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Discussions

Spatial impact and triggering conditions of the exceptional hydro-geomorphological event of December 1909 in Iberia

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Abstract

According to the DISASTER database the 20–28 December 1909 was the hydro-geomorphologic event with the highest number of flood and landslide cases occurred in Portugal in the period 1865–2010 (Zêzere et al., 2014). This event also caused important social impacts over the Spanish territory, especially in the Douro basin, having triggered the highest floods in more than 100 years at the river's mouth in the city of Oporto.

This work aims to characterize the spatial distribution and social impacts of the December 1909 hydro-geomorphologic event over Iberia. In addition, the meteorological conditions that triggered the event are analysed using the 20 Century Reanalysis dataset from NOAA and precipitation data from Iberian meteorological stations.

The Iberian Peninsula was spatially affected during this event along the SW-NE direction spanning from Lisbon, Santarém, Oporto and Guarda (in Portugal), until Salamanca, Valladolid, Zamora, Orense, León and Palencia (in Spain). In Iberia, 134 DISASTER cases were recorded (130 flood cases; 4 landslides cases) having caused a total of 89 casualties (57 in floods and 32 in landslides) and a total of 3876 people were affected, including fatalities, injured, missing, evacuated and homeless people.

This event was associated with some outstanding precipitation values at Guarda station (Portugal) in 22 December 1909 and unusual meteorological conditions characterized by the presence of a deep low pressure system located over NW Iberian Peninsula with a stationary frontal system striking the Western Iberian Peninsula. The presence of an upper-level jet (250 hPa) and low-level jet (900 hPa) located on SW-NE oriented towards the Iberia along with upper-level divergence and lower-level convergence favoured large-scale precipitation. Finally, associated with these features it is possible to state that this extreme event was clearly associated to the presence of an elongated Atmospheric River, crossing the entire northern Atlantic basin and providing a continuous supply of moisture that contributed to enhance precipitation.

This work contributes to a comprehensive and systematic synoptic evaluation of the second most deadly hydro-geomorphologic Disaster event occurred in Portugal since 1865 and will help to better understand the meteorological system that was responsible for triggering the event.

1 Introduction

In the Iberian Peninsula, extreme precipitation events that occurred during winter (December-January-February-March) have been associated historically with progressive flooding events in the major rivers (Salgueiro et al., 2013), flash floods that typically occur in small watersheds or urban areas (Fragoso et al., 2012; Llasat et al., 2005) and landslide events (Zêzere and Trigo, 2011; Zêzere et al., 2015). These events have been the source of major socioeconomic impacts, human and material damage (Barriendos and Rodrigo, 2006; García et al., 2007; Vicente-Serrano et al., 2011; Trigo et al., 2014, 2015).

Regularly, these extreme events were evaluated based on case studies, like for instance the November 1967 flash flood in the Lisbon region (Trigo et al., 2015), the large flood in Guadiana River in 1876 (Trigo et al., 2014), the 20 February 2010 flash floods in Madeira (Fragoso et al., 2012), and the 10 June 2000 flash flood in Catalonia (Llasat et al., 2003). Major floods that occurred in the Iberian Peninsula were extensively analysed in the Tagus basin (Benito et al., 2003; Machado et al., 2015; Salgueiro et al., 2013) and with less extent in the Douro basin (e.g. Morán-Tejeda et al., 2012).

Recently a long-term database of hydro-geomorphological cases was developed for Portugal for the period 1865–2010 in the project DISASTER (Zêzere et al., 2014). This database accounts 1621 flood cases and 281 landslide cases for the period 1865–2010 that were responsible for 1251 fatalities and more than 41 000 homeless people (Zêzere et al., 2014). This database includes social consequences (fatalities, injured, missing, evacuated and homeless people) caused by flood and landslide cases referred-to in Portuguese newspapers during the period of 1865–2010. The DISAS-

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TER database is the only database containing detailed data on the social impacts of hydro-geomorphologic disasters in Portugal as it accounts any flood or landslide that, independently of the number of affected people, caused casualties, injuries or missing, evacuated or homeless people. Therefore, each DISASTER case is a unique hydro-geomorphologic occurrence, which is related to a unique geographic location and a specific period of time (e.g. the place where the flood or landslide harmful consequences occurred in a specific date). Within this database, a DISASTER event is a set of flood and landslide cases sharing the same trigger mechanism and thus clustered in the temporal domain, which may have a widespread spatial extension and a certain magnitude (Zêzere et al., 2014).

December 1909 flood in Portugal is considered the most extraordinary flood of the twentieth century along the Douro River since there are systematic records of the river flow (Rodrigues et al., 2003). This particular flood also had a strong contribution from the Spanish area of the Douro basin, at a time when the hydrologic regime was only conditioned by natural factors due to the absence of dams to control the river flow (Rodrigues et al., 2003). It is worth stressing that after the flash flood of November 1967 (with circa 500 deaths) the 1909 flood was the second deadliest Disaster event in Portugal in the period 1865–2010 that generated 35 fatalities (29 caused by floods and 6 caused by landslides). In addition, according to the DISASTER database the 20–28 December 1909 was the DISASTER event with the highest number of flood and landslide cases (67 flood cases and 3 landslide cases) occurred in Portugal in the period 1865–2010 (Zêzere et al., 2014). As we show in the descriptive analysis later there were an even larger number of fatalities in Spain (54) raising the total number of deaths to 89.

The socioeconomic impacts associated to the 1909 event were particularly strong over the NW Iberian Peninsula (Fig. 1). Thus, while most observed floods were concentrated in Portuguese and Spanish provinces of the Douro basin, other areas were equally affected, including the Minho basin and Tagus valley (Santarém), Lisbon region and also the northern section of the Tagus basin in the Spanish territory (Fig. 1).

Besides the intrinsic relevance of this extreme episode from the impact perspective, this event was associated with some outstanding precipitation values and unusual meteorological conditions. However, to the best of our knowledge this extreme hydro-meteorological episode was never evaluated in detail, namely by Portuguese and Spanish authorities or research teams. This lack of previous assessments resulted in our view from several distinct factors, including, (1) lack of sufficient long-term time series of precipitation covering most of the affected territory, (2) lack of surface and upper air meteorological fields capable of describing the most important atmospheric circulation features of the episode, and (3) the inexistence of a list of places with the affected people and socio-economic impacts. These three shortcomings result to a large extent from the fact that the event occurred in early 20th century, however, these caveats have been minimised in recent years. Thus, a number of initiatives in Portugal and Spain have favoured the digitalization of time series from the late 19th century and beginning of 20th century, allowing the assessment of long term changes in daily precipitation (Gallego et al., 2011; Cortesi et al., 2014), or related to major historical floods and extreme precipitation events (Trigo et al., 2014; Domínguez-Castro et al., 2015). Likewise, a new type of long-term reanalyses has been developed (Compo et al., 2011), and despite being based on surface data, it is capable of reproducing upper air fields (e.g. Trigo et al., 2014). Finally, has stated previously, a comprehensive list of people affected (fatalities, injured, displaced, evacuated and disappeared) has been obtained through the DISASTER database (Zêzere et al., 2014) although covering only the Portuguese territory.

In this context, this work has three main goals: (i) to characterize the spatial distribution and social impacts of the December 1909 hydro-geomorphologic DISASTER event over Portugal and Spain, (ii) to determine the corresponding spatial distribution of precipitation anomalies using recently digital daily precipitation data, (iii) to analyse the meteorological conditions that triggered the event.

2 Study area and precipitation regime

Iberian Peninsula is located southwest of Europe and includes the countries of Andorra, Portugal and Spain. It is surrounded by the Mediterranean Sea (on the southeast and east), the Atlantic Ocean (on the west) and the Cantabrian Sea (on the north). The central part of the Iberian Peninsula is occupied by the Meseta, a vast plateau (Douro and Tagus Cainozoic basins) that is characterized by hilly and smooth terrain. This central Meseta is surrounded by mountains (e.g. Cantabrian Mountains, Pyrenean Mountains, Betic Range and Central Mountains) and is sculptured by the fluvial network (Santisteban and Schulte, 2007) (Fig. 1).

There are four large international Iberian rivers (Minho, Douro, Tagus and Guadiana), all flowing predominately in a NE–SW direction with their lower courses in Portugal (Fig. 1). Seasonal precipitation regime in the Iberian Peninsula controls the major river flow regime (Trigo et al., 2004) like in other Mediterranean regions, where most of the river flow is registered in winter and spring time (Daveau, 1998).

In the Iberian Peninsula, there is a high spatial and temporal variability of precipitation (Cortesi et al., 2013; Serrano et al., 1999; Trigo et al., 2004) due to its location in the southern rim of the Atlantic zonal circulation (Trigo and Palutikof, 2001). The successive passage of frontal systems from west to east over the North Atlantic basin (most frequent in the winter) produces continuous and persistent daily precipitation, mostly in the western Iberian Peninsula which can cause major river floods (Salgueiro et al., 2013). Precipitation distribution over the Iberian Peninsula depends also on the wind trajectory (SW, W or NW) and on the local orographic effects (Cortesi et al., 2014; Goodess and Jones, 2002; Salgueiro et al., 2013) that influence precipitation intensity and type (snow vs. precipitation) at the regional scale.

Numerous studies proved that the NAO has a strong impact on the occurrence of extreme flooding in the major rivers, namely along the Tagus River (Benito et al., 2003; Machado et al., 2015; Salgueiro et al., 2013; Silva et al., 2012) and the Guadiana River (Ortega and Garzón, 2004).

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In addition, Ramos et al. (2015) shows that the presence of the so called Atmospheric River (AR) structure over the Iberian Peninsula can enhance the precipitation amount, as was the case if another outstanding historical flood event in southern Iberia in 1876 (Trigo et al., 2014). Therefore this will also be taking into account when analysing the 1909 hydro-geomorphologic DISASTER event. ARs are identified as narrow plumes of enhanced moisture transport that are usually present in the core of the warm conveyor belt and occur on the oceans along the warm sector of extra-tropical cyclones (Ramos et al., 2015). They are usually W–E (or SW-NE) oriented and steered by pre-frontal low level jets along the trailing cold front and subsequently feed the precipitation in the extra-tropical cyclones. The large quantity of water vapour within the AR can generate heavy precipitation and floods when they make landfall (Dettinger, 2011; Lavers et al., 2011). Regarding the Iberian Peninsula, the impact of ARs in extreme precipitation has been assessed on a systematic manner (Ramos et al., 2015) but also in relation to several well-known events of floods and extreme precipitation with major socio-economic consequences (Couto et al., 2012; Liberato et al., 2012). There are several methodologies to identify ARs (Gimeno et al., 2014), here we opted to adopt the one that involves the existence of a long (>2000 km lenght) and narrow (<500 km width) band of water vapour at low levels from the subtropics ($>5\,\mathrm{g\,kg^{-1}}$ of specific humidity at 900 hPa), while wind speed should be considered above $12.5\,\mathrm{m\,s^{-1}}$ (Lavers et al., 2011).

3 Materials and methods

3.1 Historical data sources

The data source used to analyse the event of December 1909 in Portugal was the DISASTER Database (Zêzere et al., 2014). The data collection process used to construct the DISASTER database was based on painstaking analysis of numerous daily and weekly newspapers, and is explained in full detail in Zêzere et al. (2014).

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In 1909 there were available only 4 newspapers for data collection in Portugal (Table 1). The national daily newspaper Diário de Notícias published since 1865 in Lisbon provided the longest time period to data collection. Apart from this daily newspaper it was analysed the Jornal de Notícias published in Oporto (North of Portugal) since 1888. The remaining 2 newspapers are weekly local and regional newspapers, one located in the North (Correio de Mirandela) and another one in the South of the country (O Algarve: o semanário independente).

In Spain there is no equivalent to the DISASTER database built with similar criteria in order to allow data comparison between the two countries. As a consequence, we have adopted the same methodology and criteria used in the DISASTER database to ensure data integrity and to enable data comparison. The data collection process was supported by the systematic analysis of Spanish daily newspapers of the entire month of December 1909. Four daily national newspapers (La Época, La Correspondencia de España, El Imparcial and El Siglo Futuro) published in Madrid were used for data collection and a regional newspaper (El Liberal) with spatial incidence in Madrid, Sevilla, Barcelona, Bilbao and Murcia was also explored (Table 1). In summary, we can state that, although not included in the original DISASTER database, all locations selected in Spain relative to this event fulfil the DISASTER requirements as described in Zêzere et al. (2014). In this regard they can be considered DISASTER-like cases and the use of this denomination will be applied indiscriminately throughout this work, to both cases and locations in Portugal and Spain.

Each DISASTER case includes details about process characteristics and associated damages. The first includes data on type (flood or landslide), subtype, date, location, triggering factor and data source. In addition, the following damages were recorded: number of casualties, injuries, missing, evacuated or homeless people, type of damages in buildings, number of affected buildings, type of damage in road and railroad, extent of interruptions in road and railroad circulation (Zêzere et al., 2014). Location of DISASTER cases in both countries was done using a point shapefile. The precision of the location depends on the detail of the news and was classified in the following classes: (i) exact coordinates (accuracy associated with scale 1 : 1000), (ii) local toponymy (accuracy associated with scale 1 : 10 000), (iii) local geomorphology (accuracy associated with scale 1 : 25 000 scale), (iv) centroid of the parish; and (v) centroid of the municipality (Zêzere et al., 2014).

3.2 Precipitation data

Precipitation data for 27 different meteorological stations of Iberia used here is summarised in Table 2 including the name, elevation (in meters) mean annual precipitation (MAP), mean monthly precipitation (MMP) in December and total precipitation in 1909 (December, 22 December and 20–28 December).

According to Fig. 1, seven meteorological stations were located in Portugal (Beja, Campo Maior, Coimbra, Évora, Guarda, Lisbon and Porto) and 20 in Spain (Albacete, Alicante, Badajoz, Barcelona, Burgos, Cádiz, Ciudad Real, Granada, Huelva, Huesca, La Coruña, Madrid, Málaga, Murcia, Salamanca, Sevilla, Soria, Valencia, Valladolid, Zaragoza).

Long-term time series of daily precipitation for Portugal were digitized by the Geophysical Institute Infante Dom Luiz (IDL) within the ERA-CLIIM project (Stickler et al., 2014). For Spain daily precipitation data was obtained from the project EMULATE which are the most complete and reliable daily precipitation records extending back to the mid-19th century (Brunet et al., 2007). A large fraction of these stations were used in a long-term assessment of tendencies in the frequency of days characterised by low, medium and intense precipitation (Gallego et al., 2011).

Long-term daily precipitation data of Porto (1906–2007), Guarda (1906–1994), Lisbon (1864–2013) and Salamanca (1894–2003) was explored in further detail by considering the period from September to December. For the complete set of stations, climatological reference periods correspond to the 1971–2000 normal in Portugal (IPMA, Portuguese Meteorological Office) and to the 1981–2010 normal in Spain (AEMet, Spanish Meteorological Office).

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3.3 Synoptic data

The atmospheric circulation during the December 1909 event and prior months was evaluated at different time scales. This was achieved with the recently developed 20th Century Reanalysis version 2 (Compo et al., 2011), hereafter 20CR.

The 20 CR dataset has been shown to be suitable for long-term assessment over Iberia, such as major floods event in 1876 (Trigo et al., 2014) or the decadal change of wind resources (Kirchner-Bossi et al., 2015). Several fields related to both surface and tropospheric levels were extracted. From the surface the 6 h sea level pressure field (hPa) and 6 h accumulated precipitation were used. In addition the following variables were also extracted and analysed: (i) for the lower levels (900 hPa), the 6 h fields of wind vector ($m\,s^{-1}$) and specific humidity ($g\,kg^{-1}$) and (ii) for the upper levels (500 and 250 hPa) the 6 h fields of wind vector ($m\,s^{-1}$), geopotential height and temperature. The ensemble mean fields for all variables were assessed using a global grid of $2^{\circ} \times 2^{\circ}$.

3.4 NAO data

NAO data of monthly mean normalized difference of sea level pressures between Lisbon (Portugal) and Stykkisholmur/Reykjavik (Iceland) (Hurrell, 1995) was obtained in the National Centre of Atmospheric Research (NCAR) covering a period from 1865 onwards.

4 Results

4.1 Socio-economic impacts

The Iberian Peninsula was spatially affected during this event along the SW-NE direction spanning from Lisbon, Santarém, Porto and Guarda (in Portugal), until Salamanca, Valladolid, Zamora, Orense, León and Palencia (in Spain) (Fig. 1).

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In the Iberia, 134 DISASTER cases were recorded, 130 flood cases and 4 landslides cases (Fig. 1). Table 2 summarizes the social consequences of the December 1909 event in Iberia. Considering the data sources from both affected countries, floods of December 1909 event caused 57 fatalities, 4 injured, 15 missing people, 1104 evacuated people, and 2564 homeless people (Table 2). Landslides (debris flows) caused 32 fatalities and 100 homeless people (Table 2). In total this event affected 3876 people in the Iberia. The Douro basin and the Tagus basin registered 62 and 15 % of total disastrous floods, respectively (Table 2).

The spatial distribution of fatalities generated by floods and landslides in Iberia during the 1909 event is presented in Fig. 2a. Floods were particularly disastrous along the Douro basin, where 60 % of total fatalities associated with floods were registered (Table 2). However, the DISASTER case that generated more fatalities (26 fatalities) was produced by a single landslide (debris flow) that occurred in Orense province, in the small village of Bolo.

The DISASTER flood cases that caused more than 2 fatalities were located, in Portugal, in the district of Santarém (Constância), Coimbra (Miranda do Corvo) and Bragança (Mirandela) and, in Spain, in the provinces of Salamanca (Ciudad Rodrigo), Zamora (Villaveza del Agua and Benavente) and Pontevedra (Tui) (Fig. 2a, Table 2).

Floods generated the vast majority (96.2 %) of total homeless people, and among these, 82 % were located in the Douro basin, mostly in the Spanish side of the basin (Fig. 2b, Table 2). In Spain, the provinces of Salamanca (cities of Ciudad Rodrigo and Salamanca), Palencia (city of Palencia), Zamora (small villages of Santa Cristina de Polvorosa, Villanueva de Azoague and Micereces de Tera), Orense (small village of Barco de Valdeorras) and León (small village of Soto de la Vega) registered the highest number of homeless people due to floods along the Douro tributaries (Tormes, Carrión, Esla, Tera and Luna, respectively) (Fig. 3). In Portugal, the highest number of homeless people was registered in Santarém (village of Almeirim). In each of the abovementioned places more than 100 homeless people were recorded and the high-

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est value was registered in Ciudad Rodrigo (400 homeless people in the neighbourhood of Arrabal del Puente).

The DISASTER event of December 1909 also generated evacuated people (Fig. 2c) who were rescued from the waters or from flooded buildings. There are two major spots of evacuated people in Portugal, one in the village of Torres Vedras (Lisbon district) and other in the mouth of the Douro River in Oporto City (Oporto district), where 400 and 105 people, respectively, were evacuated. In Spain, there is an important spot of evacuated people (101 people) near the confluence of the Carrión River with the Douro River in the village of Husilos (province of Palencia) (Fig. 3). The Douro basin includes 53.9 % of total evacuated people registered during the December 1909 event.

Table 2 highlight the Douro Basin as the major zone impacted by floods. This basin registered 64 % of total Disaster flood cases and 73 % of total affected people by floods. In the case of landslides, the Minho basin had only a single DISASTER case, which was responsible for the highest number of fatalities (26) and homeless people (100).

Despite the described social impacts, the December 1909 event also caused huge economic losses in Iberia. In Spain, several settlements were completely submerged by water and a great number of buildings were destroyed, especially in the areas drained by the main tributaries of the Douro River (e.g. in the province of Zamora: San Marcial, Villanueva de Azoague, Santa Cristina de Polvorosa, Vecilla de Polvorosa, Cabañas, Molacillos; in the province of Salamanca: Arrabal del Puente neighborhood in Ciudad Rodrigo, Granja de la Serna; in the province of León: Cándana, Fresno, Vega; in the province of Palencia: Husillos; Fig. 3). Also in Portugal Peso da Régua and Barca de Alva villages and the riverside of Oporto and Vila Nova de Gaia were submerged by waters.

Major cities of Spain (e.g. Salamanca) and Portugal (e.g. Oporto) were kept isolated, without communications with the outside due to widespread cuts in the road and railroad circulation (submerged or destroyed roads and railroads, destroyed bridges). Likewise, major delays in mail delivery were noticed (up to 52 h) as well as interruption in the telegraph service (La Correspondencia de España, 22–28 December 1909; Jor-

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nal de Notícias, 22–28 December 1909). The railroad circulation between Portugal and Spain was also interrupted during several days. Problems in communications began on 22 December and have been progressively restored onwards 28 December.

In the Oporto City (mouth of Douro River) 732 boats docked in the Douro River were swept away to the sea and 32 were destroyed against the shore (Jornal de Notícias, 28 December 1909). Among the destroyed boats it is important to stress the inclusion of six steamboats (Néstor, Gascón, Douro, Cintra, Elida, Silvia) and a Portuguese navy corvette (Estefânia). The Oporto city had no supply of gas and electricity for 6 days (22–28 December) due to the flood (Jornal de Notícias, 28 December 1909).

Finally, it was also reported that some cattle herds were killed by the floods, as well as widespread destruction of cropped areas (e.g. vegetables, grain) that caused food scarcity after the floods. There are also reports of destroyed mills in Águeda River (La Correspondencia de España, 22–28 December 1909).

The daily evolution of fatalities and affected people generated during the December 1909 event is provided in Fig. 4. Between 20 and 22 December 48.8 % of the Disaster cases were registered (Fig. 4a). In addition, the highest daily number of DISASTER cases (58) and the highest number of fatalities (52) were registered in 22 December. In terms of total affected people, it is possible to discern two peaks, the major one in 22 December (1842 affected people) and the second in 25 December (1014 affected people).

In the Douro basin the daily evolution of the social impacts (Fig. 4b) is quite similar to the complete set of the event. On contrary, the Tagus basin only registered social impacts in 22, 24 and 27 December (Fig. 4c). Likewise in the Douro basin, the highest number of Disaster cases and affected people were registered in 22 December in the Tagus basin.

The spatial distribution of the DISASTER cases per day is shown in Fig. 5. In general terms, DISASTER cases that occurred between 20 and 23 December arose predominantly in Portugal with some isolated spots in Spain (Salamanca, Zamora, León and Orense). Disaster cases registered between 24 and 28 December occurred widespread in Spain with some isolated spots in Portugal in 27 and 28 December (Santarém, Bragança, Braga, Viana do Castelo). Therefore, overall the temporal distribution of DISASTER cases is consistent with an atmospheric circulation in Iberian Peninsula coming from SW to NE. However, one must keep in mind that information flow at the time was considerably slower than today, particularly so during disruptive events such as major natural hazards. In this regard, it is possible that some of these later dates correspond simply to cases that were reported/transmitted a few days after their real occurrence without correction of the reported timing.

4.2 Precipitation event and hydrologic context

Daily long-term cumulative precipitation from 1 September to 31 December is shown in Fig. 6 (grey thin lines) for the meteorological stations of Oporto, Lisbon, Guarda and Salamanca. In addition, the long term mean (magenta line) and the 95th percentile (black line) along with the 1909 year (red line) are also highlighted. It is clear that the December 1909 event was preceded by an intense precipitation in late autumn, especially since 15 November where it surpasses the mean in all locations and a period of enhanced precipitation after the 17 December. These features are particularly notorious at the Guarda station, where the cumulative precipitation between 17 December and 31 December 1909 reached a total of 406.7 mm. Mean monthly precipitation for December at Guarda station is 141.8 mm, while the total precipitation registered in December 1909 was 451.1 mm (Table 3). In December 1909 a total of 80.7 mm were registered at Salamanca (although much lower than the value observed in Guarda it corresponds to twice the amount of the mean monthly precipitation for December) (Table 3). It is important to mention that in November and December 1909 strong negative values of NAO (−1.9 and −2.5, respectively) were registered. These negative values of the NAO help to put into context the above average precipitation that occurred in the November and December (Trigo et al., 2004).

Since 22 December 1909 the cumulative precipitation (red line) was higher than the 95th percentile (black line) at Guarda and Salamanca stations, both located in

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the Douro basin. The extreme rainy period is very clear at the Guarda station where a daily maximum precipitation of 185.2 mm was recorded in the 22 December 1909, corresponding to a return period of 141 years. Regarding Oporto and Lisbon, both stations recorded values of accumulated precipitation till 22 December below the 95th percentile but still above the long term mean. In addition, for Lisbon, two particular years with major floods are also highlighted for comparison, 1876 (blue line) and 1967 (green line). The 1876 highlight the importance of previous accumulated precipitation in the occurrence of floods events in the Tagus and Guadiana basins on 7 December 1876 were a record flow was registered (Trigo et al., 2014). On the contrary, the 1967 event occurred on the night between 25 and 26 November 1967 and was much more confined to the Lisbon area, i.e. without affecting large river basins. This was the deadliest storm affecting Portugal at least since early 19th century with several flash floods in heavily constructed suburban areas around Lisbon causing more than 500 fatalities. In this case, the accumulated precipitation prior to the 25 and 26 November 1967 was below average and the flash floods occurred mainly as a result of very intense hourly precipitations, ranging in duration from 4 to 9 h, compatible with return periods of 100 years or more (Trigo et al., 2015).

As it was already mentioned, the precipitation record corresponding to the December 1909 event was particularly notorious in the Guarda station. Therefore, in order to understand the time duration and magnitude of the event, the accumulated precipitation values (from 1, 2, 5, 10, 15, 30 and 45 days) of Guarda station (88 years) were computed and all values were ranked, with the top 10 events being represented in Fig. 7. A similar methodology was applied in a previous analysis of an outstanding event, the record floods of 7 December 1876 in southern Iberia (Trigo et al., 2014). Figure 7 shows in the x axis the 10 highest values of maximum accumulated precipitation from different durations (y axis). The blue bars correspond to accumulated precipitation (z axis) for different durations of the December 1909 event. For the complete precipitation series of Guarda station, the December 1909 event occupies the first position in the cumulated precipitation for 1 day (185.2 mm) and the second position for 2 days (279.8 mm) (Fig. 7).

Interestingly, the extreme precipitation values observed in Guarda and to a less extent in Salamanca were not observed in most locations with pluviometers. Weather stations located near the Atlantic coast (Oporto and Lisbon) did not record extreme accumulated precipitation in the December 1909 event (Figs. 6 and 8) and the stations located in the eastern part of Spain registered null or low precipitation (below 20 mm). Estimated precipitation of 22 December and 20–28 December 1909 was interpolated spatially using a co-kriging geostatistical technique considering the precipitation measured in the stations (points) and the Iberia SRTM 90 m DEM's with 90 m resolution (Jarvis et al., 2008) (Fig. 8a and b). Estimated precipitation shows that the event precipitation entered in the Atlantic coast (Lisbon region and Alentejo coast) and crossed the peninsula in a SW-NE direction. In addition, it is impressive the extreme precipitation occurred during the 22 December in the Douro basin, namely in the Guarda and Salamanca regions (Fig. 8a).

According to Rodrigues et al. (2003) the flood of 1909 was referenced as the second historical flood measured at Peso da Régua, in the Portuguese sector of the Douro River (Fig. 3) in the last 300 years. River flow data was provided by the Portuguese Hydrological Services. In the historical flood of 1909 a flow rate of 16 700 $m^3 s^{-1}$ was reached, which was only surpassed by the flood of 1739 (18 000 $m^3 s^{-1}$).

A graph with the evolution of sub-daily flow rate at Peso da Régua for the period of 18–30 December 1909 is shown in Fig. 9, using data from Rodrigues et al. (2003). In the beginning of this period a constant rise in the flow rate was recorded, from 2000 $m^3 s^{-1}$ in 18 December until 6000 $m^3 s^{-1}$ at the early hours of 21 December. Then, the flow rate suddenly increased until 16 700 $m^3 s^{-1}$ during the day of 23 December, as a consequence of the extreme precipitation that was registered along the Douro basin during the previous days, especially the 22 December. The maximum flow rate of 16 700 $m^3 s^{-1}$ corresponds to a return period of 80 years (Rodrigues et al., 2003). In Peso da Régua the river level rose 25 m during this flood (Jornal de Notícias, 24 December 1909). It should be noticed that at Peso da Régua the flow rate of 6000 $m^3 s^{-1}$ has a 16 year return period and imply a 13 m rise of the river level, which is considered an extraordinary flood in the region (Rodrigues et al., 2003).

The flow rate starts to decrease in the end of the 23 December but a second peak was registered at the end of the 24 December with similar magnitude (16 200 $m^3 s^{-1}$), following a secondary precipitation peak that is not evident on precipitation daily records. Only afterwards, i.e. since the 25 December the flow rate decreased progressively until the end of the month (2800 $m^3 s^{-1}$ in 30 December). It is important to notice that the flow rate was higher that 6000 $m^3 s^{-1}$ between 21 and 28 December, coinciding with the event time interval.

4.3 Assessing atmospheric circulation

Here we intend to characterise with some detail the atmospheric circulation of the 22 December, in order to understand the occurrence of highest precipitation values within this day. It has already been shown in Sect. 4.2 the importance of the accumulated precipitation observed between mid-November and mid-December culminating with the intense precipitation on 22 December that triggered several socio-economic impacts in the following days (Sect. 4.1). The low pressure system that affected the Iberian Peninsula on the 22 December had its cyclogenesis on the 13 November and become stationary in the Atlantic near the Azores isles (not shown) and from this day onwards affected the western Iberian Peninsula with almost continuous precipitation every day till the 22 December (as seen in Fig. 6). The sequential panels every 6 h of SLP and the corresponding accumulated precipitation (both from the 20CR) are represented from the 22 December at 00:00 UTC till 23 December at 00:00 UTC (Fig. 10). This figure reveals the presence of a large deep low pressure system (966 hPa) located over the Atlantic Ocean, northwestern of the Iberian Peninsula and extending from Iceland to southern Portugal and to Central France. This low pressure system remains quasi stationary from 22 December 00:00 till 12:00 UTC when it started to move east towards the British Isles and its central core begin to increase pressure (Fig. 10d

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and e). In addition, the frontal system associated with this low pressure struck western Iberian Peninsula from a SW-NE direction. It was this relatively stationary frontal system that continually affected the Iberian Peninsula with precipitations every 6 h inducing heavy daily precipitation in some regions of the Iberian Peninsula as shown before in Fig. 8.

With the aim of further analyse the upper and lower level dynamics of this event we computed the divergence fields simultaneously with the wind speeds for both the 900 and 250 hPa (Fig. 11). The wind speed and associated divergence at the 250 hPa level is shown in the upper panels of Fig. 11, for 00:00 and 12:00 UTC respectively. The most interesting feature for this event is associated to the presence of an upper-level jet branch, oriented along a SW-NE direction towards the Iberian Peninsula but with its origin in the eastern coast of USA. This feature presents an area with strongest upper-level divergence over Portugal at 00:00 and 12:00 UTC, with values above $3 \times 10^{-5}\,s^{-1}$ favouring deep convection. In addition, at lower levels (900 hPa), a very intense low level jet (winds up to $30\,m\,s^{-1}$ close to Portugal) associated with the frontal system embedded within the southern flack of the low pressure system is also present with a similar SW-NE orientation. This intense advection of mass implies strong low level convergence at the western coast of the Iberian Peninsula ($-3 \times 10^{-5}\,s^{-1}$). In summary we can state that the large-scale conditions in the area of the western Iberian Peninsula were optimal for intense precipitation, i.e., frontal uplift associated with upper-level divergence and low level convergence. The displacement of the jet stream so further south also was also responsible for the stationary position of the low pressure system for so long.

However, one should bear in mind that the presence of low pressure system and its associated frontal system and the favourable dynamical mechanisms for intense precipitation explained before, alone cannot explain the intense precipitation that occurred during the 22 December.

The analysis of the Fig. 12 (upper panel, geopotential height and temperature at 500 hPa), show that the geopotential height is characterized by a strong trough located

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south of the Azores Islands thus favouring the southerly displaced position of the jet in the middle of the Atlantic (Fig. 11). Along with this trough there is a negative temperature gradient between 60 and 30° N with dry and cold air aloft near the Iberian Peninsula which also could enhance the formation of convection within the frontal system.

To analyse the moisture availability, which can enhanced the precipitation intensity, the specific humidity and wind vectors at 900 hPa are also shown for the 00:00 and 12:00 UTC (Fig. 12, lower panels). In both time steps, a narrow and prolonged band of moisture being transported from sub-tropical latitudes can be seen, with origin close to the Caribbean Islands. This narrow band presents an intense core with values above 9 $g\,kg^{-1}$, over the Atlantic Ocean, and moves towards extratropical latitudes, by a southwestern low level jet with wind speeds clearly above 24 $m\,s^{-1}$ (Fig. 11). Therefore the criterion of the identification of AR (see Sect. 2) is matched in the 22 December, enhancing the precipitation intensity during this particular day.

Summarizing, the synoptic analysis shows that the 22 December was characterized by the presence of a deep low pressure system located over NW Iberian Peninsula with a stationary frontal system striking the Western Iberian Peninsula. The presence of an upper-level jet (250 hPa) and low-level jet (900 hPa) located on SW-NE oriented towards the Iberian Peninsula along with upper-level divergence and lower-level convergence favoured large-scale precipitation. Along with these two features, the presence of an AR (with high content of moisture) contributed to a large extend to enhanced precipitation.

5 Discussion and conclusions

This study provides the first comprehensive assessment of the December 1909 hydrogeomorphologic DISASTER event over Iberia, including: (i) the spatial and temporal characteristics of the socio-economic impacts based on newspapers analysis, (ii) the corresponding spatial distribution of precipitation anomalies using recently digital daily

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precipitation data; and (iii) the meteorological conditions that triggered the event using the 20 CR.

The length of this event extended from 20 to 28 December 1909 and represented an extreme episode affecting most of the NW of Iberian Peninsula from the impact perspective, generating 3876 affected people taking into account fatalities, injured, missing people, evacuated people and homeless people. In the Iberia, 134 DISASTER cases were recorded, 130 flood cases and 4 landslides cases. The Douro basin and the Tagus basin registered 62 and 15 % of total disastrous floods, respectively (Table 2). Floods caused 64 % of total fatalities, and were particularly disastrous along the Douro basin. Moreover the socio-economic impact of the December 1909 event in Iberia highlights the Douro Basin as the major zone impacted by floods. In addition, the temporal distribution of DISASTER cases is consistent with a frontal system that crossed the Iberian Peninsula traveling on a SW to NE orientation and associated with a low pressure system located near the British Isles.

Data collection on newspapers of socio-economic disaster impacts was very useful to obtain the spatial distribution of the hydro-geomorphologic DISASTER cases in both countries and an historical complement to the lack of precipitation data in some of the affected areas.

December 1909 event was preceded by an intense precipitation throughout late autumn, especially since 15 November and was characterized by a period of enhanced precipitation after the 17 December. This event was associated with some outstanding precipitation values particularly notorious at the Guarda station, where the cumulative precipitation between 17 December and 31 December 1909 reached approximately 3 times more than the mean monthly precipitation for December. Since 22 December 1909 the cumulative precipitation was higher than the 95th percentile at Guarda and Salamanca stations, both located in the Douro basin.

The extreme precipitation values were not observed in most locations of the Iberian Peninsula where pluviometers were available. Weather stations of Oporto and Lisbon located near the Atlantic coast in the mouth of the Douro and Tagus Rivers, respectively, did not record extreme accumulated precipitation in the December 1909 event. Nevertheless these areas were also affected by floods as a result of the intense precipitation that occurred upstream the Douro and Tagus hydrographic basins.

It is important to highlight that the DISASTER event of December 1909 took place at a time when the relationship between the precipitation and the river flow was more straightforward due to the absence of dams. Nowadays, Douro and Tagus rivers have several dams that control flow rates and reduce flood peaks, thus reducing also the risk of flooding's even when higher than normal precipitation occurs.

The assessment of the large-scale atmospheric conditions suggests that the extreme precipitation event verified in December 1909 resulted from the merging of unusual meteorological conditions. The presence of atmospheric instability due to the existence of a low pressure system and its associated frontal and post-frontal sectors and also the presence of an AR structure (with particularly high content of humidity) responsible for the advection of moisture towards the Iberian Peninsula that contributed to enhance precipitation.

Spatial distribution of socio-economic consequences matches with the location of frontal system associated with the identified AR and the corresponding atmospheric circulation conditions depicted from the Reanalyses data. The limited available daily precipitation data do not shows the precipitation amount that may have occurred in the affected area of the event especially on higher mountains ranges like Gerês or Cantabria Mountains. Since the ARs are rich in water vapour and are associated with strong winds that force the water vapour up mountain sides, the atmospheric conditions at that time did not inhibit upward motions which were responsible for high precipitation values in mountain areas than at flat areas. This can only be seen at Guarda rain gauge (altitude of 1019 m) that registered a daily precipitation record, but we believe that equally extremely high precipitation values must have occurred also in other mountain ranges especially in Cantabria Mountains due to the nature of the floods that occurred in northern Spain.

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It was shown by Ramos et al. (2015) that 60 % of the most anomalous precipitation days are associated with the presence of an AR in the Iberian Peninsula. Since the average frequency of ARs during the extended winter (ONDJFM) over the Peninsula is around 10 % (although at different latitudes) we believe that more historical Douro floods (Rodrigues et al., 2003) could be associated also with the presence of ARs and deserve a specific assessment.

This work contributes to a comprehensive and systematic synoptic evaluation of the second most deadly hydro-geomorphologic Disaster event occurred in Portugal since 1865 and will help to better understand the meteorological system that was responsible for triggering the event. The correct understanding of the meteorological drivers of major flood events like the December 1909 event may improve the early warning systems for floods in Iberia as the critical meteorological conditions can be nowadays anticipated some days prior the event.

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Trigo, R. M., Pozo-Vázquez, D., Osborn, T. J., Castro-Díez, Y., Gámiz-Fortis, S., and Esteban-Parra, M. J.: North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula, Int. J. Climatol., 24, 925–944, doi:10.1002/joc.1048, 2004.

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Table 1. Newspapers explored for December 1909 event data collection.

	Newspaper	Reference period	Category	Distribution	Spatial incidence
Portugal	Diário de Notícias	Since 1865	Daily	National	Mainly the metropolitan area of Lisbon and the Tagus valley region
	Jornal de Notícias	Since 1888	Daily	Regional	North region (mainly the metropolitan area of Oporto)
	Correio de Mirandela	1907–1937	Weekly	Local	North region (Trás-os-Montes)
Spain	La Época	1849–1936	Daily	National	Madrid
	La Correspondencia de España	1859–1925	Daily	National	Madrid
	El Imparcial	1867–1933	Daily	National	Madrid
	El Siglo Futuro	1875–1936	Daily	National	Madrid
	El Liberal	1879–1939	Daily	Regional	Madrid, Sevilla, Barcelona, Bilbao y Murcia

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Table 2. Social consequences of the December 1909 event per hydrographic basin.

Hydrographic Basin	Area (km^2)	Nr. of Disaster Cases	Nr. of Fatalities	Nr. of Injuries	Nr. of Evacuated People	Nr. of Homeless People	Nr. of Missing People	Total of affected people
Floods								
1 – Coruña basin	12 663	2	0	0	3	84	0	87
2 – Minho basin	16 993	8	9	0	18	196	0	223
3 – Lima and Cávado basins	6277	9	2	0	14	0	8	24
4 – Douro basin	97 502	83	34	2	595	2104	6	2741
5 – Águeda, Mondego and West basins	14 119	7	4	0	410	3	0	417
6 – Tagus basin	81 115	20	8	2	61	177	1	249
7 – Sado basin	10 074	1	0	0	3	0	0	3
Floods Total		130	57	4	1104	2564	15	3744
Landslides								
2 – Minho basin	16 993	1	26	0	0	100	0	126
4 – Douro basin	97 502	2	3	0	0	0	0	3
6 – Tagus basin	81 115	1	3	0	0	0	0	3
Landslides Total		4	32	0	0	100	0	132
Total		134	89	4	1104	2664	15	3876

Note: Hydrographic basins are shown in Fig. 1.

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Table 3. Available precipitation stations for December 1909 event in Iberia.

	Rain gauge	Elevation (meters)	MAP (mm)	MMP in Dec (mm)	TP in Dec 1909 (mm)	TP (mm) in 22 Dec 1909	TP (mm) 20–28 Dec 1909
Portugal	Beja	246	571.8	100.6	132.9	0.0	58.9
	Campo Maior	280	*	*	125.1	2.0	57.3
	Coimbra	141	905.1	126.8	225.3	31.3	83.9
	Évora	200	609.4	102.7	172.2	1.5	85.8
	Guarda	1019	882.0	141.8	451.1	185.5	343.9
	Lisbon	77	725.8	121.8	139.1	60.9	84.0
	Porto	93	1253.5	194.7	287.0	63.0	158.6
Spain	Albacete	699	353.0	31.0	14.5	0.0	0.0
	Alicante	82	311.0	25.0	12.6	0.0	0.0
	Badajoz	185	447.0	69.0	129.8	0.9	51.3
	Barcelona	420	588.0	40.0	13.9	0.0	0.0
	Burgos	881	546.0	63.0	119.2	23.2	53.0
	Cádiz	30	523.0	92.0	81.7	9.1	27.5
	Ciudad Real	627	402.0	59.0	70.0	6.0	22.6
	Granada	685	365.0	56.0	45.8	10.0	17.0
	Huelva	19	525.0	99.0	48.8	5.7	13.1
	Huesca	541	480.0	44.0	52.6	0.0	16.9
	La Coruña	67	1014.0	131.0	166.1	13.0	53.2
	Madrid	679	421.0	51.0	88.8	0.5	32.0
	Málaga	7	534.0	100.0	49.1	12.8	15.5
	Murcia	57	297.0	29.0	11.6	0.0	0.0
	Salamanca	790	372.0	42.0	80.7	20.6	36.4
	Sevilla	31	539.0	99.0	69.3	19.2	36.3
	Soria	1083	512.0	50.0	80.4	7.5	25.9
	Valencia	11	475.0	48.0	33.3	0.0	0.0
	Valladolid	691	433.0	53.0	137.0	18.0	51.5
	Zaragoza	245	322.0	21.0	8.2	0.0	0.0

Note: MAP – Mean annual precipitation; MMP – Mean monthly precipitation; TP – Total precipitation; * Campo Maior station was only in operation between Dec 1872 and Dec 1909

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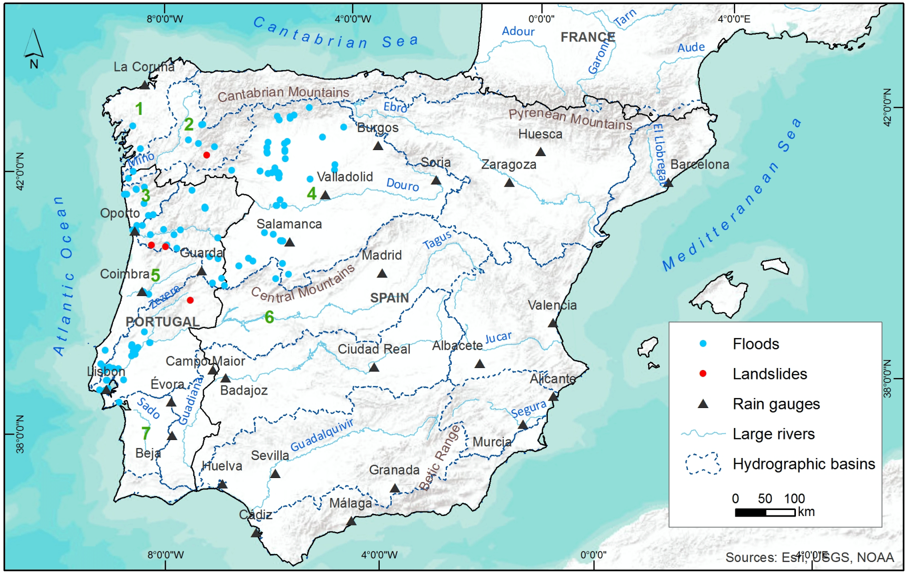

Figure 1. Study area and flood and landslide DISASTER cases from 20 to 28 December 1909 event over Iberia. Source: disaster database for Portugal and Spanish newspapers from Table 1. Numbers in the map correspond to the affected hydrographic basins: (1) Coruña basins; (2) Minho basin; (3) Lima and Cávado basins; (4) Douro basin; (5) Águeda, Mondego and West basins; (6) Tagus basin; (7) Sado basin.

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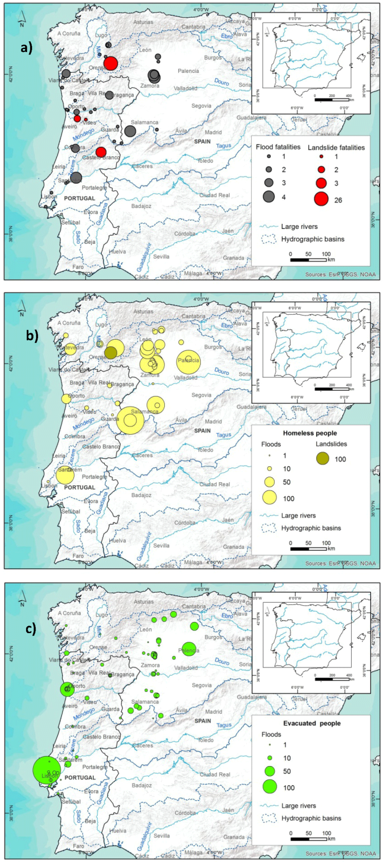

Figure 2. Social consequences of the DISASTER cases: fatalities **(a)**, homeless people **(b)** and evacuated people **(c)**.

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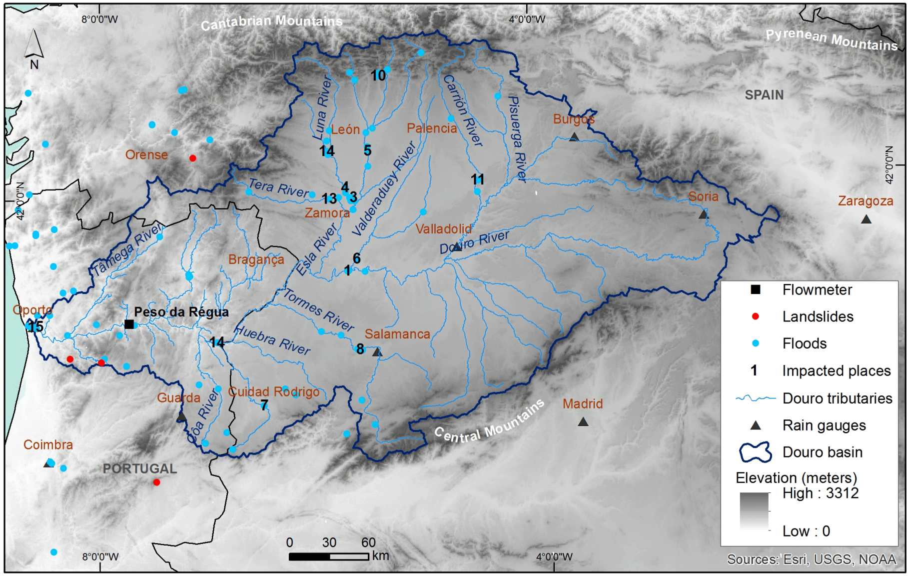

Figure 3. Douro basin and DISASTER cases of the December 1909 event. Impacted places: (1) San Marcial; (2) Villanueva de Azoague; (3) Santa Cristina de Polvorosa; (4) Vecilla de Polvorosa; (5) Cabañas; (6) Molacillos; (7) Cuidad Rodrigo (Arrabal del Puente); (8) Granja de la Serna; (9) Fresno de la Veja; (10) Cándana; (11) Husillos; (12) Villanueva de Azoague; (13) Micereces de Tera; (14) Barca de Alva; (15) Vila Nova de Gaia.

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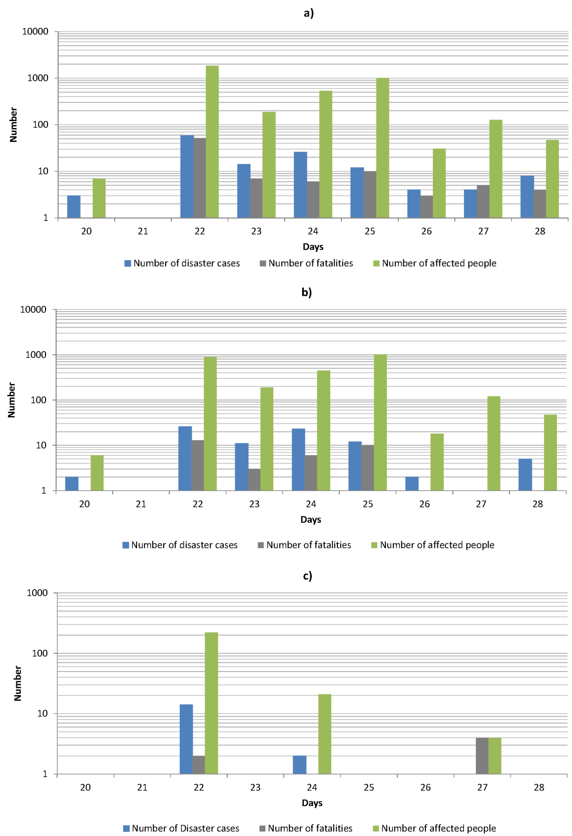

Figure 4. Daily number of DISASTER cases, fatalities and affected people generated by the December 1909 event **(a)**, in the Douro basin **(b)** and in the Tagus basin **(c)**. Notice the logarithmic scale used.

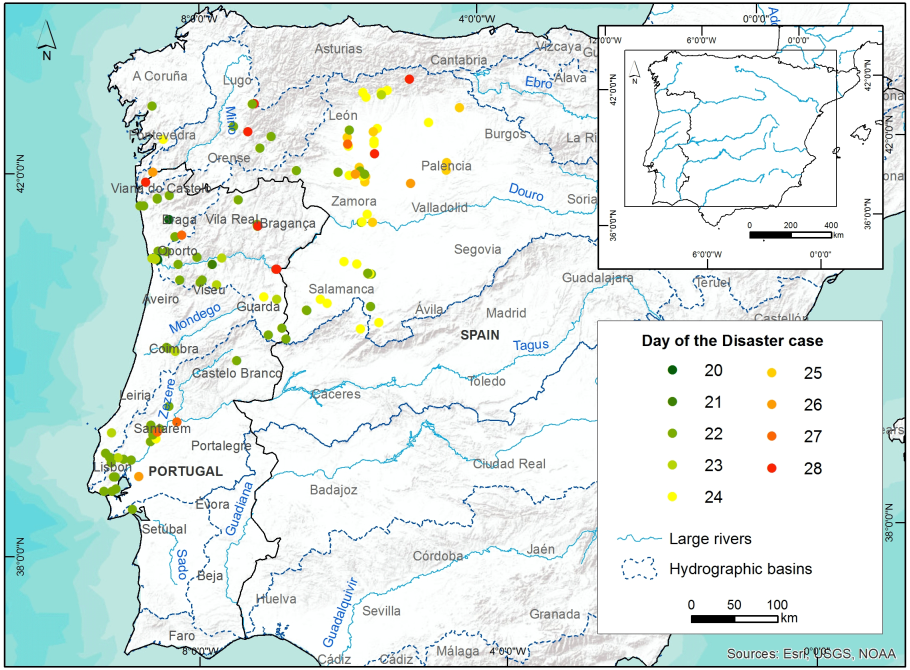

Figure 5. DISASTER cases of the December 1909 event per day.

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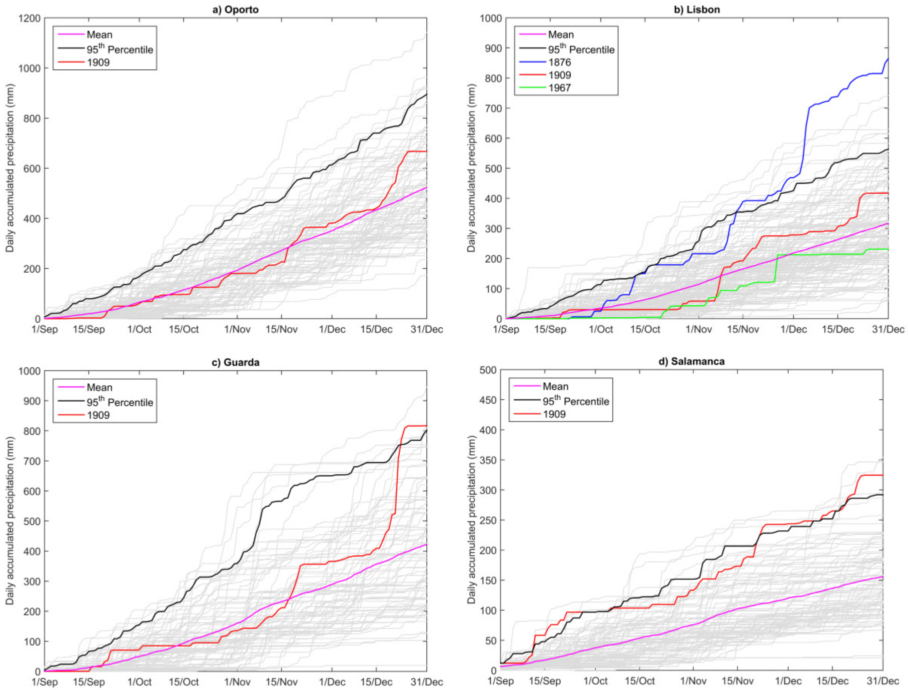

Figure 6. Cumulative precipitation from the 1 September to the 31 December using daily precipitation data from **(a)** Oporto; **(b)** Lisbon; **(c)** Guarda and **(d)** Salamanca. Each year of cumulative precipitation is represented in gray. The mean and the 95th percentile of precipitation are represented in magenta and black respectively and accumulated precipitation in the year of 1909 is represented by the red line. In addition, the historical storm years of 1876 (blue) and 1697 (green) in Lisbon are also highlighted.

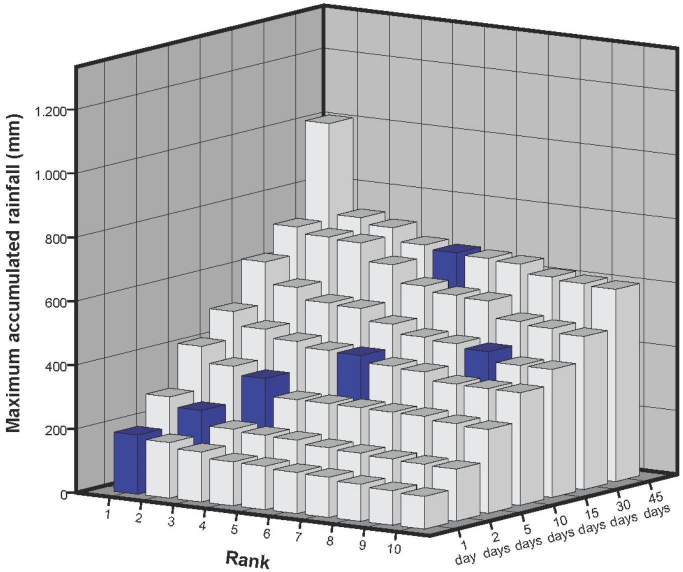

Figure 7. The ten highest values (rank) of maximum accumulated precipitation from 1, 2, 5, 10, 15, 30 and 45 days in Guarda for the period 1906–1994. Blue bars correspond to December 1909 event.

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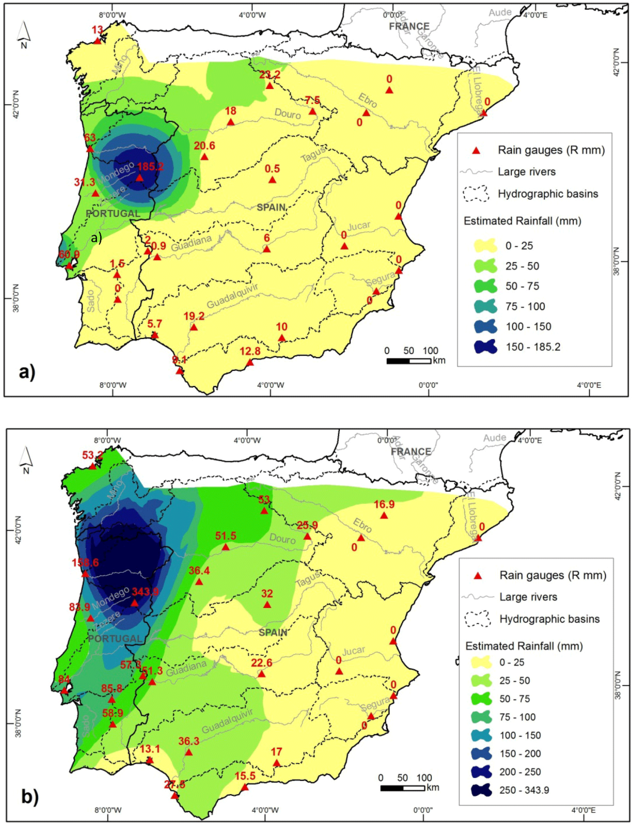

Figure 8. Co-kriging interpolation of total precipitation of 22 December **(a)** and event cumulated precipitation in 20–28 December 1909 **(b)** in Iberia.

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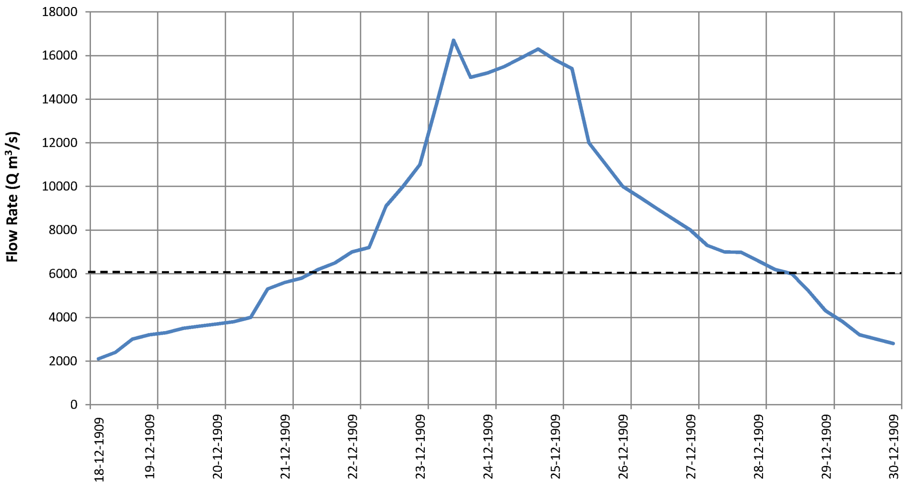

Figure 9. Flow rate ($m^3 s^{-1}$) at Peso da Régua from18 to 30 December 1909. Source: SNIHR (Rodrigues et al., 2003). The dashed line corresponds to an extraordinary flood at Peso da Régua (Portugal).

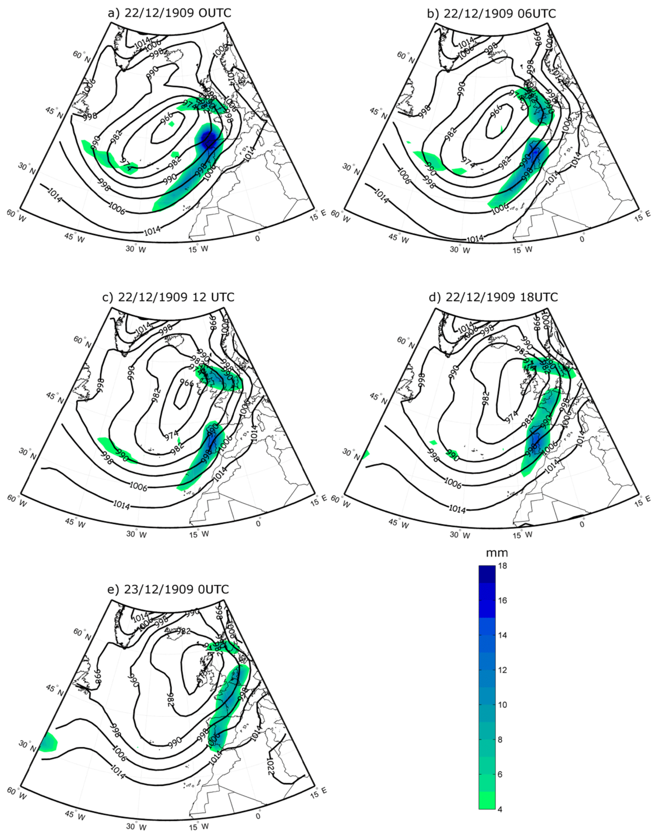

Figure 10. The sea level pressure field (contour, hPa) and 6 h accumulated precipitation (shaded, mm) for the 22 December 1909 at **(a)** 00:00 UTC, **(b)** 06:00 UTC, **(c)** 12:00 UTC, **(d)** 18:00 UTC and **(e)** 23 December at 00:00 UTC.

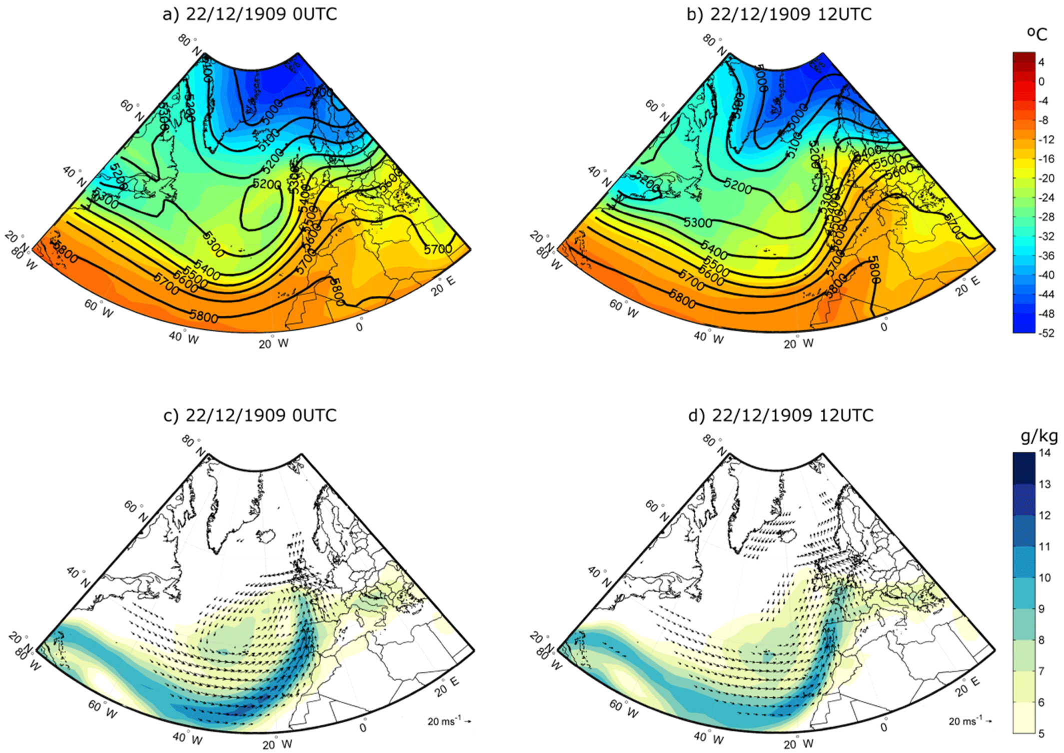

Figure 11. Divergence (contours; 10-5s-1) at 22 December 1909 at 00:00 and 12:00 UTC for **(a, b)** the 250 Pa level, and **(c, d)** at the 900 Pa level. Along with the divergence field, the respective wind speed (shaded, $m\,s^{-1}$) is also shown.

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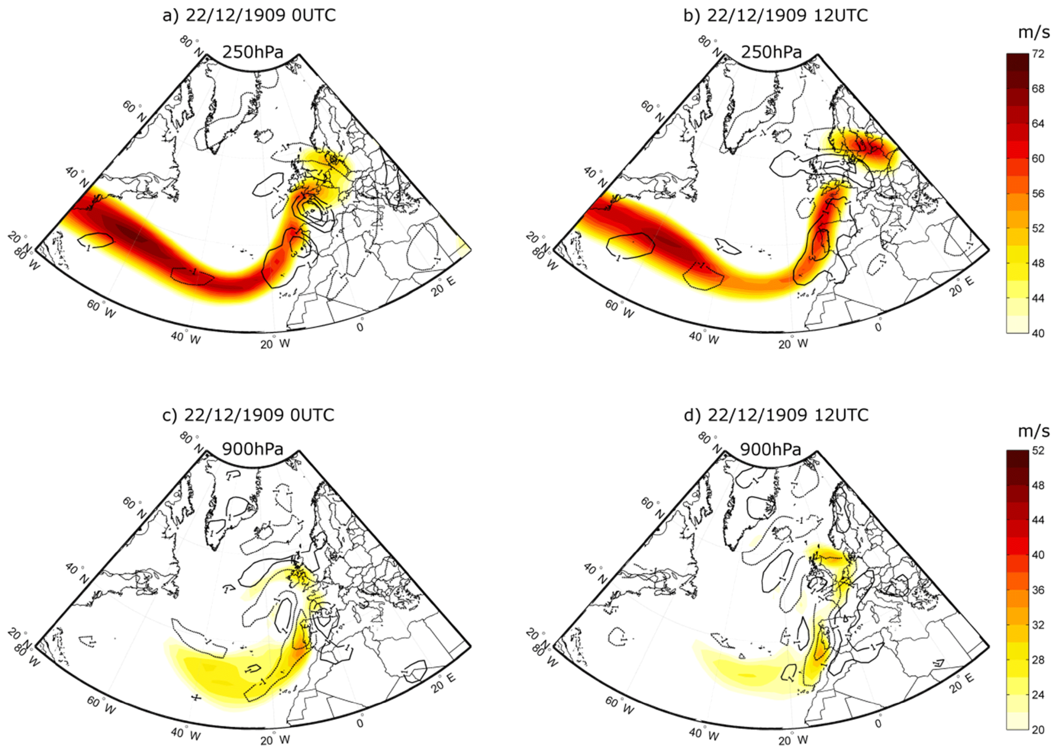

Figure 12. The geopotential height (contour, m) and air temperature (shaded; °C) at 500 hPa level for the 22 December: **(a)** 00:00 UTC and **(b)** 12:00 UTC. In addition, the wind vector ($m\,s^{-1}$) and specific humidity (shaded, $g\,kg^{-1}$) at 900 hPa level for the 22 December 1909 at **(c)** 00:00 UTC and **(d)** 12:00 UTC are also shown. Only wind vectors with wind speeds above 12.5 $m\,s^{-1}$ are shown.

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