Extreme precipitation events and related impacts in western Iberia

MARGARIDA L. R. LIBERATO[1,2] & RICARDO M. TRIGO[2]
1 Escola de Ciências e Tecnologia, Universidade de Trás-os-Montes e Alto Douro (UTAD), Vila Real, Portugal
mlr@utad.pt
2 Instituto Dom Luiz (IDL), Universidade de Lisboa, Lisboa, Portugal

Abstract Flash flooding induced by extreme precipitation events is one of the deadliest natural hazards in the Iberian Peninsula. In this study we perform an assessment of the most extreme precipitation events that occurred over the last century in Portugal, and which produced flash flooding, urban inundations and landslides, causing considerable infrastructure damage and human fatalities. This analysis provides an in-depth characterization of the synoptic conditions and large-scale dynamic mechanisms that promoted the events, primarily associated with low pressure systems that passed over the area. We show that these events are usually triggered by poleward water vapour transport from the tropics and subtropics enhanced by extratropical cyclones. Recent work has shown that quite often these lows favoured large streams of (sub) tropical air across the North Atlantic – the so-called atmospheric rivers. The relationship between North Atlantic atmospheric rivers, extratropical cyclones and the occurrence of heavy precipitation and flash-flood events on Iberia is also addressed.

Key words heavy precipitation; flash-flooding; high impact hazards; hydro extremes; extratropical cyclones; heat and moisture transport pathways; Portugal

INTRODUCTION

Over the Iberian Peninsula (IP), precipitation is one of the key meteorological parameters controlling climate due to its irregular inter-annual, seasonal, monthly and daily distribution. Precipitation variability plays an essential role on the spatial and temporal regional distribution of water, thus affecting the water cycle, water resources management and water supply for agriculture, natural ecosystems, hydro-electricity production and for water consumption. This is especially true in Portugal (western Iberia) where precipitation exhibits large variability on both intra- and inter-annual time scales (Corte-Real *et al.*, 1998; Gallego *et al.*, 2011) with severe, sometimes disastrous, consequences such as flash flooding, urban inundations and landslides causing considerable infrastructure damage and human fatalities (e.g. Liberato *et al.*, 2012).

The relationship between precipitation variability over the IP and the large-scale circulation has long been investigated (Ulbrich *et al.*, 1999; Trigo *et al.*, 2004; Vicente-Serrano *et al.*, 2011). At the monthly and seasonal scales, there are a few modes of atmospheric circulation that explain most of the variability over the North Atlantic (NA) and southern Europe, including the North Atlantic Oscillation (NAO), the Eastern Atlantic (EA) and the Scandinavian (SCAN) patterns that, amid other features, control the Iberian precipitation regime (Trigo *et al.*, 2008). Among these patterns the NAO plays the most important role as it modulates the westerly atmospheric flow by shifting the polar jet and the associated storm-tracks (Ulbrich *et al.*, 1999; Trigo *et al.*, 2004). At the sub-monthly scale, extratropical cyclones have a significant impact on the hydrological cycle of Iberia (Ulbrich *et al.*, 1999; Trigo *et al.*, 2002) and are one of the primary causes of the occurrence of extreme events over the region (e.g. Liberato *et al.*, 2011; 2013).

Research on high impact events occurring on the western Iberia region and associated dynamical mechanisms and variability is of utmost importance. Namely it allows improved understanding of the occurrence of such extreme events, contributing to enhance forecast and prevention of severe hydro-meteorological hazards. An analysis was performed of the most extreme precipitation events that have occurred in the Lisbon area since 1863. However, the focus was on those events that have occurred in the last four decades (when we have good quality meteorological datasets) and which produced flash flooding, urban inundations and landslides and caused considerable socio-economic negative impacts in the urban area of Lisbon, capital of Portugal. This analysis provides an in-depth characterization of the synoptic conditions and large-scale dynamic mechanisms promoting the outcome of these extreme events, mainly explained by the storms that passed over the area.

DATA AND METHODS

The meteorological data consisted of horizontal fields, extracted from the ERA-Interim Reanalysis as obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-Interim is the latest ECMWF global atmospheric reanalysis available since 1979 up to the present (Dee *et al.*, 2011). The following meteorological variables were extracted, at full temporal (six hourly) and spatial resolutions, over the Euro Atlantic sector (85°W–12°E, 9°N–57°N) for the study periods (October, November and December of 1983, 1997 and 2012), and then projected onto a 0.75° × 0.75° latitude/longitude grid: mean sea level pressure (SLP); total column water vapour (TCWV); the geopotential height fields, temperature, zonal and meridional wind components, divergence and the specific humidity at all pressure levels. Finally, we used the daily precipitation data recorded since December 1863 at the Dom Luiz Observatory in Lisbon, Portugal, i.e. the only station with a 150-year-long record of daily data in Portugal.

PRECIPITATION EXTREMES IN THE REGION OF LISBON, PORTUGAL

For this study on extreme precipitation events with high socio-economic impacts occurring in western Iberia we relied on the daily precipitation data recorded since 1863 at the longest serving station in Portugal (Lisbon's Dom Luiz Observatory) as well as on historical press reports. Lisbon metropolitan area has more than 2.5 million inhabitants and is situated close to the Atlantic Ocean, just 30 km from the western-most point of continental Europe (Cabo da Roca). The conjunction of these facts raises the risk of the Lisbon area to hazards of storms and floods with a consequence of a higher exposure. The historical daily precipitation records allow identifying the maxima top 11 events obtained since 1863 in the Lisbon region (Table 1). It should be noted that daily precipitation records obtained at classical stations in Portugal for any given day n correspond to the precipitation registered between 09 UTC of day n–1 and 09 UTC of day n. Therefore, the maximum at Lisbon's Dom Luiz Observatory on 18 February, for example, reflects the 24 h rainfall that fell between 09:00 h UTC of 17 February and 09:00 h UTC of 18 February.

Table 1 Historical daily maxima precipitation in Lisbon's Dom Luiz Observatory (1863–2013).

Date	Highest daily precipitation (mm)
18 February 2008	118.4
5 December 1876	110.7
30 January 2004	101.2
19 November 1983	95.6
19 October 1997	92.6
2 November 1997	91.3
11 October 1962	91.2
7 December 2012	91.0
25 November 2012	89.8
26 November 1967	89.2
18 November 1945	87.5

To put in perspective the relevance of these heavy precipitation events for the hydrology of the region, the mean annual precipitation (climatological year) value from 1971 to 2000 was 715 mm.

It is a well-known fact that over western Iberia the wet season occurs during the extended winter season, i.e. from October to April (Trigo *et al.*, 2004). From Table 1 it is confirmed that most of these extreme phenomena occurred predominately from early October to early December and increasingly so in the last few decades. This is in agreement with the findings of Ramos & Reis (2001) regarding floods in Portugal, who state that over the last decades of the 20th century there has been a clear intensification of flood importance during autumn months, in contrast with an accentuated diminishing in winter and spring months. Moreover, according to Table 1 we can observe that seven of these heavy precipitation events occurred during the most recent 30 years (from the last 150 years), which suggests an increase of this kind of extreme event in this region: fourth top event was the rainiest day during the 20th century (19 November 1983; Liberato *et al.*, 2012); the first and third events took place in the 21st century, having been assessed in some detail (Fragoso *et al.*, 2010); only the second top event occurred as early as 1876. This is also consistent with the evidence of a positive trend in the occurrence of floods in Portugal over the last decades of the 20th century (Ramos & Reis, 2001). Additionally, it is worth noting that four of these 11 most extreme events (Table 1) occurred within the same hydrologic years: 1997 and 2012, on both occasions, two heavy precipitation events occurred within a 2-week interval.

This preliminary analysis of the historical daily precipitation data recorded in Lisbon, at the station with the longest continuous records available since 1863, provided the ranking of maximum daily precipitation for the last 150 years. Furthermore, it offers the motivation to undertake a more detailed study of the dynamical processes associated with these high impact events, thus allowing gaining knowledge on the mechanisms behind their occurrence and the variability in western Iberia. Naturally, due to data availability constraints, this study must be limited to the last few decades where robust large-scale meteorological fields are available.

FLASH FLOOD EVENTS AND IMPACTS

Flash floods induced by extreme precipitation events are one of the most life-threatening hazards in Iberia. Throughout the 20th century, in Portugal, floods were the deadliest natural disaster, followed by earthquakes: for every death due to earthquakes seven people died due to floods (Ramos & Reis, 2001).

The region of Lisbon was hit by two deadly flash floods during the second half of the 20th century. On 25–26 November 1967 flooding occurred with unprecedented intensity and causing significant damage and disruption. Without proper warning approx. 700 people are known to have died as a consequence of the floods in the heavily populated metropolitan area of Lisbon (Ramos & Reis, 2001). More than 1100 people lost their homes and communications were disrupted by mud flows. At the time, estimated losses were US$3 million (values of 1967). This is considered one of the deadliest historical floods worldwide. Sixteen years later, on 18–19 November 1983, another heavy precipitation event occurred, soon followed by urban flash flooding and a burst of landslides around Lisbon (Zêzere *et al.*, 2005). Despite the absence of an official report on the impacts of this event, the total loss of human lives was estimated to be 10 fatalities, and in addition more than 1800 people lost their homes, with further large financial losses due to electric power blackouts and road and rail links blocked (Liberato *et al.*, 2012). Anther three events with large socio-economic damages have occurred more recently in the Lisbon area (albeit with less human fatalities), as can be inferred by the numerous top rank positions observed in Table 1, including the 1997 episodes and the more recent 2008 event (Fragoso *et al.*, 2010). The two extremes of the 2012 wet autumn raised societal awareness to the high risk of Lisbon to urban flooding and to the real need for flood risk assessment in order to implement adaptation strategies.

LARGE-SCALE ATMOSPHERIC CONDITIONS ASSOCIATED WITH THE AUTUMN FLASH FLOODS IN LISBON

The main characteristics of the large scale atmospheric circulation and related physical processes responsible for the high rainfall in the region of Lisbon during the five autumn severe hydro-extremes since 1979 are discussed in this section. Figure 1 shows simultaneously, for each event, the SLP and TCWV fields. From these figures it is clear that the common feature of all these events is the associated presence of an extratropical cyclone, centred at relatively low latitudes, between Portugal and the Azores archipelago. Furthermore, these are mostly large, slow moving, low pressure systems (Fig. 1(a)–(c)). Both 2012 examples (Fig. 1(d) and (e)) are already smaller, decaying cyclones by the time they reached IP, still enhancing strong moisture advection.

From the analysis of Fig. 1 the presence of long, elongated plumes of moist, tropical and subtropical air – or, in some cases, the remains of these plumes – associated with the warm conveyor belt of the cyclones is also evident. Thus, these results show that during these autumn extreme events there is a significant contribution from tropical and subtropical NA moisture sources to feed these large, low latitude extratropical cyclones. Therefore we confirmed the relevant role of these systems in the advection of water vapour towards the extratropics, in particular towards the region affected by the flash flood events (Liberato *et al.*, 2012).

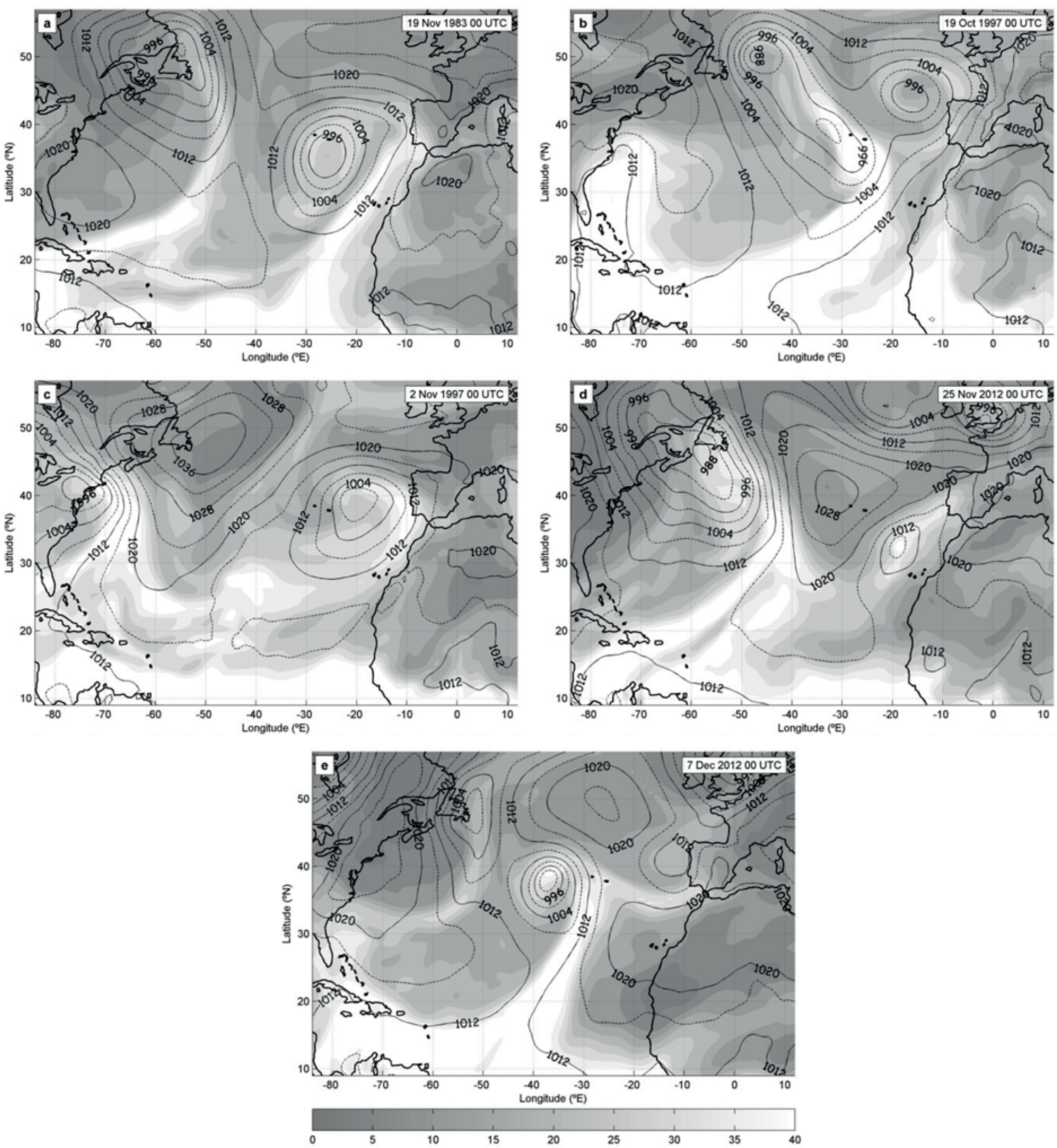

Fig. 1 Large scale atmospheric conditions associated with the flash flood events. The SLP field (contour interval 4 hPa) and TCWV (shaded; mm) for 00 UTC: (a) 19 November 1983; (b) 19 October 1997; (c) 2 November 1997; (d) 25 November 2012; and (e) 7 December 2012.

This tropical, moist air, transported within the warm sector of the cyclone, is in accordance with the occurrence of an Atmospheric River (AR; Ralph *et al.*, 2006). Figure 2(a) shows, for one of the events (7 December 2012), the SLP field and the vector wind and wind speed at 900 hPa. In all these cases, at some stage, the criteria for an AR occurred previous to these phenomena: a long plume of tropical air with values of TCWV over 25 mm is observed (Fig. 1(e)) within the warm sector of the cyclone, coinciding with an area of relatively strong winds (wind speed greater than 12.5 m s^{-1}; Fig. 2(a)). Figure 2(b) shows the wind speed and divergence at the jet stream level (250 hPa). It is worth noting that the upper-level jet stream meanders across the NA but substantially southward of its usual latitude. Furthermore, a particularly strong branch of the upper-level jet crosses over western Iberia being preceded with strong upper-level divergence over Lisbon at 00 UTC on 7 December 2012, with values above 2×10^{-5} s^{-1}. Favourable large-scale conditions for vertical movements – uplift mechanism, which induce deep convection activity (Fig. 2(b)) – along with the presence of an AR (high specific humidity; Fig. 2(c)) contributed to enhanced precipitation. These facts support the hypothesis that large-scale forcing was crucial to the occurrence of these record breaking precipitation and flash flood events.

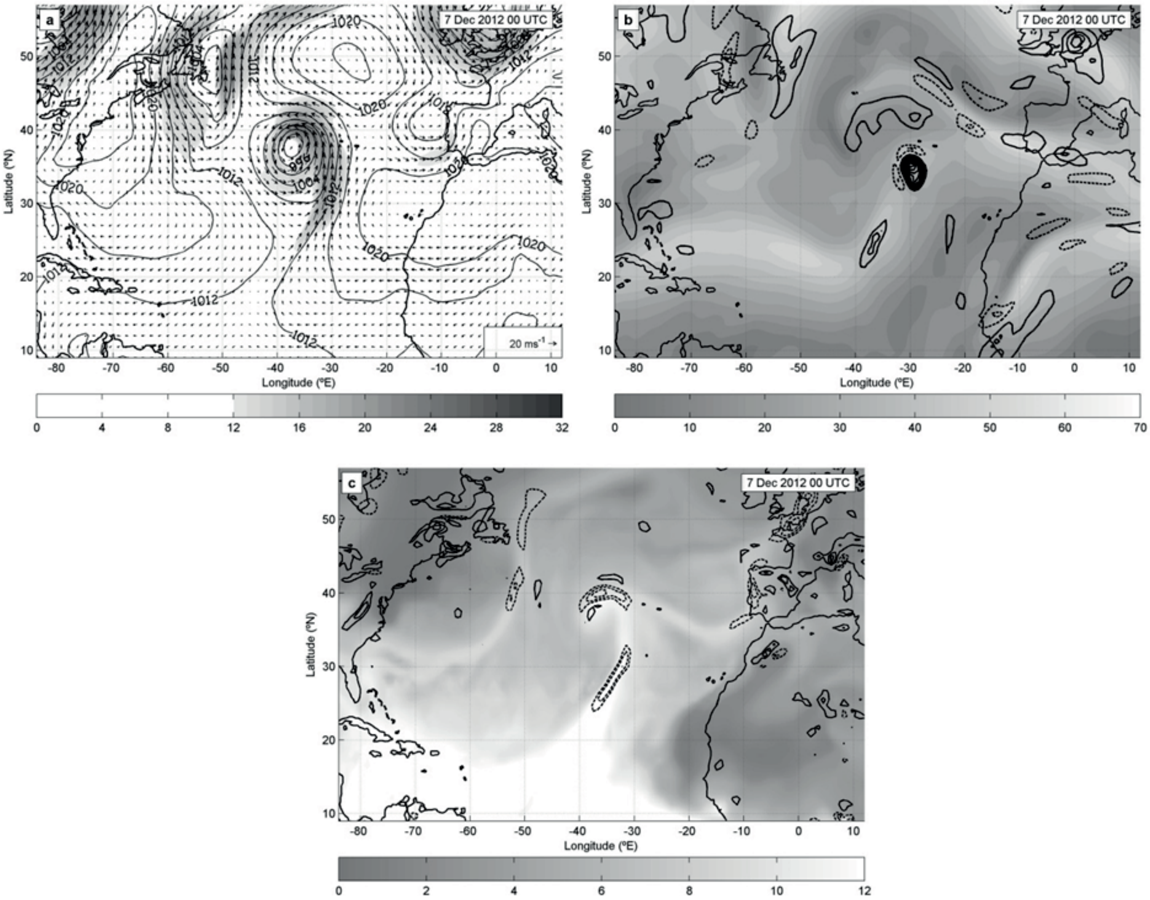

Fig. 2 (a) The SLP field (contour interval 4 hPa), the vector wind and wind speed (shaded; ms^{-1}) at 900 hPa. (b) Wind speed (shaded; m s^{-1}) and divergence (contours every 10^{-5} s^{-1}, delimiting areas above 2 (solid lines) and below –2 (dashed lines)) at the 250 hPa level. (c) Specific moisture content (shaded; g kg^{-1}) and divergence (contours every 10^{-5} s^{-1}, delimiting areas above 2 (solid lines) and below –2 (dashed lines)) at the 900 hPa; all for 00 UTC on 7 December 2012.

SUMMARY AND CONCLUDING REMARKS

Throughout the 20th century, in Portugal, floods induced by extreme precipitation events were the deadliest natural disaster. An analysis was performed of the historical daily precipitation data recorded in Lisbon, the station with the longest continuous records available in Portugal (150 years). Having noted a tendency towards more frequent peaks in recent decades, we decided to evaluate in more detail the dynamical processes associated with these high impact events in recent decades, thus improving our knowledge on the mechanisms behind their occurrence and variability in western Iberia.

Results from this study showed that these high-impact episodes were associated with large, mid-latitude, quasi-stationary low-pressure systems, which could not be considered as extreme cyclones. The assessment of the large-scale atmospheric flow associated with the extreme rainfall and flash flood episodes during autumn months results from the fortuitous merging of favourable thermodynamic conditions, including: (1) a lower than-usual latitudinal location of the jet stream related to the presence of a strong meridional temperature gradient; (2) intense vertical instability in an area of upper-level divergence; and (3) the presence of an AR structure, i.e. a plume of high humidity and wind speeds at the surface, transporting water vapour from the tropical and subtropical NA Ocean to the extratropics. These results confirm the Liberato *et al.* (2012) study, which showed how long-range transport of water vapour from the subtropics was important in setting up the large-scale conditions required for a particular extreme precipitation event.

Finally, this work raises the need for further climatological research on the relation between extratropical cyclones, AR and the occurrence and variability of hydro-extremes on Iberia.

Acknowledgements The authors wish to thank Dr. Maria Antónia Valente for providing the Lisbon's Dom Luiz Observatory precipitation data and the ECMWF for ERA-Interim Reanalysis data. This work was supported by FEDER (Fundo Europeu de Desenvolvimento Regional) funds through the COMPETE (Programa Operacional Factores de Competitividade) and by national funds through FCT (Fundação para a Ciência e a Tecnologia, Portugal) under project STORMEx FCOMP-01-0124-FEDER-019524 (PTDC/AAC-CLI/121339/2010).

REFERENCES

Corte-Real, J., Qian, B. & Xu, H. (1998) Regional climate change in Portugal: precipitation variability associated with large-scale atmospheric circulation. *Int. J. Climatol*. 18, 619–635.

Dee, D. P., *et al.* (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. Roy. Meteorol. Soc.* 137, 553–597.

Fragoso, M., Trigo, R. M., Zêzere, L., & Valente, M. A. (2010) The exceptional rainfall episode registered in Lisbon in 18 February 2008. *Weather* 65, 31–35.

Gallego, M. C., Trigo, R. M., Vaquero, J. M., Brunet, M., García, J. A., Sigró, J, & Valente, M. A. (2011) Trends in frequency indices of daily precipitation over the Iberian Peninsula during the last century *J. Geophys. Res. – Atmospheres*, 116, D02109.

Liberato, M. L. R., Ramos, A. M., Trigo, R.M., Trigo, I. F., Durán-Quesada, A. M., Nieto, R. & Gimeno, L. (2012) Moisture sources and large-scale dynamics associated with a flash flood event. In: *Lagrangian Modeling of the Atmosphere* (ed. by J. Lin, D. Brunner, C. Gerbig, A. Stohl, A. Luhar & P. Webley), American Geophysical Union, Washington, DC doi: 10.1029/2012GM001244.

Liberato, M. R. L., Pinto, J. G., Trigo, I. F. & Trigo, R. M. (2011), Klaus – an exceptional winter storm over northern Iberia and southern France. *Weather* 66(12), 330–334 doi:10.1002/wea.755.

Liberato, M. L. R., Pinto, J. G., Trigo, R. M., Ludwig, P., Ordóñez, P., Yuen, D. & Trigo, I. F. (2013), Explosive development of winter storm Xynthia over the subtropical North Atlantic Ocean. *Nat. Hazards Earth Syst. Sci*. 13, 2239–2251, doi:10.5194/nhess-13-2239-2013.

Ralph, F. M., Neiman, P. J., Wick, G. A., Gutman, S. I., Dettinger, M. D., Cayan, D. R. & White, A. B. (2006), Flooding on California's Russian River: role of atmospheric rivers. *Geophys. Res. Lett.* 33, L13801.

Ramos, C. & Reis, E. (2001) As cheias no sul de Portugal em diferentes tipos de bacias hidrográficas. *Finisterra* XXXVI, 71, 61–82.

Trigo, R. M., Trigo, I. F., DaCamara, C. C. & Osborn, T.J. (2004) Climate impact of the European winter blocking episodes from the NCEP/NCAR Reanalyses. *Clim. Dyn.* 23, 17–28 doi: 10.1007/s00382-004-0410-4.

Trigo, R. M., T. J. Osborn, & Corte-Real J. M. (2002), The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms. *Clim. Res*. 20, 9–17.

Trigo, R. M., Valente, M. A., Trigo, I. F., Miranda, M., Ramos, A. M., Paredes, D. & García-Herrera, R. (2008) North Atlantic wind and cyclone trends and their impact in the European precipitation and Atlantic significant wave height. *Annals of the New York Academy of Sciences* 1146, 212–234, doi: 10.1196/annals.1446.014.

Ulbrich, U., Christoph, M., Pinto, J. G. & Corte-Real, J. (1999) Dependence of winter precipitation over Portugal on NAO and baroclinic wave activity. *Int. J. Climatol.* 19, 379–390.

Vicente-Serrano, S. M., Trigo, R. M., López-Moreno, J. I., Liberato, M. L. R., Lorenzo-Lacruz, J., Beguería, S., Morán-Tejeda, E. & El Kenawy, A. (2011) Extreme winter precipitation in the Iberian Peninsula in 2010: anomalies, driving mechanisms and future projections. *Clim. Res*. 46, 51–65.