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A dependence modelling study of extreme rainfall in Madeira Island

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ABSTRACT

The dependence between variables plays a central role in multivariate extremes. In this paper, spatial dependence of Madeira Island's rainfall data is addressed within an extreme value copula approach through an analysis of maximum annual data. The impact of altitude, slope orientation, distance between rain gauge stations and distance from the stations to the sea are investigated for two different periods of time. The results obtained highlight the influence of the island's complex topography on the spatial distribution of extreme rainfall in Madeira Island.

1. Introduction

In mountainous regions, such as the high, steep mountains and deep valleys of Madeira Island, extreme rainfall can trigger flash floods (Spreafico, 2006), landslides and debris flows (Kalvoda and Rosenfeld, 1998; Rodrigues and Ayala-Caicedo, 2003), particularly during the wet season. Although rare, such events can have significant impacts on the local natural environment and disastrous consequences for the affected communities and populations (Woo and Jones, 2002). Rainfall-induced debris flows are one of the most dangerous natural hazards in mountain regions (Hu et al., 2009), because their occurrence is unpredictable and this type of water-related natural disaster can be catastrophic, affecting significantly not only the landscape, but also causing damage to houses and infrastructures (Kanji et al., 2008), loss of lives (Wilford et al., 2004), and other negative economic and social impacts due to the increasing anthropisation of such areas (Hürlimann et al., 2006). Floods and associated landslides and debris-flows triggered by extreme rainfall events have been in reality the most devastating of natural disasters, both in Madeira Island (Baioni, 2011; Quintal, 1999) as in the rest of the world (Hong et al., 2007).

Madeira Island has in its history a significant number of rainfall-induced flash floods, landslides and debris flows. The first event of this nature described in the literature occurred in November 1724, which caused the death of 26 people and serious damage to 80 houses in the city of Machico, and damages to buildings in Santa Cruz and Funchal. In the following century, more precisely in October 1803, Madeira suffered its worst calamity, a flash flood with approximately six hundred deaths and a huge devastation in Funchal. Other southern areas like Machico, Santa Cruz, Campanário, Ribeira Brava and Calheta were also affected by this devastating event. In the last century, six catastrophic rainfall-induced events were registered in Madeira, namely in 1920, 1929, 1956, 1979, 1993 and 1997, totaling more than 60 deaths and several dozens of injured people and houses destroyed (see, e.g., Baioni, 2011; Fragoso et al., 2012; Quintal, 1999). More recently, already in the 21st century, two significant events of this type were registered in Madeira Island, the first in March 2001, with five deaths and material damages of several tens of million euros (Rodrigues and Ayala-Caicedo, 2003), and the second one in February 2010, which caused 45 casualties, six missed people, more than a hundred injured and about 1.4 billion euros of material losses (Baioni, 2011; Fragoso et al., 2012), which indicate an increase in the frequency of such events and in the damage caused by them.

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This emphasize the need for appropriate statistical models of extreme hydrological events, particularly in the current context of global and regional climate and environmental changes, since the modelling of extreme rainfall has an important role in the design of water-related structures, in rural and agricultural engineering, and in many other areas, such as civil defense, where the hydrological monitoring and the knowledge concerning weather and climate extremes are fundamental. However, in many mountain regions, such as Madeira Island, the lack of sufficiently long series of rainfall data at different time scales leads to the challenge of estimating statistical characteristics of extreme rainfall from relatively short records (Koutsoyiannis, 2004). Moreover, in mountainous areas, the rainfall distribution is strongly influenced by factors such as the topography and the direction and intensity of wind, which make local and spatial analysis of the available data a difficult topic. This is clearly the case in Madeira Island, where the exact distribution of rainfall is strongly dependent upon the complex topography and the prevailing winds during the rain events, and where the estimation of hydro-meteorological extremes continues to be highly uncertain.

A review of spatial extremes methods based on latent variables, copulas and spatial max-stable processes was presented by Davison et al. (2012), who refer that appropriately chosen copula or max-stable models seem to be essential for the modelling of spatial extremes. The ability to describe and model the dependence between variables, regardless of their marginal distribution functions, is the major advantage of the copula functions approach. In practice, the application of these functions to the data can be considered based on an estimate of a measure of association, such as the Kendall's τ (Nelsen, 2006; Salvadori et al., 2007). A survey on the relationships between concordance of random variables and their copulas was made by Nelsen (2002), focusing on the relationship between concordance and measures of association such as Kendall's τ, Spearman's ρ, and Gini's coefficient. The two first measures, Kendall's τ and Spearman's ρ, play an important role in applications, since the practical fit of a copula to the available data is often carried out via the estimation of these values. In fact, according to Salvadori et al. (2007), Kendall's τ and Spearman's ρ are the two most widely known and used scale-invariant measures.

In this paper, a study of the dependence between extreme rainfall values from 12 rain gauge stations distributed over Madeira Island was carried out based on the Kendall's τ association measure (Genest and Favre, 2007). An adjustment was also made to a family of extreme value copulas and return period estimates for a given extreme event were obtained. The structure of this paper is as follows. The study area and the available rainfall data used are described in Section 2, while the methodology applied in this study is described in Section 3. This is followed by Section 4, where the results of the analysis are presented and discussed. Finally, Section 5 contains a summary of the main findings and some final comments.

2. Study area and data

2.1. Study area

Madeira Island is a volcanic island located in the Atlantic Ocean off the coast of Northwest Africa, between latitudes 32°30'N–33°30'N and longitudes 16°30'W–17°30'W. Madeira is 57 km long and 22 km wide and has an area of approximately 737 km^2 (Gorricha et al., 2012). The island has a near E–W oriented orographic barrier, approximately perpendicular to the prevailing N-SE wind direction, which induces a remarkable variation of rainfall between the northern and southern slopes (Fragoso et al., 2012). Madeira Island's mountain ridge located along its central part presents Pico Ruivo, the highest peak with 1861 m, and Pico do Areeiro, with 1818 m, in its eastern part, while Paul da Serra massif is located above 1400 m in the western part of the island.

The spatial distribution of rainfall in Madeira Island is strongly affected by its highly rugged topography, characterized by deep valleys and high and steep mountains, with 90% of the island's surface lying above 500 m, and one third above 1000 m (Sziemer, 2000). The amount of rainfall increases with altitude and the northern slopes are more humid than the southern ones (Prada et al., 2009). Madeira's location, topography and natural vegetation originate a variety of micro-climates, and this Portuguese island has essentially a Mediterranean climate with mild summers and winters (Couto et al., 2012). Some exceptions are found at the highest altitudes, where the mean annual air temperature can decrease to 8° C, while in the coastal regions it ranges between 18° C and 19° C (Lima and Lima, 2009).

The rainfall regime over the island is not only affected by local air circulation, but also by synoptic systems typical of mid-latitudes such as fronts and extra-tropical cyclones. During the summer season, the rainfall regime is also affected by the Azores anticyclone (Couto et al., 2012). The island's mountain streams have a high seasonal, torrential flow regime, with high waters during the months of October to March/April (Shahin, 2012) and very low flows during the rest of the year.

2.2. Rainfall data

Relatively to Madeira's rainfall data records, it is known that the oldest weather station in Madeira, the one from Funchal, started to operate in January 1865 and that only in November 1936 another weather station located in Pico do Areeiro began to collect rainfall and temperature data. In order to provide useful information for agriculture, more weather stations were settled on the island from 1936 to 1955, at different altitudes, by the General Council of the Autonomous District of Funchal (JGDAF). However, in 1990, some stations would no longer be functioning, others would provide data only concerning to the prevailing wind direction and intensity and other stations ceased to be maintained by JGDAF. Nowadays Madeira Island is covered by rain gauge stations maintained by three different institutions, namely the Madeira's Investments and Water Management (IGA) company, the Portuguese Institute for Sea and Atmosphere (IPMA), and the Madeira Regional Laboratory of Civil Engineering (LREC) (Fragoso et al., 2012). As referred before, the data used in this study correspond to maximum annual rainfall records from 12 rain gauge stations distributed over the island. Two measurement periods were considered for comparison purposes, being the record values corresponding to the period 1970–1994 (hereafter Period 1) provided by IPMA and those corresponding to the period 1950–1980 (hereafter Period 2) by the Department of Hydraulics and Energy Technologies of LREC. The rain gauge stations are distributed by four altitude classes, termed as Class 1 (>900 m), 2 (600–900 m), 3 (300–599 m) and 4 (<300 m), in descending order of altitude (A to L), and represented in Fig. 1 by different marker colours (in the web version), namely green, yellow, orange and red, respectively. Besides the six stations from Period 1 (Areeiro, Bica da Cana, Santo da Serra, Santana, Funchal and Lugar de Baixo), six more stations are considered in Period 2: one from Class 1 (Montado do Pereiro), three from Class 2 (Ribeiro Frio, Queimadas and Camacha), one from Class 3 (Sanatório), and one from Class 4 (Ponta Delgada). The altitude class, identification name and ID label for each rain gauge station, as well as the altitude and the slope where each one of these stations is located are indicated in Table 1, where N denotes the northern slope and S the southern one.