and 2) to identify typical atmospheric patterns related to damaging floods in Northern Portugal.
The manuscript is organized as follows: Section 2 describes the study area and datasets of damaging flood records and of atmospheric patterns. The results are presented and discussed in Section 3 and the conclusions are summarized in Section 4.

2. Methodology

2.1. Study area

The administrative region of Northern Portugal covers an area of ca. 21 278 km² and depicts strong spatial heterogeneity in the mean annual precipitation totals, ranging from 500 mm in the upper Portuguese Douro Valley to 3500 mm in the Peneda-Gerês mountain range (Fig. 1). The climate in the northwestern area is largely influenced by the proximity to the Atlantic Ocean, while the low-elevation inner areas are much more continental, typifying Mediterranean-like climates (Daveau, 2000). This west-east contrast is due to the mountain relief effect, since the geographic orientation of the main mountain ranges is parallel to the coastline, thus blocking the moist westerly winds blowing from the North Atlantic (Santos, 2009). As such, the Peneda, Amarela and Gerês mountains (on the windward side) record some of the highest precipitation amounts in western Europe (Ferreira, 2005), while inner areas, including the uppermost section of the Douro valley and of some of its tributaries, are among the driest regions in the country (Santos et al., 2014).

2.2. Data

2.2.1. Damaging Floods

In the present study, a damaging flood (DF, hereafter) is defined as a flood event that have caused some kind of damage reported by national and regional newspapers, regardless of the
number of people affected or the economic value of the resulting damages. The methodology used for the data flood collection and storage is summarized in Fig. 2. Five daily newspapers and ten weekly newspapers were systematically checked (Table 1). In total, 145 709 periodicals, corresponding to a surveyed period of 147 years (1865 to 2011), were analysed. The daily newspapers Diário de Notícias and Jornal de Notícias provide the longest time period. Five additional newspapers (O Século, Comércio do Porto, O Primeiro de Janeiro, Público and Correio da Manhã) were also surveyed for some specific dates in order to complete or validate DF occurrences. It is assumed that the damaging flood events are important enough to be reported by regional/local and national newspapers. Significant amount of work was carried out to check and validate all the damaging flood occurrences, using written press and cross checking different sources, from national to regional and local newspapers (Zêzere et al., 2014). For each DF occurrence, the following information was collected: sub-type (i.e. river flood, flash flood, urban floods), date, location (municipality, parish and x/y-coordinates according to the PT-TM06/ETRS89 projected coordinate system), triggering factor and information source (name, source type and reliability of the news, source, date of source, page number), number of deaths, injured, displaced, homeless or missing people, the entities involved and material losses. As this dataset is developed in a GIS (Geographic Information System) environment, each occurrence is coded and georeferenced using a point shapefile (Fig. 2). It is worth emphasising the high scientific value of this dataset, being a unique historical data source for Portugal.

2.2.2. Circulation weather types

Precipitation in Portugal, including its extreme episodes, is largely controlled by large-scale anomalies in the North Atlantic atmospheric flow (Santos et al., 2007; Santos et al., 2009), with important implications in the Portuguese hydrological budgets and river flows (Andrade et al., 2011). In fact, the latitudinal location of the North Atlantic eddy-driven jet stream is the main underlying mechanism for the occurrence of precipitation extremes in Portugal (Santos et al.,
2013b; Woollings et al., 2011), by e.g. governing the phase and magnitude of the North Atlantic Oscillation (NAO (Hurrell et al., 2001)) and the frequency of occurrence of strong and persistent ridge episodes (SPRE, (Santos et al., 2009)) in the eastern North Atlantic. Furthermore, both the frequency of occurrence and the strength of precipitation extremes are projected to increase under future climate change scenarios (Costa et al., 2012). Aiming at establishing relationships between flood historical records in the Douro River and the underlying patterns of the large-scale atmospheric flow, the daily means of the sea level pressure (SLP) fields are classified into circulation weather types (CWT). The 56-member ensemble means of SLP, produced by the 20th century reanalysis v2 (Compo et al., 2011), are retrieved from the NOAA Earth System Research Laboratory – Physical Sciences Division (http://www.esrl.noaa.gov/psd/). Data for the full temporal period (1871-2012, 142 years) within a Euro-Atlantic sector (60ºW-20ºE, 26-64ºN) are extracted. Daily means are obtained by averaging 6-hourly data and are defined on a regular grid of 0.20º latitude × 0.2º longitude (~200 km grid spacing).

To identify CWTs, a K-means clustering is applied onto the leading twenty principal components of the daily SLP for the subsector (30ºW-10ºE, 26-64ºN), which represent approximately 98% of the total temporal variance of this field within this subsector. The K-means on the empirical orthogonal basis is a common procedure to reduce the dimensionality of the clustering approach, to improve the signal-to-noise ratio and to attain more stable solutions (Wilks, 2011). SLP has proven to be useful in isolating CWTs over Portugal (e.g. Santos et al., 2005; Trigo and DaCamara, 2000) and is adequate for representing the near-surface mid-latitude atmospheric flow (Holton and Hakim, 2013) . The daily SLP anomalies at each grid point are determined with respect to their corresponding calendar long-term means, calculated over the full period (1871-2012) on a daily basis. Noisy (high-frequency) fluctuations in the long-term means are smoothed out by 5-day running means. Squared Euclidean distances are used for the distance-matrix computations (Seber, 2008). For the cluster seeding, a preliminary clustering on a random 10% subsample of days is undertaken to select the centroids for initializing the
iterative process (Spath, 1985). Further, the entire clustering approach is replicated ten times so as to attest the stability of the centroids (convergence of the iterative process).

Following the parsimony principle, the most physically meaningful solution is obtained for K=6 clusters. In effect, a higher number of clusters result in CWTs with very low frequencies of occurrence and thus with low significance and representativeness. Conversely, a lower number of CWTs lead to an oversimplification of the regimes, merging very different conditions into the same CWT. Similar methodologies were applied by Santos et al. (2005), for isolating wintertime precipitation regimes in Portugal, and by Fraga et al. (2014), for isolating CWTs relevant for wine production in northwestern Portugal. Therefore, 6 CWTs are eventually isolated. A calendar of CWTs is then produced, as each day is keyed to a specific regime. The composite fields of each CWT are also computed by averaging all daily fields within each cluster, representing a typical flow pattern (cluster centroid).

The 6-means clustering enables the isolation of 6 CWTs of the large-scale atmospheric circulation within a Euro-Atlantic sector relevant to the weather conditions in Portugal. These synoptic scale CWT are identified on a coarse grid resolution that does not properly resolve mesoscale systems, which can also play an important role on precipitation. However, as stated above, precipitation in Portugal is largely controlled by the North Atlantic large-scale flow, mainly in the winter half of the year, when the bulk of precipitation falls. As such, mesoscale systems tend to be of secondary relevance. Moreover, local conditions and small-scale processes are usually not fundamental for the occurrence of severe and widespread floods.

2.2.3. Relationship between circulation weather types and damaging floods

As previously stated, floods are strongly controlled by atmospheric conditions, which can be categorized in weather types that are manifestations of different dynamical regimes in the
atmospheric flow. Many previous studies were based on weather types, e.g. Pattinson and Lane (2012) refers some advantages of using a weather type classification to investigate multivariate climatological factors: low number of classes (dimensionality reduction), the length of the record allows research for long term trends and highlight dynamical linkages between large-scale processes and local weather conditions. The present study aims to identify relationships between CWTs and DF occurrences. As a common period is required for this analysis, only DF occurrences between 1871 and 2011 (141 years) are considered henceforth (the DF database starts in 1865).

DF – CWTs relationships were assessed by applying contingency statistical analysis. For each DF occurrence, a daily classification of CWTs during the entire episode was obtained. This methodology was originally developed by Duckstein et al. (1993) and later modified by Cony et al. (2008). A statistical coefficient was obtained to assess the occurrence of a given CWT, using the relationship between partial and total relative frequencies of the CWTs and DF occurrences. An effectiveness coefficient (EC) is defined as follows:

\[
EC = \frac{F_{A \text{ floods}}}{N_{\text{floods}}} = \frac{\% \text{floods}}{F_{\%}} \tag{1}
\]

where \( F_{A \text{ floods}} \) is the frequency of occurrence of a given CWT conditional to DF occurrences, \( N_{\text{floods}} \) is the total number of DF during the period of study, \( F_{A} \) is the frequency of occurrence of each CWT for the whole period and \( N_{T} \) is the total number of days.

This coefficient was then calculated for the frequency of CWTs over the 9 preceding days to the DF outbreak. The day of the DF occurrence is also considered in the study (day 10). The EC is now defined by the following expression:

\[
EC = \frac{F_{A \text{ floods}}}{N_{\text{floods}}} = \frac{\% \text{floods}}{F_{\%}} \tag{1}
\]
where \( F_{A_{10\text{days,floods}}} \) is the frequency of CWTs for the 10 days before the DF outbreak. An EC equal to 0.5 indicates that a given CWT occurred only half of the time during a DF occurrence than on average, while e.g. an EC equal to 2 indicates that the certain CWT occurred two times more often in the days up to the DF than on average (Prudhomme and Genevier, 2011).

Owing to the strong seasonality of the precipitation regime in Mediterranean climates, this methodology was applied to each DF type and to each meteorological season separately (winter: December, January, February, spring: March, April, May, summer: June, July, August, autumn: September, October, November).

3. Results

3.1. Damaging floods

The target period, from 1871 to 2011 (141 years), comprises 1861 records in Northern Portugal, with 27% of these occurrences having direct consequences to the population. From these occurrences, 58% correspond to river floods, 9% to flash floods and 33% to urban floods. A total of 186 people were killed, 59 injured, 29 missing, 1873 displaced and 15924 homeless people (Table 2). The number of DF reports is ca. 1.2% of the total number of newspapers consulted. Most river floods and urban floods take place mainly in winter, whereas flash floods are more spread throughout the year. Nonetheless, a significant percentage of flash floods (47% of total) occur in the June-September period in association with short duration heavy rainfall episodes. Overall, there is an average of 13 occurrences per year with one death toll, 13 people displaced and 113 homeless (Table 2).
3.1.1. Temporal trends

With regards to the temporal distribution of DFs over the 141-year period, there is a high inter-annual variability. By using the method of classification of natural breaks, the time series can be split into 3 sub-periods (classes): before 1930, 1931-1971 and 1972-2011. The first period represents 43% of the total time series length, but includes only 17.2% of all DF occurrences in Northern Portugal. The annual mean number of DF occurrences is 5. This period also comprises the year with the maximum number of occurrences (101), though most of them are related to the progressive flood of the Douro River. It began in 22 December 1909 and can be considered the largest DF throughout the twentieth century. This single episode killed 19 people.

The second time period, from 1931 to 1971, represents 29% of the time series length. It is characterized by the occurrence of the highest number of DFs, in a total of 997 (53.6% of total occurrences). In this period, the years of 1936, 1966, 1935, 1948, 1955 and 1939 show more than 55 occurrences per year. The last time period (1972–2011) corresponds to 28.4% of the time series length and recorded 543 DFs (29.2% of total occurrences). The annual mean number of occurrences is 14. The years with higher number of DFs are associated with anomalously wet years: 1978, 1979, 1989, 1996, 2000 and 2001. There are also years without occurrences, such as 1973, 1980, 1984, 1988, 2005 and 2007 (Fig. 3).

3.1.2. Geographical Distribution

The urban centers and the areas along major rivers concentrate most of the occurrences. The Douro catchment presents the highest number of DF episodes (57%). The majority of death, injured and missing people due to DF also occurred in the Douro catchment (68.4% of total). The lowest number of death, injured and missing people is registered in the Vouga (1%) and
Minho catchments (3.7%). The Douro catchment contributes to 93.6% of total homeless and displaced people, which results predominantly from river floods affecting the Oporto, Vila Nova de Gaia and Peso da Régua municipalities. The Minho and Cávado catchments recorded the lowest percentages of homeless and displaced people (0.2% and 0.3%, respectively). The majority of DF occurrences (82%) are located in areas where the annual mean precipitation totals are higher than 1000 mm (Fig. 4). The municipalities with the highest DF occurrences also have the highest population densities. The maximum number of occurrences is found for Oporto metropolitan area, followed by Braga, Ponte de Lima and Viana do Castelo (Fig. 4). More affected people are located in Peso da Régua, Porto, Vila Nova de Gaia and Chaves municipalities, mainly due to river flooding that caused many evacuees and displaced people along riverside areas (Fig. 4).

3.2. Circulation weather types

The SLP composite for each CWT indicates its typical flow conditions (Fig. 5). The CWTs are roughly the same as those identified by Fraga et al. (2014). Hence, their dynamical features are quite similar and the same designations are used henceforth. The AA (dual anticyclonic) type shows two high pressure systems, the Azores and central European highs (Fig. 5 a), accompanied by a strong low pressure system over the high-latitude North Atlantic. The E (easterly wind) type depicts a strong British anticyclone, driving easterly winds over Iberia (Fig. 5 b). The NW (northwesterly wind) type features a SLP pattern that may drive important westerly winds over Portugal (Fig. 5 c). The C (cyclonic) type reveals a strong cyclonic circulation northwestwards of Iberia, triggering westerly-southwesterly winds over Portugal (Fig. 5 d). The R (ridge) type shows an eastern North Atlantic ridge that may induce strong northerly-northwesterly winds over Portugal (Fig. 5 e). Lastly, the A (anticyclonic) type is a manifestation of the NAO positive phase (Fig. 5 f). These CWTs are in clear agreement with
previous classifications for Portugal (Santos et al., 2005; Trigo and DaCamara, 2000) and also with other classifications for the Euro-Atlantic sector, such as in Plaut and Simonnet (2001). The monthly frequencies of occurrence of each CWT (Fig. 6) show that A and E are prevalent in winter, whereas R tends to prevail in the summer half of the year. In the summer half, A, C and NW reveal quite low frequencies of occurrence. By the end of the year, as the occurrence of R decreases, A, C and NW present higher frequencies. The AA type is uniformly distributed, but with slightly more occurrences in September-October.

3.3. Relationships between circulation weather types and damaging floods

The aim of this analysis is to compare DF occurrences with CWTs. The results show that 70% of the occurrences recorded C type. If the ten days before the DF occurrence are considered, C type was recorded in 45% of days (Fig. 7). The other CWTs types have a much lower representation: 8% of the days are keyed to R type and 7% AA and NW types. The AA (17% of the days) and E (13% of the days) types also stand out ten days before the DF.

For all sub-periods, the C type prevails in the days of the DF occurrence (Fig. 8). In the first period, 71% of occurrences are keyed to C type, while 52% of the ten days before the DF occurrence are of C type. The second time period (1931-1971) is characterized by a slight decrease of days with record type C in the days of DFs (67% of days) and ten days before the DF (41%). The other CWTs types have more importance in the ten days before the DF occurrences: AA (18% of the days), R (13% of the days) and NW (11% of the days). In the last period (1972-2011), 74% of the DF occurrence days are of C type. In the ten days before the DF, 50% and 17% of days are of C and AA types, respectively (Fig. 8).

For the days that most affected people, whether killed, injured, missing, displaced or homeless people, the type C is predominant, with the exception of 27 December 1909, 22 December 1989
and 2 January 1962, when the NW and E types were recorded, respectively. In all of these days, the C type prevails over the 9 preceding days (Table 3).

Table 4 shows the EC for DF occurrence day by each flood type and CWT and indicates that the C type occurs 7 times more often in DF days than on average. The other CWT occurrences are smaller than 1, i.e. they occur less frequently during floods than on average. For river floods, the C type is largely prevalent, with a ratio of 8, which means that it is 8 times more frequent in DF days than on average. The same applies to urban flooding, with a ratio of 7. Conversely, the coefficient is close to zero for the other CWTs in both river and urban floods. For flash floods, C type remains prevalent, with a coefficient of 3. However, other CWTs now acquire more significance (Table 4).
Table 5 shows the EC for the 10 days before DF occurrences by each flood type and CWT. The high EC is obtained for C type and for all DF (4.8%), river floods (3.4%) and urban floods (1.2%). In contrast, EC is close to zero for all CWTs in flash floods, generally associated with short-lived and small-scale episodes.

The EC was also calculated for each season, when the DF occurring within a 3-month period (DJF, MAM, JJA, SON) were selected. In autumn, winter and spring, the C type is largely related to DFs. Nevertheless, in summer, A and E are the types most associated to DFs (Table 6). This may be due to the fact that summer flooding rarely occurs at wider regional scales, being often linked to mesoscale systems, not properly resolved by the synoptic-scale CWTs. Furthermore, under specific conditions, severe thunderstorms can occur in Portugal along the southern flanks of the anticyclones featured by these weather types, through the development of cut-off systems and upper-level troughs that may trigger strong atmospheric instability and heavy precipitation (Santos et al., 2012; Sousa et al., 2013). These summertime thunderstorms can be particularly strong and frequent in the Douro River catchment, particularly in the Spanish mountain ranges encircling it (Santos et al., 2013a).

### 3.4. Case study

In order to improve the analysis, a closer inspection to the most severe DF in the Douro River is carried out herein. The December 1989 flood in the Douro River caused severe damage and destruction along the downstream sector of the valley, with most of the human consequences being reported for the main riverine urban centres, such as Peso da Régua, Mesão Frio, Castelo de Paiva, Oporto and Gaia. Two persons were injured during the flood, a total of 1809 people were dislodged and 117 needed to be displaced, accounting for the most harmful DF event in terms of number of affected people during the study period (Table 3). The downstream segment of the Douro valley is historically the most critically affected by exceptional floods (Silva and
December 1989 is still today remembered in Portugal by the flooding events occurred in small catchments of eastern Algarve on the first decade of the month, and also by the end of its third week, affecting the larger Tagus and Douro catchments. A survey conducted by the Portuguese water resources institute (Rodrigues et al., 2003) highlights the 1989 flood among the main DF events in the Douro during the twentieth century, with peak flow discharges above 11800 m$^3$s$^{-1}$ at Peso da Régua, although this magnitude did not reach the extraordinary DFs occurred in 1909, 1910, 1962 and 1966.

This December 1989 DF occurred after a rainy autumn in Northern Portugal, particularly after the second fortnight of October. A general illustration of the DF is depicted in Fig. 9, showing relevant features of the temporal and spatial distribution of rainfall preceding the extreme DF event. The daily precipitation is represented in Fig. 9 for three meteorological stations located at the mountain ridges draining to the terminal sector of the Douro valley (Fig. 9a–c), also close to the estuary (Fig. 9c), where the flood reached its highest levels (Crestuma hydrometric station). The increase of precipitation intensity in the second week of December caused a first and brief peak flood (18 December), conditioning the magnitude of the second and culminating peak flood, clearly triggered by a heavy rainfall event in 21 and 22 December. Interestingly, the cumulated precipitation in these two single days was particularly higher (above 140 mm) over the mountainous limits of the western sub-catchments of the Douro system (namely Tâmega and Corgo at the right margin, and Paiva at the left margin) and over its estuary (downstream of Crestuma, Fig. 9c). These high precipitation amounts produced a rapid response of the discharges and a notable DF, taking into account the high levels of the river flow. Just a few days later, the precipitation stopped (on 27 December) and the discharges decreased rapidly by the end of 1989. This event exhibited particularities relatively uncommon to the Douro floods, since it has occurred in the late fall season and was linked with a very intense precipitation episode, while typically floods in Portuguese Douro system are of progressive type, controlled by steady and long duration rainfall (Ferreira and Zêzere, 1997; Rodrigues et al., 2003),
conditions that tend to happen more likely later in the course of the winter (e.g. Santos et al., 2005).

The atmospheric circulation directly responsible for the December 1989 DF in the Douro River corresponded to a C type, which prevailed during nine days prior to the extreme hydrological event. In Fig. 10 are represented some dynamic features of the synoptic situation over the Euro-Atlantic sector, including basic aspects of the atmospheric circulation (top panels) and relevant forcings for convection and heavy precipitation (bottom panels). A deep trough over the eastern Northern Atlantic extended its influence to western Iberia, as this region was also crossed by west-southwesterly winds at lower levels. An impressive band of moisture advecting northeastwards and moving into Portugal is visible in Fig. 10c, where precipitable water is represented (PW; note the maximum values above 30 mm) at 12:00, 21 December 1989. This humid air mass arrived into this area under highly unstable thermodynamic conditions, which is clearly suggested by the synchonic field of the convective available potential energy (CAPE), illustrating strongly favourable conditions for convection, particularly over the northwestern sector of Iberia. Therefore, the conjunction of these dynamic conditions bring some clues about the atmospheric environment that triggered the intense rainfall episode in 21 December 1989 over Northern Portugal and, subsequently, the next-day exceptional flood in the Douro River. Following the accumulation of rainfall during autumn, and particularly the contribution of the continuous wet spell since 9 December, the intense rainfall that hit the western sector of the Douro River was critical to trigger this historical flooding.

4. Discussion and Conclusions

This manuscript evaluates whether CWTs are related to the DF occurrences in Northern of Portugal. For this purpose, a database of DF occurred in Northern Portugal was used, as well as CWTs produced by the 20th century reanalysis v2, between 1871 and 2011. In total, 1861 DF
occurrences, 27% of which have resulted in direct consequences on the population, i.e., killed, injured, missing and displaced, was used. These occurrences were responsible for 186 killed people, 59 injured, 29 missing, 1873 displaced and 15924 homeless people.

Three time periods were established: before 1930, 1931-1971 and 1972-2011. The first period (1871–1930) was characterized by the lowest number of occurrences: 5 DFs per year on average. Conversely, the second period (1931–1971) shows the highest number of flood occurrences: 24 DFs per year. Finally, the third period (1972–2011) recorded an annual mean number of 14 DFs. It is worth noting that for the first period this database might be incomplete, as the number of sources is relatively small and the likely occurrences in rural areas had not always been reported by newspapers published in Oporto. The decrease of occurrences in the third period may, at least partially, be attributed to flow regulation by several installed dams between 1950 and 1985. The most important dam was built in 1970 (Bastos et al., 2012). However, according to Silva and Oliveira (2001), dams existing in the Douro catchment do not decisively contribute to the attenuation of major DFs in the main river course within the Portuguese territory. On the other hand, decreased rainfall in winter and spring (Santos and Fragoso, 2013), associated with the predominance of the positive phase of the NAO index between the 1960s and 1990s (Paredes et al., 2006; Trigo, 2008), has also contributed to lower the number of occurrences in the third period.

The most affected areas exhibit natural predisposing conditions favoring DF occurrences, but the spatial pattern of occurrences also reflects population distributions. Thus, the urban centers and the areas along major rivers concentrate most of the occurrences. The highest number of occurrences is indeed found in the Oporto metropolitan area.

One indicator was used to quantify this relationship, measuring whether a given CWT occurs more frequently than usual prior/during a DF occurrence. The results showed that at regional scale some CWTs have significant positive frequency anomalies with DF occurrence, i.e. they occur more frequently before and during a DF than in any other period. The results obtained
show the importance of C type in the occurrence of DFs, both on the day and on the previous nine days. These results are in line with the results reported by some previous studies, despite regional differences. Pattison and Lane (2012), found that five weather types (cyclonic, westerly, southwesterly, cyclonic-westerly, and cyclonic southwesterly) have triggered approximately 80% of extreme floods in the River Eden (UK). For all Britain, Wilby and Quinn (2013) found five weather types accounting for 68% of floods during the period 1961–2000 (cyclonic: 30%, southwest: 14%, westerly: 12%, cyclonic southwest: 7% and cyclonic westerly: 5%). Prudhomme and Genevier (2011), an European-wide study obtained a high association with a cyclonic west weather type for the majority of river catchments. This weather type is characterized by a dipole, with low pressures over north Atlantic and high pressures over the Azores, and was associated with flooding in northwestern Europe and western Alps, in both winter and summer.

From a seasonal viewpoint, however, types A and E are also related to the occurrence of DFs in summer. This may be due to temporal and spatially localized systems, not properly resolved by atmospheric reanalysis datasets. This seasonal variation has also been observed by Prudhomme and Genevier (2011), who concluded that summer floods are generally associated with intense and localized precipitation, which are linked to small pressure anomalies that are poorly resolved by large-scale atmospheric patterns.

The present study is an important contribution to a systematization of the historical DFs in Northern Portugal and their driving mechanisms. In forthcoming studies, it is aimed to improve the databases and to analyze the linkage between the CWTs and other weather extremes, as well as to extend the study to the whole of mainland Portugal.

Acknowledgements

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Parajka, J. et al., 2010. Seasonal characteristics of flood regimes across the Alpine–Carpathian range. J. Hydrol., 394(1–2): 78-89. DOI:10.1016/j.jhydrol.2010.05.015


UNISDR, 2012. Economic and Human Impact of Disasters in the last 12 years - Graphic. (1).


Table 1. Newspapers consulted within the Disaster Project framework.

<table>
<thead>
<tr>
<th>Newspaper</th>
<th>Period of Publication</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diário de Notícias</td>
<td>1865-2010</td>
<td>Daily</td>
</tr>
<tr>
<td>Jornal de Notícias</td>
<td>1888-2011</td>
<td>Daily</td>
</tr>
<tr>
<td>Diário de Coimbra</td>
<td>1931-2010</td>
<td>Daily</td>
</tr>
<tr>
<td>Correio do Minho</td>
<td>1955-1959</td>
<td>Daily</td>
</tr>
<tr>
<td>Comércio do Minho</td>
<td>1904-1910</td>
<td>Daily</td>
</tr>
<tr>
<td>Notícias de Chaves</td>
<td>1950-2010</td>
<td>Weekly</td>
</tr>
<tr>
<td>Correio de Mirandela</td>
<td>1907-1937</td>
<td>Weekly</td>
</tr>
<tr>
<td>Mensageiro de Bragança</td>
<td>1940-2010</td>
<td>Weekly</td>
</tr>
<tr>
<td>Notícias do Douro</td>
<td>1934-2007</td>
<td>Weekly</td>
</tr>
<tr>
<td>Soberania do Povo</td>
<td>1936-2010</td>
<td>Weekly</td>
</tr>
<tr>
<td>Região de Leiria</td>
<td>1935-2010</td>
<td>Weekly</td>
</tr>
<tr>
<td>Jornal do Fundão</td>
<td>1946-2010</td>
<td>Weekly</td>
</tr>
<tr>
<td>Reconquista</td>
<td>1950-2000</td>
<td>Weekly</td>
</tr>
<tr>
<td>Diário do Alentejo</td>
<td>1933-2002</td>
<td>Daily until 1982 and weekly thereafter</td>
</tr>
<tr>
<td>O Algarve: o semanário independente</td>
<td>1908-2001</td>
<td>Weekly</td>
</tr>
</tbody>
</table>
Table 2. Total number of occurrences and damages for each type of damaging flood.

<table>
<thead>
<tr>
<th></th>
<th>River Floods</th>
<th>Flash Floods</th>
<th>Urban Floods</th>
<th>Others</th>
<th>Total</th>
<th>Total/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of occurrences</td>
<td>1074</td>
<td>175</td>
<td>608</td>
<td>4</td>
<td>1861</td>
<td>13</td>
</tr>
<tr>
<td>Number of deaths</td>
<td>135</td>
<td>43</td>
<td>6</td>
<td>2</td>
<td>186</td>
<td>1</td>
</tr>
<tr>
<td>Number of missing people</td>
<td>23</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>Number of injured people</td>
<td>30</td>
<td>10</td>
<td>19</td>
<td>0</td>
<td>59</td>
<td>0</td>
</tr>
<tr>
<td>Number of displaced people</td>
<td>1117</td>
<td>167</td>
<td>586</td>
<td>3</td>
<td>1873</td>
<td>13</td>
</tr>
<tr>
<td>Number of homeless people</td>
<td>15407</td>
<td>194</td>
<td>323</td>
<td>0</td>
<td>15924</td>
<td>113</td>
</tr>
</tbody>
</table>
Table 3. Days with more people affected by the DFs and CWTs on the day and 9 days before.

### Days with more Deaths, Injured or Missing People (Top five)

<table>
<thead>
<tr>
<th>Date</th>
<th>Occurrences</th>
<th>Deaths, Injured or Missing People</th>
<th>Displaced or Homeless People</th>
<th>CWT</th>
<th>CWTs in 9 days before</th>
</tr>
</thead>
<tbody>
<tr>
<td>27-12-1909</td>
<td>5</td>
<td>7</td>
<td>0</td>
<td>NW</td>
<td>NW,NW,C,C,C,C,C,C,C</td>
</tr>
<tr>
<td>07-12-1915</td>
<td>1</td>
<td>11</td>
<td>0</td>
<td>C</td>
<td>C,C,AA,C,C,C,C,AA</td>
</tr>
<tr>
<td>22-12-1909</td>
<td>42</td>
<td>17</td>
<td>79</td>
<td>C</td>
<td>C,C,C,AA,E,E,E</td>
</tr>
</tbody>
</table>

### Days with more displaced and homeless people (Top five)

<table>
<thead>
<tr>
<th>Date</th>
<th>Occurrences</th>
<th>Deaths, Injured or Missing People</th>
<th>Displaced or Homeless People</th>
<th>CWT</th>
<th>CWTs in 9 days before</th>
</tr>
</thead>
</table>
Table 4. Effectiveness coefficient (%) for the day of the DF occurrence, by each flood type and CWT

<table>
<thead>
<tr>
<th>CWTs</th>
<th>All Damaging Floods</th>
<th>River Floods</th>
<th>Flash Floods</th>
<th>Urban Floods</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1</td>
<td>0.0</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>AA</td>
<td>0.5</td>
<td>0.4</td>
<td>1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>C</td>
<td>7.4</td>
<td>8.1</td>
<td>3.3</td>
<td>7.2</td>
</tr>
<tr>
<td>E</td>
<td>0.4</td>
<td>0.3</td>
<td>1.3</td>
<td>0.3</td>
</tr>
<tr>
<td>NW</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>R</td>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Table 5. Effectiveness coefficient (%) for 10 days before the DF occurrence, by each flood type and CWT.

<table>
<thead>
<tr>
<th>CWTs</th>
<th>All Damaging Floods</th>
<th>River Floods</th>
<th>Flash Floods</th>
<th>Urban Floods</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>AA</td>
<td>1.0</td>
<td>0.5</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>C</td>
<td>4.8</td>
<td>3.4</td>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>E</td>
<td>0.8</td>
<td>0.4</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>NW</td>
<td>0.7</td>
<td>0.3</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>R</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Table 6. Effectiveness coefficient (%) for each season and CWT.

<table>
<thead>
<tr>
<th>CWTs</th>
<th>Autumn</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1</td>
<td>0.0</td>
<td>0.2</td>
<td>2.6</td>
</tr>
<tr>
<td>AA</td>
<td>0.6</td>
<td>0.3</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>C</td>
<td>5.9</td>
<td>6.2</td>
<td>5.3</td>
<td>0.8</td>
</tr>
<tr>
<td>E</td>
<td>0.5</td>
<td>0.2</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>NW</td>
<td>0.6</td>
<td>0.3</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>R</td>
<td>0.4</td>
<td>0.8</td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Fig. 1. Location of Northern Portugal and average annual rainfall (1931–1960) in study area (Adapted from Daveau (1977)).
Fig. 2. Methodological scheme for collecting and storing data on the DISASTER Database.
Fig. 3. Chronogram of the DF occurrences for the period of 1871-2011. The average annual occurrences and the 5 years moving average are also plotted (cf. legend). The 3 sub-periods in the dataset are also delimited by vertical dashed lines.
Fig. 4. (A) Catchments in Northern Portugal, along with the spatial distribution of DFs; (B) annual mean precipitation; (C) population density (people per km², 2011); and (D) people affected by municipality.
Fig. 5. Mean sea level pressure (SLP) composite for each CWT: a: AA - dual anticyclonic; b: E - easterly wind; c: NW - northwesterly wind; d: C - cyclonic; e: R - ridge; f: A – anticyclonic.
Fig. 6. Monthly frequencies of each CWT.
Fig. 7. (1) CWTs registered in day of DF occurrence and (2) CWTs in 10 days before each flood occurrence.
Fig. 8. (1) CWTs registered in day of DF occurrence and (2) CWTs in 10 days before each DF occurrence by 3 sub-periods (classes): before 1930, 1931-1971 and 1972-2011.
Fig. 9. Temporal (left panels) and spatial (right panels) features associated with the 22 December 1989 flood in Douro River: a, b and c graphs show the daily evolution of precipitation and discharges in selected locations of Douro drainage basin (Portuguese sector) during December 1989. The limits and drainage network of Douro basin are depicted in panel d, as well as the locations of the rain gauges and hydrometric stations represented on left panels. The cumulated precipitation in 21 and 22 December 1989 is mapped on panel d.
Fig. 10. Dynamic features of the synoptic situation in 21.12.1989 (12:00) over the Euro-Atlantic sector: SLP (panel a; shading in hPa), 500 geopotential height (b; shading in gpm), PW (c; shading mm) and CAPE (d; shading in J kg\(^{-1}\)). (Data source: 20th century reanalysis v2 (Compo et al., 2011).)
Highlights

The relationships between damaging floods and circulation weather types are studied.
The damaging flood database has 1861 records in Northern Portugal for 1871-2011.
Results showed that the cyclonic type has a positive frequency with damaging flood occurrence.
In autumn, winter and spring, the cyclonic type is largely related to damaging floods.
In the summer the anticyclonic and easterly wind types acquire higher preponderance.