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Abstract

Madeira Island is located in the Atlantic Ocean off the coast of Northwest Africa, between latitudes 32º30'N–33º30'N and longitudes 16º30'W–17º30'W. Extreme rainfall events have triggered a significant number of flash floods, landslides and debris flows in this volcanic island along its past and recent history. One of the most significant events was the one that happened on the 20th of February 2010, which caused 45 casualties, six missed people and extensive damage to properties and infrastructures. Madeira Island is therefore a natural laboratory for the study of extreme precipitation events and its consequences. In this study, tests based on the likelihood ratio statistic and the probability-weighted moments were used to test the hypothesis of a Gumbel distribution for the annual 1-day maximum rainfall data, from 19 rain gauge stations, provided by the Department of Hydraulics and Energy Technologies of the Madeira Regional Laboratory of Civil Engineering. The rainfall records, with 22, 23 and 31 years of extension, were drawn from rain gauge stations located in the northern and southern hillsides of the island. The estimates for the generalised extreme value distribution (GEV) obtained by the methods of maximum likelihood and probability-weighted moments revealed the influence of the proximity to the sea and altitude on the spatial distribution of extreme rainfall, in addition to the natural differences observed on the windward and lee sides of any mountainous island. Estimates for 50- and 100-year return levels were also obtained. The existence of trends in the parameters' values was also analysed, revealing a significant evidence of a linear trend, both in location and scale parameters, for one location in the north side of the island.

1 INTRODUCTION

Madeira Island is a volcanic island located in the Atlantic Ocean off the Northwest African coast, between latitudes 32º30'N–33º30'N and longitudes 16º30'W–17º30'W, that presents a significant number of rainfall-induced flash floods along its history. There are reports from the 17th century mentioning the occurrence of flash floods (Silva & Menezes, 1945), but the one known to have caused the largest number of casualties, with more than 800 deaths, occurred on the 9th of October 1803 (Fragoso *et al.,* 2012). After that major occurrence, other extreme precipitation events have triggered at least thirty significant flash floods (Quintal, 1999). More recently, the most significant one was the one that happened on the 20th of February 2010, which caused 45 casualties, six missed people and extensive damage to properties and infrastructures, being Funchal and Ribeira Brava the most affected areas (Fragoso *et al.,* 2012; Nguyen *et al.,* 2013). The weather station of Funchal is the oldest in Madeira Island, having started to operate in January 1865 (Silva & Menezes, 1945). Already in 1895, there was the intention of installing another weather station in Pico do Areeiro whose observations, combined with Funchal weather station measurements, would constitute important data for the study of Madeira Island climate and its comparison with other health resort islands (Silva & Menezes, 1945). Its facilities belonged to the General Council of the Autonomous District of Funchal from 1911, but only began providing rainfall and temperature data in November 1936 (Silva & Menezes, 1945). In order to provide useful information for agriculture, more weather stations were settled on the island, at different altitudes, from 1936 to 1955 (Pereira, 1989). Nowadays, Madeira Island is well covered by rain gauge stations maintained by three different organizations, namely the Portuguese Institute of the Sea and Atmosphere, the Madeira's Investments and Water Management company, and the Regional Laboratory of Civil Engineering (Fragoso *et al.,* 2012). Madeira Civil Engineering Laboratory's Department of Hydraulics and Energy Technologies provided for this study annual 1-day maximum rainfall data from 19 rain gauge stations maintained in the past by the General Council of the Autonomous District of Funchal.

On the other hand, the generalised extreme value distribution (GEV) is widely used for modelling extremes of natural phenomena (cf., e.g., Hosking *et al.,* 1985), and GEV distributions are also used in this work to model the available data. Also in this study, tests based on the likelihood ratio statistic and the probability-weighted moments were used to test the hypothesis of a Gumbel distribution. Two methods, maximum likelihood (ML) and probability-weighted moments (PWM) were used to obtain estimates for the GEV parameters. The 50- and 100-year return level estimates were also obtained and, in addition, we explored the existence of trends in the parameters' values.

2 STATISTICAL ANALYSIS

2.1 Methodology

The generalised extreme value (GEV) family of distributions, that arises as the limiting distribution of the maximum of a series of independent and identically distributed random variables, has the distribution function given by $G_\gamma(\sigma x + \mu)$ where

$$G_\gamma(x) = \begin{cases} \exp\left(-(1+\gamma x)^{-1/\gamma}\right), & 1+\gamma x > 0,\ \gamma \neq 0 \\ \exp\left(-\exp(-x)\right), & x \in IR,\ \gamma = 0 \end{cases} \quad (1)$$

and γ, μ and σ are, respectively, the shape, location, and scale parameters. This distribution will here be referred to as Model 1 when $\gamma \neq 0$. The particular case of $\gamma = 0$ is the Gumbel distribution and will be referred as Model 2. Since Models 1 and 2 are nested in the GEV family, a model choice can be made applying the likelihood ratio test (Coles, 2001). At the significance level α, Model 2 is rejected in favour of Model 1 i$2(l_1(M_1) - (l_2(M_2)) > \chi^2_{1-\alpha,1}$f where $l_1(M_1)$ and $l_2(M_2)$ are the maximised values of the log-likelihood for Models 1 and 2, respectively. When considering variations of Models 1 and 2 characterised by a linear trend in one or both location and scale parameters, the applied chi-square (1–α)-quantile will be $\chi^2_{(1-\alpha,k)}$, where *k* is the number of parameters equal to zero in the sub-model considered. The hypothesis of a Gumbel distribution can also be analysed by a test based on the probability-weighted moments estimate of γ presented by Hosking *et al.* (1985), where the value for the test statistic $\hat{\gamma}\,(n / 0.5633)^{1/2}$ is compared with the critical values of the standard normal distribution. The good performance of the method of probability-weighted moments for small samples made this method more popular than the maximum likelihood estimation method in applications to hydrologic extremes (Hosking *et al.,* 1985). On the other hand, it is usually more convenient to interpret extreme value models in terms of return levels. The return level estimates, $\hat{q}_p$, are obtained by the estimation of the extreme quantiles of the annual maximum distribution, given by

$$\hat{q}_p = \begin{cases} \mu - \frac{\sigma}{\gamma}\left(1-\left(-\log(1-p)\right)^{-\gamma}\right), & \gamma \neq 0 \\ \mu - \sigma\left(1-\left(-\log(1-p)\right)\right), & \gamma = 0 \end{cases} \quad (2)$$

Where μ, σ, and γ and are replaced by their respective estimates (Coles, 2001).

2.2 Data

The data set analysed in this study, as mentioned before, consists of annual daily maximum rainfall records from 19 rain gauge stations in Madeira Island. Figure 1 shows the location of each station, where the colours (blue, green, orange, and red) of the markers correspond to the four altitude classes considered (<300 m, 300–600 m, 600–900 m, and >900 m, respectively). The markers identification can be found in Table 1, which also provides additional information about each station used in this study, namely its latitude, longitude and altitude, and the measurement period considered.

Figure 1: Location of the rain gauge stations considered

Table 1: Details of the rain gauge stations

Name (Marker)	Latitude	Longitude	Altitude (m)	Period
Areeiro (A)	32º 43'N	16º 55'W	1610	1950–1980
Bica da Cana (B)	32º 45'N	17º 03'W	1560	1950–1980
Poiso (C)	32º 42'N	16º 53'W	1360	1959–1980
Montado do Pereiro (D)	32º 42'N	16º 53'W	1260	1950–1980
Encumeada (E)	32º 45'N	17º 01'W	900	1959–1980
Ribeiro Frio (F)	32º 43'N	16º 53'W	874	1950–1980
Queimadas (G)	32º 46'N	16º 54'W	860	1950–1980
Porto Moniz (H)	32º 50'N	17º 11'W	653	1950–1972
Ponta do Pargo (I)	32º 47'N	17º 14'W	570	1950–1972
Santo António (J)	32º 40'N	16º 57'W	525	1950–1972
Sanatório (K)	32º 39'N	16º 54'W	380	1950–1980
Santana (L)	32º 48'N	16º 53'W	380	1950–1980
Loural (M)	32º 46'N	17º 02'W	307	1950–1972
Machico (N)	32º 43'N	16º 47'W	160	1959–1980
Ponta Delgada (O)	32º 49'N	16º 59'W	136	1950–1980
Funchal (P)	32º 38'N	16º 53'W	58	1950–1980
Santa Catarina (Q)	32º 41'N	16º 46'W	49	1959–1980
Lugar de Baixo (R)	32º 40'N	17º 05'W	15	1950–1980
Ribeira Brava (S)	32º 40'N	17º 04'W	10	1950–1972

2.3 Results and discussion

The hypothesis of a Gumbel distribution was only rejected with the likelihood ratio test for three locations in the north of the island. The shape parameter estimate is negative for Queimadas (G), a rain gauge located further from the sea than Porto Moniz (H) and Ponta Delgada (O) stations, which present positive shape parameter estimates. All choices resulting from the application of the likelihood ratio test and the corresponding model parameters' estimates, obtained by the application, for each location, of the ismev and extRemes R language packages (R, 2011), are presented in Table 2.

Table 2: Chosen models and maximum likelihood parameter estimates

Station Name (Marker)	Model	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\gamma}$
Areeiro (A)	Model 2	162.49	42.71	-
Bica da Cana (B)	Model 2	128.68	36.86	-
Poiso (C)	Model 2	127.04	34.69	-
Montado do Pereiro (D)	Model 2	129.10	40.00	-
Encumeada (E)	Model 2	158.62	45.89	-
Ribeiro Frio (F)	Model 2	125.33	39.62	-
Queimadas (G)	Model 1	111.70	25.04	–0.209
Porto Moniz (H)	Model 1	57.43	24.41	0.326
Ponta do Pargo (I)	Model 2	60.21	18.60	-
Santo António (J)	Model 2	66.41	27.80	-
Sanatório (K)	Model 2	67.58	24.92	-
Santana (L)	Model 2	89.87	35.75	-
Loural (M)	Model 2	119.59	46.02	-
Machico (N)	Model 2	60.73	27.21	-
Ponta Delgada (O)	Model 1	74.43	28.69	0.236
Funchal (P)	Model 2	47.49	20.29	-
Santa Catarina (Q)	Model 2	52.38	16.89	-
Lugar de Baixo (R)	Model 2	42.16	14.85	-
Ribeira Brava (S)	Model 2	52.38	17.01	-

When testing Model 2 using the test presented by Hosking *et al.* (1985) the results are similar (see Table 3), with the exception of Queimadas (G) and Santo António (J). Table 3 also shows the corresponding model parameter estimates obtained by the use of the *fExtremes* R package (R, 2011).

Table 3: Chosen models and probability-weighted moments parameter estimates

Station Name (Marker)	Model	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\gamma}$
Areeiro (A)	Model 2	96.86	154.02	-
Bica da Cana (B)	Model 2	76.82	123.34	-
Poiso (C)	Model 2	75.33	125.75	-
Montado do Pereiro (D)	Model 2	77.23	128.24	
Encumeada (E)	Model 2	94.68	152.60	-
Ribeiro Frio (F)	Model 2	74.75	127.66	-
Queimadas (G)	Model 2	65.07	97.66	-
Porto Moniz (H)	Model 1	56.51	23.88	0.335
Ponta do Pargo (I)	Model 2	35.83	60.98	-
Santo António (J)	Model 1	70.87	30.37	–0.319
Sanatório (K)	Model 2	40.44	72.15	-
Santana (L)	Model 2	53.89	99.39	-
Loural (M)	Model 2	72.04	124.34	-
Machico (N)	Model 2	36.49	69.44	-
Ponta Delgada (O)	Model 1	73.14	27.50	0.283
Funchal (P)	Model 2	28.49	53.86	-
Santa Catarina (Q)	Model 2	31.30	53.04	-
Lugar de Baixo (R)	Model 2	25.24	43.62	-
Ribeira Brava (S)	Model 2	31.18	54.24	-

We observe that for Ponta Delgada (O) and Porto Moniz (H) data, where we reject Model 2 independently of the method used, the parameter estimates are relatively similar. This is not the case when Model 2 is chosen since the maximum likelihood scale parameter estimates are much smaller than the corresponding probability-weighted moments estimates. The opposite happens with the location parameter estimates, but in a less pronounced way. Although for the distributions corresponding to these cases there is not significant evidence to choose Model 1 in opposition to Model 2, we observe that the corresponding shape parameter estimates are not zero independently of the method applied. Following Coles (2001), who states that the safest option is to accept that there is uncertainty about the value of the shape parameter and to prefer the inference based on the

GEV model whether the Gumbel model is adequate or not, we here chose to deal only with the general GEV distribution. Variations of Model 2 characterised by a linear trend in one or both of the location and scale parameters were also tested. Only in the case of Bica da Cana (B), the rain gauge station located at the highest altitude in the northern side of the island, there is evidence to suggest a linear trend with respect to time at a 0.05 level of significance. More precisely, there is evidence for a linear trend both in location and scale parameters, with $\hat{\mu}(t) = 115.99 + 1.26t$ and $\hat{\sigma}(t) = 2.45 + 0.06t$ On the north side of the island, we observe that the value of the shape parameter for the GEV distribution is positive for the rain gauge stations located nearest to the sea and it is negative for the the stations located in the interior of the island, namely Bica da Cana (B), Encumeada (E) and Loural (M). For the rain gauge stations on the south side, there are cases of positive and negative shape parameter estimates both in the interior and near the coast. Besides the shape parameter estimates, Table 4 presents the maximum likelihood and probability-weighted moment estimates for the location and scale parameters for each station.

Table 4: GEV parameters estimates by ML and PWM

Station Name (Marker)	Method	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\gamma}$
Areeiro (A)	ML	166.07	44.22	–0.153
Areeiro (A)	PWM	165.94	45.69	–0.167
Bica da Cana (B)	ML	131.47	37.07	–0.143
Bica da Cana (B)	PWM	129.40	34.15	–0.033
Poiso (C)	ML	124.81	32.74	0.125
Poiso (C)	PWM	125.15	36.50	0.045
Montado do Pereiro (D)	ML	133.85	42.77	–0.214
Montado do Pereiro (D)	PWM	133.45	45.27	–0.223
Encumeada (E)	ML	167.24	49.10	–0.347
Encumeada (E)	PWM	165.69	51.73	–0.319
Ribeiro Frio (F)	ML	125.98	40.16	–0.031
Ribeiro Frio (F)	PWM	126.04	43.76	–0.071
Queimadas (G)	ML	111.70	25.04	–0.209
Queimadas (G)	PWM	111.99	23.68	–0.214
Porto Moniz (H)	ML	57.43	24.41	0.326
Porto Moniz (H)	PWM	56.51	23.88	0.335
Ponta do Pargo (I)	ML	60.60	18.90	–0.038
Ponta do Pargo (I)	PWM	60.34	20.55	–0.061
Santo António (J)	ML	70.86	29.02	–0.293
Santo António (J)	PWM	70.88	30.37	–0.319
Sanatório (K)	ML	67.96	25.22	–0.028
Sanatório (K)	PWM	67.75	27.04	–0.050
Santana (L)	ML	84.78	36.75	0.021
Santana (L)	PWM	84.73	38.40	0.002
Loural (M)	ML	122.29	46.22	–0.119
Loural (M)	PWM	123.23	46.78	–0.158
Machico (N)	ML	60.49	27.06	0.016
Machico (N)	PWM	59.80	27.62	0.030
Ponta Delgada (O)	ML	74.43	28.69	0.236
Ponta Delgada (O)	PWM	73.14	27.50	0.283
Funchal (P)	ML	46.79	19.77	0.066
Funchal (P)	PWM	46.35	20.32	0.070
Santa Catarina (Q)	ML	53.24	17.39	–0.094
Santa Catarina (Q)	PWM	52.80	17.81	–0.071
Lugar de Baixo (R)	ML	43.33	15.45	–0.145
Lugar de Baixo (R)	PWM	42.68	15.66	–0.091
Ribeira Brava (S)	ML	51.74	16.55	0.070
Ribeira Brava (S)	PWM	51.43	17.28	0.060

Although the altitude appears to be a factor influencing the spatial distribution of extreme rainfall, in general we cannot say that the values of the location parameter estimates increase with altitude. Even though Queimadas (G) rain gauge station presents a higher altitude when compared to Loural

(M), the latter shows a location parameter estimate (of approximately 123 mm) greater than the corresponding value for Queimadas (G). Unlike Loural (M), Queimadas (G) is not located on the E-W oriented orographic barrier in the interior of the island and therefore, besides altitude, the proximity to the sea seems to be a factor influencing the spatial distribution of extreme rainfall. Loural (M) is also near the Encumeada (E) rain gauge station, which presents the highest values for the location and scale parameters estimates. Just below the values observed at Encumeada (E), are the values corresponding to Areeiro (A), the rain gauge station located in the south with the highest altitude in the island. Revealing the natural differences observed on the windward and lee sides of any mountainous island, we have the rainfall data from Sanatório (K) and Santana (L) rain gauge stations. These stations have the same altitude, but Sanatório (K), which is located in the southern part of the island, presents lower values for all the estimated values.

The differences between the northern and the southern part of Madeira Island can also be found in terms of return levels. Illustrating these differences, Figures 2 and 3 present the diagnostic plots for the GEV fit to Ribeira Brava (S) and Ponta Delgada (O) rain gauge data, respectively.

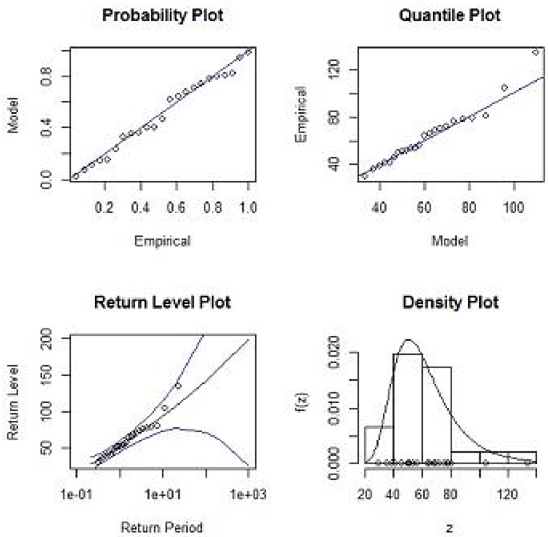

Figure 2: Diagnostic plots for the GEV fit to the Ribeira Brava (S) station data

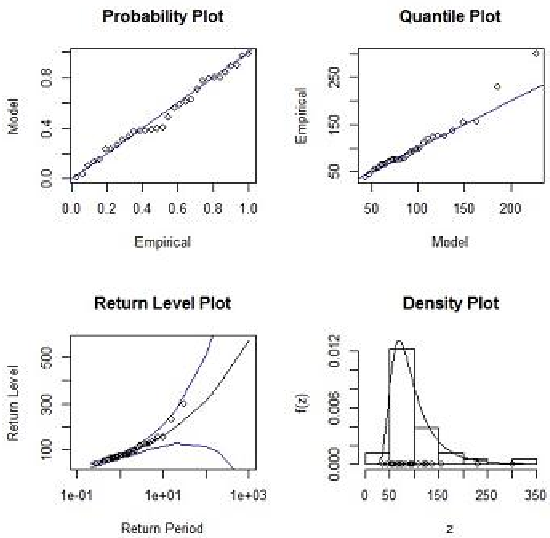

Figure 3: Diagnostic plots for the GEV fit to the Ponta Delgada (O) station data

Table 5 shows the 50- and 100-year return level estimates obtained for each location with the Model 1's parameter estimates produced by ML and PWM methods. For Areeiro (A), Ribeiro Frio (F), Porto

Moniz (H), Ponta do Pargo (I), Santo António (J) and Ribeira Brava (S), the 50- and 100-year return values calculated by both methods are approximately similar ($\hat{q}_{0.02}^{ML} \approx \hat{q}_{0.02}^{PWM}$ and $\hat{q}_{0.01}^{ML} \approx \hat{q}_{0.01}^{PWM}$, respectively). The largest parameter estimates for Poiso (C), Queimadas (G), Santana (L) and Loural (M) were obtained by the maximum likelihood method. For all the rest of rain gauge stations, the higher values for the return levels were found when calculated by the method of probability-weighted moments.

Table 5: Estimates for 50- and 100-year return levels

Station Name (Marker)	$\hat{q}_{0.02}^{ML}$	$\hat{q}_{0.02}^{PWM}$	$\hat{q}_{0.01}^{ML}$	$\hat{q}_{0.01}^{PWM}$
Areeiro (A)	296.09	297.05	312.24	312.77
Bica da Cana (B)	242.23	254.33	256.29	275.02
Poiso (C)	289.29	280.82	328.12	311.66
Montado do Pereiro (D)	247.01	251.50	259.05	263.78
Encumeada (E)	272.22	281.18	280.09	290.52
Ribeiro Frio (F)	273.50	275.31	298.05	297.95
Queimadas (G)	178.53	174.60	185.73	181.26
Porto Moniz (H)	249.67	249.71	317.92	318.01
Ponta do Pargo (I)	129.07	129.07	140.28	140.28
Santo António (J)	138.28	138.66	144.11	144.14
Sanatório (K)	161.09	163.62	176.69	178.89
Santana (L)	249.39	239.26	284.97	266.50
Loural (M)	266.48	259.36	285.93	276.02
Machico (N)	169.47	174.08	189.70	195.98
Ponta Delgada (O)	258.24	268.99	312.96	332.94
Funchal (P)	134.70	137.48	152.94	156.56
Santa Catarina (Q)	110.05	113.56	118.20	122.77
Lugar de Baixo (R)	89.38	94.12	95.21	101.55
Ribeira Brava (S)	125.95	125.93	141.50	141.48

In the northern part of Madeira Island, all return level estimates calculated are higher than 240 mm, excluding the values corresponding to Queimadas (G). In turn, on the south side of the island the return values are less than 180 mm for all rain gauge stations with altitudes below 600 m, with the exception of Machico (N). For Areeiro (A), Poiso (C), Montado do Pereiro (D) and Ribeiro Frio (F), the 50- and 100-year return level estimates are greater than 245 mm.

The proximity between the return value estimates for Queimadas (G) and Machico (N) rain gauge stations suggests the proximity to the sea as a factor to be taken into account in the study of return levels, in addition to natural factors such as altitude or location in the northern or southern part of the island. These two rain gauge stations have distinct altitudes and are located at different but nearby hillsides. In the southwest, we observed another pair of rain gauge stations, Ponta do Pargo (I) and Ribeira Brava (S), with similar return values but closer parameter estimates. Although the distance between rain gauge stations might seem an influential factor, closer rain gauge stations does not mean similar return level estimates. To exemplify this, we may mention the set of three rain gauge stations located in Funchal municipality, namely Santo António (J), Sanatório (K) and Funchal (P).

3 CONCLUSIONS

In this work, an application of extreme value theory to the annual 1-day maximum rainfall data from 19 rain gauge stations in Madeira Island was presented. Although most of the rain gauge stations considered are deactivated, and consequently the rainfall time series are relatively short, it is important to analyse all the available data, given the number of major flash flood events reported so far in Madeira Island. The most recent of these significant events occurred on the 20th of February 2010, with 146.9 mm observed in Funchal and 333.8 mm in Areeiro (Fragoso *et al.,* 2012). Given the GEV estimates obtained in this work by ML, these values correspond to return periods of approximately 79 and 292 years, respectively, or 70 and 297 years when GEV estimates by PWM are used. Although for almost all rainfall data series there was not significant evidence to choose the GEV distribution in opposition to the Gumbel distribution, GEV parameters estimates by ML and

PWM methods were provided in this work given that the corresponding shape parameters estimates are not zero and that location and scale GEV estimates are relatively similar for both methods. The hypothesis of a Gumbel distribution was tested by the likelihood ratio test and by the test presented by Hosking *et al.* (1985), and the same conclusions were obtained for both methods, with the exception of the data from Queimadas (G) and Santo António (J) rain gauge stations. A significant evidence for a linear trend in location and scale parameters was found in the data from Bica da Cana (B), the rain gauge station located at the highest altitude in the northern side of the island. Estimates for the 50- and 100-year return levels were also determined for all rain gauge stations data using the GEV parameter estimates obtained from both methods.

The parameter and return level estimates, regardless of the method used to obtain them, suggest a complex characterization of the spatial distribution of extreme rainfall in Madeira Island. It seems that there is a simultaneous influence of factors such as altitude, proximity to the sea, distance, and location in nearby hillsides or in the northern or the southern part of the island. Besides that, there are differences in the return levels estimates according to the method applied, except for Areeiro (A), Ribeiro Frio (F), Porto Moniz (H), Ponta do Pargo (I), Santo António (J) and Ribeira Brava (S) rain gauge stations. Nevertheless, it can be observed that the 50- and 100-year return levels estimates are greater than 245 and 255 mm, respectively, for all the seven rain gauge stations located farther from the sea, namely Areeiro (A), Bica da Cana (B), Poiso (C), Montado do Pereiro (D), Encumeada (E), Ribeiro Frio (F) and Loural (M). The same can be observed for three more stations, Porto Moniz (H), Santana (L) and Ponta Delgada (O), that are closer to the sea but located in the northern part of the island. There is proximity between the estimates' values for Queimadas (G) and Machico (N) data, although Queimadas (G) and Machico (N) rain gauge stations belong, respectively, to the northern and southern parts of the island. These two stations are located in nearby hillsides, as Ponta do Pargo (I) and Ribeira Brava (S) that are located in the southwest and also present similar return value estimates. For all the rest of the rain gauge stations located in the southern part of the island the 50- and 100-year return levels estimates are smaller than 164 mm and 179 mm, respectively. The rain gauge stations that present the highest and the smallest return level estimates, Areeiro (A) and Lugar de Baixo (R), are both located in the south side of Madeira Island.

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