

# *Climate change impacts in the design of drainage systems: case study of Portugal*

Article

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1 **Climate change impacts in the design of drainage systems –**

2 **A case study for Portugal**

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16 **Abstract**

17 This study aims to assess the necessity of updating the Intensity-Duration-Frequency  
18 (*IDF*) curves used in Portugal to design building storm-water drainage systems. A  
19 comparative analysis of the design was performed for the three pre-defined rainfall  
20 regions in Portugal using the *IDF* curves currently in use and estimated for future  
21 decades. Data for recent and future climate conditions simulated by a global/regional  
22 climate model chain (ECHAM5/MPI-OM1/COSMO-CLM) are used to estimate  
23 possible changes of rainfall extremes and its implications for the drainage systems. The  
24 methodology includes the disaggregation of precipitation up to sub-hourly scales, the  
25 robust development of *IDF* curves and the correction of model bias. Obtained results  
26 indicate that projected changes are largest for the plains in Southern Portugal (5 – 33%)  
27 than for mountainous regions (3 – 9%) and that these trends are consistent with  
28 projected changes in the long term 95<sup>th</sup>-percentile of the daily precipitation throughout  
29 the 21<sup>st</sup> century. We conclude for the need to review the current precipitation regime  
30 classification and change the new drainage systems towards larger dimensions to  
31 mitigate the projected changes in extreme precipitation.

32

33 ASCE Subject Headings: Climate change, Hydraulic design, Drainage systems,  
34 Precipitation, Portugal

35 Author keywords: *IDF* curves; Climate change; Drainage systems design; Extreme  
36 precipitation.

## 37 **Introduction**

38 The recent IPCC Special Report on Managing the Risks of Extreme Events and  
39 Disasters to Advance Climate Change Adaptation (IPCC 2012) have recently provided  
40 evidence that the intensity of extreme precipitation may increase even in areas where  
41 total precipitation decreases (Diodato et al. 2011; IPCC 2012). This implies shorter  
42 return periods for extreme rainfall. In particular, the changes in the water cycle are  
43 likely change the frequency and intensity of floods and droughts for many parts of the  
44 world (IPCC 2012); hence, the knowledge of the regime of heavy precipitation in  
45 regional terms both under recent and future climate conditions is critical (Beijo et al.  
46 2005; IPCC 2012).

47 From the engineering point of view, empirical approaches are used to link extremes of  
48 precipitation with physical structures. The Intensity-Duration-Frequency (*IDF*) curves  
49 represent key information for the design of urban and building storm-water drainage  
50 systems, as they provide maximum precipitation intensity related to a given length and a  
51 given return period (Brandão et al. 2001). The *IDF* curves are mathematically described  
52 by the power law behaviour dependence of the precipitation intensity (*I*) of the duration  
53 (*t*),

54

$$I = a \times t^b \quad (1)$$

55

56 where *a* and *b* are the *IDF* parameters. In Portugal, the designers of building storm-  
57 water drainage systems work according to the Portuguese law (DR 1995), which  
58 stipulates the *IDF* curves developed by Matos and Silva (1986). However, long-term  
59 trends in rainfall intensities and the projected climate change in terms of the water cycle  
60 fosters the assessment of the impact of extreme precipitation in the current and future  
61 design of building storm-water drainage systems and the possible update of *IDF* curves

62 (e.g. Fowler and Kilsby 2003 and Vasiljevic et al. 2012). Recently, the impact of  
63 climate change on *IDF* curves have been assessed in several studies performed for the  
64 U.S. and Canada (Mailhot et al. 2007; Peck et al. 2012; Zhu et al. 2012; Das et al. 2013;  
65 Zhu 2013; Zhu et al. 2013). However, these studies did not assess the possible  
66 consequences of such changes to the design of building storm-water drainage systems  
67 as the one conducted in northern Europe, for the sewer system of Fredrikstad, Norway  
68 by Nie et al. (2009).

69 Global circulation models (GCM) and regional climate models (RCM) are important  
70 tools to study the impact of climate change on meteorological, chemical, hydrological  
71 and hydraulic processes. Given pre-defined scenarios of the world development, these  
72 models provide projections of different meteorological variables for possible future  
73 conditions of the climate system (Meehl et al. 2007; Taylor et al. 2012). The GCMs  
74 used for these climate projections have typically resolutions of 100-300 km, which is  
75 typically too low for direct use of model output in regional studies. Downscaling  
76 techniques, using RCMs, statistical downscaling or a combination of both have been  
77 used to obtain results at a finer spatial and temporal time scale (e.g. Maraun et al. 2010).  
78 Furthermore, model biases towards the real climate conditions must be adequately  
79 assessed, interpreted and corrected before applications can be performed.

80 In the specific case of urban building drainage systems, the design requires knowledge  
81 of rainfall depth intensity values over short periods of time (between minutes to hours).  
82 On this assumption, it is necessary to use appropriate methodology capable of  
83 performing the disaggregation of daily precipitation depth in sub-daily and sub-hourly  
84 precipitation (e.g., Pui et al. 2012). A possible approach is the method of the fragments,  
85 introduced by Svanidze in the 1960s (Svanidze 1964, Svanidze 1980), as it is a  
86 commonly used method in the precipitation disaggregation (Sharif and Burn, 2007;

87 Arganis-Juárez et al. 2008) used to obtain the disaggregation coefficients presented in  
88 Brandão et al. (2001), which is an official publication of the national Directorate of  
89 Services of Water Resources with the results of the analysis of extreme precipitation in  
90 Continental Portugal.

91 Several studies have assessed the impact of climate change on the design of drainage  
92 systems, using model simulations/climate scenarios, with converging results in different  
93 parts of the world towards increased precipitation intensity and the potential under-  
94 designing of drainage systems (e.g. Nie et al 2009; Rosenberg et al. 2010; He et al.  
95 2011; Rosenzweig et al. 2007). Some of these studies have provided evidence that the  
96 design of building storm-water drainage systems may be inadequate or at least under  
97 designed for future climate conditions.

98 The purpose of this study is the assessment of possible changes in the *IDF* curves and  
99 consequent designing of building storm-water drainage systems as a result of changes in  
100 the distribution of extreme values of precipitation intensity due to the projected climate  
101 change for Continental Portugal. Section 2 deals with description of the data and the  
102 methodology used in this study. Results are presented and discussed in section 3.  
103 Finally, section 4 is devoted to the conclusions.

104

## 105 **Material and Methods**

### 106 **Database / Data analysis**

107 In this work, the characterization of intense precipitation was substantiated with three  
108 distinct databases. The first database consist of hourly precipitation time series obtained  
109 from the database of the *Sistema Nacional de Informação e Recursos Hídricos*  
110 [National System of Water Information and Resources] (SNIRH) for previously

111 selected weather stations, with the purpose of being representative of the three rainfall  
112 areas defined in Matos and Silva (1986), (Fig. 1) and present in the Portuguese  
113 Regulation-decree n.º 23/95 of August 23 (DR 1995). The selection criteria were based  
114 on longevity and quality the historical series of hourly precipitation values (Table 1).  
115 Time series cover between 8.2 (Castelo Melhor) and 12 (Covilhã) consecutive years,  
116 which corresponds to 72 000 and 93 000 records, and have less than 5% of missing  
117 values, excepting for stations located in mountainous rainfall region C (Covilhã and  
118 Pega) but even so, with the 2<sup>nd</sup> and 3<sup>rd</sup> largest number of observed values (92 860 and  
119 84 430 records).

120 With the aim to characterize the spatial distribution of extreme daily precipitation over  
121 Continental Portugal, a second database of observed daily rainfall used in this study:  
122 The most recent 8.0 version of the E-OBS gridded dataset (0.25 degree regular lat-lon  
123 grid), released in April 2013 by ECA&D (<http://www.ecad.eu>) project (Haylock et al.  
124 2008).

125 Finally, the third database consists of precipitation data simulated by the COSMO-CLM  
126 [CONsortium for Small-scale MOdelling and Climate Limited-area Modelling  
127 Community] (Rockel et al. 2008) regional climate model (RCM). The simulations are  
128 run with ECHAM5/MPI-OM1 boundary conditions for recent climate conditions (20C,  
129 1961 – 2000) and for two SRES scenarios (Nakicenovic et al. 2000), A1B and B1  
130 (2000 – 2100). The resolutions of the rainfall data is roughly 18 km (0.165° latitude)  
131 and 6-hourly. For this study, data for the spatial sub-domain defined between 36.6° N –  
132 42.4° N and 6.2° W – 9.8° W is considered as it encompasses Portugal and the nearby  
133 areas. The COSMO-CLM model has demonstrated its capacity to model the weather  
134 and climate conditions, particularly temperature and precipitation, in different regions of  
135 Europe. Furthermore, it has been used in several climate change studies analysing



136 changes of precipitation over Europe (e.g., Haslinger et al. 2012; Kotlarski et al. 2012)  
137 and specifically in Portugal (Costa et al. 2012).

138 Precipitation indices suggested by the joint project Commission for  
139 Climatology/Climate Variability and Predictability (CLIVAR)/Joint WMO/IOC  
140 Technical Commission for Oceanography and Marine Meteorology Expert Team on  
141 Climate Change Detection and Indices (Frich et al. 2002; Karl et al. 1999; Peterson  
142 2005) are used to study climate change scenarios for precipitation extremes in Portugal  
143 (cf. also Costa et al. 2012).

144

#### 145 **Aggregation and disaggregation of precipitation**

146 The precipitation datasets described in the previous section are not available on time  
147 scales adequate for this study. Consequently, it was necessary to use methods of  
148 aggregation and disaggregation of precipitation, in order to have data of maximum  
149 precipitation for the duration of 5 min, 10 min, 15 min, 30 min, 1 h, 2 h, 6 h, 12 h, 24 h  
150 and 48 h. The aggregation process consisted on the use of precipitation depth values  
151 obtained for smaller sampling durations to calculate precipitation depth values for  
152 higher durations. For example, having hourly precipitation depth, it is rather easy to  
153 obtain precipitation depth for 2, 6, 12, 24 and 48 h, simply by summing hourly values  
154 that integrate the desired duration. This procedure was adopted for both databases  
155 (observed and simulated), for higher durations than the sample ones. The disaggregation  
156 of COSMO-CLM daily data to sub-daily data, namely, 1, 2, 6 and 12 h, was performed  
157 using the method of fragments or coefficients of disaggregation of the maximum  
158 precipitation values. Fragments ( $w_i$ ) are the fraction of daily precipitation that occurred  
159 at a given hour of the day ( $h_i$ ),

$$w_i = \frac{h_i}{\sum_{i=1}^{24} h_i} \quad (2)$$

160

161 Consequently, the sum of the coefficients ( $w_i$ ) for the 24 hours of the day is equal to the  
 162 unit. Then, to estimate the precipitation depth in each hour of the day ( $h'_i$ ), the  
 163 corresponding fragment ( $w_i$ ) is multiplied by the daily precipitation depth ( $d$ ),

$$h'_i = w_i \times d \quad (3)$$

164

165 This disaggregation procedure assures that the hourly precipitation estimation ( $h'_i$ ) does  
 166 not change the total daily precipitation. The disaggregation fragments for 1, 2, 6 and  
 167 12 hours were estimated from the hourly observed data by using the Equation (2).  
 168 Fragments for each duration were computed and sorted in descending order, revealing  
 169 that the arithmetic averages computed for 50, 100 and 200 highest values were very  
 170 similar, and were adopted as the values of the coefficients of disaggregation,  $w_i$ . This  
 171 disaggregation procedure assures that the adopted fragments allow an adequate  
 172 estimation of the maximum precipitation depth for each duration while retaining  
 173 consistency with the observed data. The adopted coefficients of disaggregation  $w_i$  were  
 174 then applied to daily simulated data by the COSMO-CLM model using Equation (3) to  
 175 estimate maximum precipitation depth for 1, 2, 6 and 12 hours for each cell of the  
 176 model grid. This procedure was applied for to the recent and the future periods. The  
 177 inexistence of observed precipitation data for sub-hourly sampling time compel the  
 178 disaggregation precipitation process for these temporal scales to rely on the fragments  
 179 obtained from the relationship between hourly and sub-hourly precipitation proposed  
 180 for Portugal by Brandão et al. (2001). These disaggregation coefficients are in good  
 181 agreement with those proposed in the Guide to Hydrological Practices of the World  
 182 Meteorological Organization and studies performed by the Portuguese Meteorological  
 183 Institute.

184

## 185 **Intensity-Duration-Frequency Curves**

186 The development of *IDF* curves that consider future climate conditions is critical for the  
187 adequate design of building storm-water drainage systems, as it would allow mitigating  
188 a possible change in the frequency and intensity of floods, and thus reducing the  
189 damage associated with them. The methodology followed to develop the *IDF* curves is  
190 equivalent to the estimation of the *a* and *b* parameters (Equation (1)), which includes  
191 the: (i) computation of maximum precipitation intensity time series for each of ten  
192 durations (5, 10, 15 and 30 min and 1, 2, 6, 12, 24 and 48 h); (ii) fitting of the Gumbel  
193 distribution function to those time series, which mean estimate the location ( $\mu$ ) and  
194 scale ( $\sigma$ ) parameters in each case (cf. Coles 2001); (iii) estimation of precipitation  
195 intensity for each duration and eight different return periods (2, 5, 10, 20, 50, 100, 500  
196 and 1000 years) using Gumbel inverse distribution function; (iv) representation of the  
197 precipitation intensity (mm/h) as a function of precipitation duration (min) in a log-log  
198 plot to estimate the slope and intercept regression parameters. This last procedure  
199 corresponds to linearization of the Intensity-Duration-Frequency curves (Equation (1)),

200

$$\log(I) = \log(a) + b \times \log(t) \quad (4)$$

201

202 which led to the estimation of the (*a* and *b*) *IDF* parameters with a statistical  
203 significance level of 5%. The quality of the linear regression fit is also assessed by the  
204 coefficient of determination ( $R^2$ ), the *F-statistic* (*p* – *value*) and the error variance.

205 The adopted methodology is similar to that described in Brandão et al. (2001). The  
206 major differences reside, on the one hand, on the way of adjusting the Gumbel law to

207 the data (likelihood estimation, using *evfit* function of MATLAB) and assessing the  
208 quality of the fitting, made in this case with the Quantile-Quantile plots and  
209 Kolmogorov-Smirnov test (*KStest*) and the use of robust regression method (RR) to  
210 estimate the *IDF* parameters *a* and *b*. Major difference of RR in relation to the ordinary  
211 least square method (OLS) used in Brandão et al. (2001) lies in the attribution of  
212 weights to the observed points, as higher as the corresponding regression residual. A  
213 deeper description of the RR method as well as the comparison with OLS may be found  
214 in Holland et al. (1977), Huber (1981) and Street et al. (1988).

215 Many different methods can be used to derive *IDF* curves, from the usual univariate  
216 empirical analysis of the intensity of rainfalls at fixed time intervals, to bivariate  
217 frequency analysis using the copula method (Ariff et al. 2012), partial duration series  
218 (Ben-Zvi 2009; Kingumbi and Mailhot 2010), multifractal approaches (Garcia-Marin et  
219 al. 2013; Veneziano et al. 2013), ensemble empirical mode decomposition and scaling  
220 properties (Bougadis and Adamowski 2006; Kuo et al. 2013). Several studies  
221 comparing methodologies have been conducted but generally all methods seem to be  
222 able to produce accurate *IDF* estimates (Mohyont et al. 2004; Veneziano et al. 2007;  
223 Dame et al. 2008). The type I extreme value, (EVI or Gumbel) distribution has been  
224 used successfully in many recent rainfall intensity studies in Europe (Llasat 2001; Bara  
225 et al. 2010; Olsson et al. 2012), Asia (Ariff et al. 2012; Ben-Zvi 2009; Ahammed and  
226 Hewa 2012), Africa (Kuo et al. 2013; Mohyont et al. 2004) and America (Lumbroso  
227 et al 2011; Pizarro et al. 2012). EVI is currently the recommended distribution function  
228 for use in Canada and the best choice for the estimation of *IDF* curves under changing  
229 climate conditions (Das et al. 2013). Other distribution functions such as the general  
230 extreme value type II (EVII or Fréchet) have also been used, e.g. to estimate the *IDF*  
231 curves using short-record satellite data in Ghana (Endreny and Imbeah 2009).

232 The estimation of the *IDF* curves was performed for precipitation simulated by the  
 233 ECHAM5/MPI-OM1 / COSMO-CLM model chain for the grid cells including the  
 234 location of the six weather stations (cf. Table 1). With this aim, time series for 30 years  
 235 period 1971 – 2000 for the C20 scenario, corresponding to the recent past weather  
 236 conditions, and for two future climate scenarios SRES A1B and B1, regarding the  
 237 periods 2011 – 2040, 2041 – 2070 and 2071 – 2100, were considered. In general,  
 238 climate models are not capable of accurately reproduce the observed precipitation.  
 239 Several methods can be used to correct this bias, ranging from the more traditional  
 240 methods to the Delta Change approach, in order to include projected future changes in  
 241 some key precipitation statistics (Olsson et al. 2012; Pereira et al. 2013). The procedure  
 242 adopted here to correct the model bias is conditioned by just knowing the final values of  
 243 the *IDF* parameters proposed in Matos and Silva (1986) and consisted of matching the  
 244 values of the parameters obtained by the robust regression method for C20 ( $a_{C20}$  and  
 245  $b_{C20}$ ) with the values ( $a_{MS}$  and  $b_{MS}$ ) proposed by Matos and Silva (1986) which are the  
 246 *IDF* parameters adopted by the Portuguese law (DR 1995). The correction factor of  
 247 parameter  $a$  ( $\Delta a$ ) results from the difference between the logarithm of parameter  $a_{C20}$   
 248 associated to scenario C20 and the logarithm of parameter  $a_{MS}$  from Matos and Silva  
 249 (1986),

250

$$\Delta a = \log_{10} a_{C20} - \log_{10} a_{MS} \quad (5)$$

251

252 In turn, the corrective factor of parameter  $b$  ( $\Delta b$ ) results from the ratio between  
 253 parameter  $b_{C20}$  associated to scenario C20 and parameter  $b_{MS}$  resulting from Matos and  
 254 Silva's (1986) study,

255

$$\Delta b = \frac{b_{C20}}{b_{MS}}. \quad (6)$$

256 Afterwards, these same correction factors were applied to parameters  $a_{A1B}$  and  $b_{A1B}$   
257 obtained for scenario A1B, proceeding as follows:

258

$$a_{A1B\ corr} = 10^{(\log_{10} a_{A1B} - \Delta a)} \quad (7)$$

259

260 and

$$b_{A1B\ corr} = \frac{b_{A1B}}{\Delta b} \quad (8)$$

261

262 which allowed obtaining corrected versions of parameters  $a$  and  $b$ . The same procedure  
263 was applied to intermediate results obtained for scenario B1.

264 The two-sample Kolmogorov-Smirnov test is used to compare the distributions of the  
265 precipitation depth intensity simulated for future ( $I_{future}$ ) and recent climate conditions  
266 ( $I_{past}$ ). The null hypothesis is that  $I_{future}$  and  $I_{past}$  are from the same continuous  
267 distribution, while the alternative hypothesis is that they belong to different continuous  
268 distributions. In both cases, the *IDF* curves ( $I = a \times t^b$ ) are used to generate  $I$  values  
269 for different duration times, by resorting to parameters estimated for future  
270 periods/scenarios after correcting climate model bias and proposed by Matos and Silva  
271 (1986), respectively.

272

### 273 **Design of the urban building drainage system**

274 The main goal of this study focuses on the comparison between the design of building  
275 drainage systems, based on the *IDF* curves proposed in Matos and Silva (1986) and the  
276 design based on *IDF* curves estimated for different periods of future scenarios for the  
277 three rainfall regions (A, B and C, in Fig. 1). For quantitative comparison purpose and

278 sake of simplicity, specific residential roof drainage gutter and rainwater pipe were  
279 considered as examples of building storm-water drainage systems to be designed. The  
280 flows were calculated with the rational method equation,

281

$$Q = C.I.A \quad (9)$$

282

283 where, the contribution area ( $A$ ) of the gutter is  $100.14 \text{ m}^2$ , whereas the area of the  
284 devices that reach the rainwater pipe is  $155.69 \text{ m}^2$ , the flow coefficient ( $C$ ) used for  
285 building coverings is equal to the unit while the precipitation intensity ( $I$ ) was  
286 calculated according to the Equation (1) for a duration ( $t$ ) of 5 minutes and a return  
287 period ( $T$ ) of 10 years. Parameters  $a$  and  $b$  used in the calculation of the precipitation  
288 intensity follow the *IDF* curves established in the Regulation-decree n.º 23/95 (DR  
289 1995), and those obtained for precipitation data simulated for future scenarios A1B and  
290 B1, after correction of the climate model bias.

291 The gutter defined for conducting the storm water has a rectangular shape, with a base  
292 ( $B$ ) of 20 cm and inclination ( $i$ ) of 0.5%. It was dimensioned so that the height of the  
293 water depth ( $h$ ) therein does not exceed  $7/10$  of the total height of the gutter. The  
294 Manning-Strickler's formula, Equation (10), was used with a roughness coefficient ( $K$ )  
295 of  $90 \text{ m}^{1/3}/\text{s}$ , corresponding to metal plate. The hydraulic radius ( $R$ ) and the area  
296 occupied by the fluid ( $A_f$ ), in the case of rectangular sections, are determined by the  
297 Equation (11) and Equation (12), respectively:

$$Q = K \times A_f \times R^{2/3} \times i^{1/2} \quad (10)$$

$$R = \frac{B \times h}{(B + 2h)} \quad (11)$$

$$A_f = B \times h \quad (12)$$

298

299 The residential rainwater pipe was designed using the Manning-Strickler formula (10)  
300 for full section, roughness ( $K$ ) of  $120 \text{ m}^{1/3}/\text{s}$  corresponding to polyvinyl chloride (PVC)  
301 and inclination ( $i$ ) of 2%. The hydraulic radius ( $R$ ), in the case of a filled circular  
302 section, is given by Equation (13), where  $D_i$  is the internal diameter of the piping.

$$R = \frac{D_i}{4} \quad (13)$$

303

## 304 **Results and discussion**

305 Before focussing in the *IDF* curves in three precipitation regions, we analyse the  
306 precipitation distribution and projected changes for Continental Portugal. With this aim,  
307 the long term (1961 – 2000) average of the annual maximum daily precipitation depth  
308 was computed based on the ECAD precipitation dataset (Fig. 2). The obtained spatial  
309 pattern is dominated by a region of very large values ( $>60 \text{ mm}$ ), located over NW  
310 Portugal. This pattern is quite different from the three rainfall areas configuration  
311 proposed by Matos and Silva (1986) and adopted by the Portuguese legislator (Fig. 1).  
312 Then, to assess potential future changes on extreme precipitation regime, four extreme  
313 precipitation indices were computed using the precipitation dataset simulated by  
314 COSMO-CLM for each of the 30-year periods for the C20, B1 and A1B scenarios,  
315 namely: the total precipitation depth ( $PRCTOT$ ); the long-term 95th percentile  
316 ( $PRC95p$ ); the ratio between  $RR95pTOT$  and  $PRCTOT$  ( $R95T$ ); and, the total  
317 precipitation depth falling in days with daily precipitation amounts greater than the  
318 corresponding  $PRC95p$  ( $RR95pTOT$ ). The computations were performed taking only  
319 into account wet days defined as days with precipitation depth above or equal to 1.0  
320 mm.



321 Results obtained for simulated recent–past climate conditions (C20 scenario, 1971 –  
322 2000) over continental Portugal (Fig. 1) reveals high spatial variability in the total  
323 precipitation depth, with values ranging between  $11 \times 10^4$  mm in the NW part of the  
324 country and  $1 \times 10^4$  mm, in the remaining area of the country (Fig. 3(a)) resembling the  
325 configuration of the average annual maximum daily precipitation depth (Fig. 2). This  
326 spatial pattern is also very similar to the long term 95<sup>th</sup> percentile of the daily  
327 precipitation depth (Fig. 3(b)), with highest values (as higher as 80 mm) located over  
328 the NW quarter of country and in the southernmost region (of about 60 mm) and much  
329 lower values (smaller than 45 mm) elsewhere.

330 The spatial distribution of *RR95pTOT* and *R95T* also helps to understand the regime of  
331 extreme precipitation in Portugal. The spatial pattern of *RR95pTOT* (Fig. 3(c)) is very  
332 similar to the *PRCTOT* but, as expected, with much lower values. This means that  
333 precipitation amount falling in the days of extreme precipitation assume higher values  
334 in the same regions where total precipitation depth is greater. The *R95T*, which is a  
335 fraction (%) of total precipitation depth falling during extreme rainfall days, present a  
336 pattern characterized by highest values (of about 30%) in the southern part of the  
337 country and (of about 23%) on NW part of the country and along the Tagus river basin  
338 (Fig. 3(d)).

339 Differences between the *PRC95p* ( $\Delta PRC95p$ ) obtained for each of the 30-year period of  
340 the future climate change SRES scenarios (B1 and A1B) and for the recent–past climate  
341 conditions (C20 scenario) are displayed in Fig. 4. For the B1 scenario, positive  
342 differences of 7 to 10 mm may be expected in the NW region with smaller magnitudes  
343 elsewhere for the 2011-2040 period (Fig. 4(a)). The pattern for the following period  
344 (2041 – 2070, Fig. 4(b)) is characterized by generally smaller values (< 5 mm) while for  
345 the last 30-year period (2071 – 2100, Fig. 4(c)), resembles the 2011-2040 pattern except

346 in the southernmost area, where a decrease (of about -5 mm) in  $PRC95p$  should be  
347 expected. This is a clear indication that natural variability on longer time scales may be  
348 superimposed on the long-term trends of precipitation associated with climate change.  
349 For the A1B scenario and 2011 – 2040 period (Fig. 4(d)), a modest increase of the  
350  $PRC95p$  is revealed in all territory, except in small and sparse regions in NW part of the  
351 country. For latter periods (Fig. 4(e) and Fig. 4(f)), the pattern of the  $\Delta PRC95p$  has the  
352 same but amplified spatial configuration with values as high as +10 to 15 mm in the  
353 NW region, over the Tagus river basin and southern part of the country for the 2071 –  
354 2100 period.

355 Next, time series for the six weather stations are analysed. Given the ten temporal  
356 durations, three 30-year periods (2011 – 2040, 2041 – 2070, and 2071 – 2100) for each  
357 of the two future scenarios (A1B and B1) and one period for the recent past climate  
358 conditions, a total of 420 time series is considered. The visual inspection of the  
359 Quantile-Quantile plots and the value of the Kolmogorov-Smirnov statistical test (and  
360 corresponding  $p - value$ ) confirm the goodness of fit of the Gumbel distribution  
361 function to all these time series. The probability density function for each scenario  
362 suggests that the return period for a given amount of precipitation intensity decreases  
363 for the three periods of the future scenarios vis-à-vis the period observed (not shown).

364 Values of the  $IDF$  parameters  $a$  and  $b$  used here were obtained by linear regression, for  
365 durations times between 5 min and 30 min and return periods of 2, 5, 10, 20, 50 and 100  
366 years. The quality of the regression was confirmed by the values of the coefficient of  
367 determination ( $R^2$ ),  $F$ -statistic and by the estimated error variance. The  $R^2$  represents  
368 fraction of the variance of the dependent variable (in this case, the precipitation intensity)  
369 by the linear model using the independent variable (in this case the duration). In all  
370 cases the values of  $R^2$  were always higher than 0.99, which means that more than 99%

371 of the variance of intensity of precipitation can be explained by the variance of the  
372 duration. The values of the *F-statistic* are used to assess the tests of nullity of  
373 parameters for a given level of significance and it is reasonable to assume that the linear  
374 regression equation fits the data well because of the high value of the *F-statistic* and the  
375 *p – values* tends to zero for a significance level of 5%. Finally, the extremely small  
376 value of the estimated error variance obtained in all cases supports the idea that the  
377 regression line provides a good fit to the data.

378 The linear regression models based on the minimization of the squared error are based  
379 on a number of assumptions which are not always verified, e.g. the non-normality of the  
380 residuals, the existence of an asymmetric distribution of errors and outliers. This fosters  
381 the use of the RR method in this study, which constitutes an alternative approach that  
382 aims to be more robust and resistant than the OLS. Table 2 allows assessing changes in  
383 the design of a residential gutter and rainwater pipe, as a consequence of variations  
384 recorded in the *IDF* curves, as a result of the changes in the distribution of the  
385 maximum precipitation values due to climate change. The determination of the design  
386 flow was performed on the basis of the values of precipitation intensities estimated from  
387 the *IDF* curves for all time periods and both scenarios (after bias correction) and *IDF*  
388 curves currently used in designing building drainage systems in Portugal, developed by  
389 Matos and Silva (1986) and embraced by the Portuguese legislation (DR 1995).

390 Overall, there is a clear tendency to increase the size of gutters and rainwater pipes  
391 compared to the current dimensions defined in the Portuguese legislation (Table 2).  
392 However, changes are not uniform: For region A, the estimated increases in the height  
393 of the gutter for scenario A1B, range from 6% (2041 – 2070) to 11% (2071 – 2100) in  
394 the station of Ponte da Barca, to 30% (2011 – 2040) to 39% (2071 – 2100) in São  
395 Manços. For region B, the estimated increase may vary from 11% (2041 – 2070) to 39%

396 (2071 – 2100) for Castelo Melhor and scenario A1B and from 12% (2041 – 2070) to  
397 28% (2071 – 2100) for scenario B1. In the station of Pinelo, the design of the gutter  
398 varies from -7% (2011 – 2040) and 18% (2071 – 2100) for scenario A1B, whereas, for  
399 scenario B1, it varies from 3% (2011 – 2040 and 2041 – 2070) and 10% (2071 – 2100).  
400 In order to obtain an average value representative for the mid-21st century, averages  
401 were built for each station over the three time periods, thus sampling decadal variability.  
402 This results for example on an estimated average increase of 39% in São Manços and  
403 9% for Ponte da Barca for the A1B scenario (both Region A). For region B, changes are  
404 larger for Castelo Melhor (20%) than for Pinelo (5%) for both scenarios. On the  
405 contrary, little differences are found for region C: ranges are 3% to 16% for scenario  
406 A1B and from 3% to 9% for scenario B1 in the station of Covilhã, whereas for the  
407 station of Pega, it ranges from 4% to 16% and from 3% to 6%, respectively.  
408 Furthermore, averages were built over both stations in each region and both scenarios to  
409 obtain values representative per region considering scenario uncertainty. Averaged  
410 increase in Gutter dimension is likely to be higher in Region A (21%) than in region B  
411 (12%) and in region C (7%).  
412 The projected changes in the rainwater pipe size are essentially proportional to the  
413 gutter (Table 2). Therefore, a detailed presentation of the results is omitted. The main  
414 results are: (i) averaged changes in the rainwater pipe diameter increases from 4% in  
415 region C, to 7% in region B and 11% in region A; (ii) different behaviour in region A is  
416 characterized by higher changes in the weather stations located in the southern (São  
417 Manços) than in the northern part (Ponte da Barca) and, in region B, at lower (Castelo  
418 Melhor) than at higher altitude (Pinelo); (iii) higher homogeneity in the expected  
419 changes in mountainous region C and (iv) changes are typically smaller than for the  
420 gutter.

421 In general terms, the estimated changes are projected to be largest at the end of the 21<sup>st</sup>  
422 century and under the conditions of scenario A1B scenario. In region C, there is a clear  
423 increasing trend in the changes (increases) in the size of these building storm-water  
424 drainage systems when the results for the three consecutive 30-year periods are  
425 analysed, independently of the scenario considered. However, this behaviour is not  
426 always observed in other regions where may even be expected decreasing trends (as in  
427 São Manços, located in region A, for the conditions of scenario B1), probably  
428 associated with natural variability on longer time scales. The temporal evolution of  
429 patterns of the 95th percentile, allow the interpretation of the results obtained for the  
430 expected changes in the dimensions of the rainwater collecting organs. In the case of the  
431 A1B SRES scenario, the expected changes in the size of the gutter and rainwater pipe  
432 along the three 30-year periods are characterized by increasing long-term trends in the  
433 Pinelo, Pega and Covilhã stations; for São Manços and Castelo Melhor, changes of  
434 similar magnitude are found for 2011 – 2040 and 2041 – 2070, which are enhanced for  
435 2071 – 2100; For Ponte da Barca, a relative decrease is detected in the latter period at  
436 least for the B1 scenario (Table 2). As mentioned above, part of these relative changes  
437 between periods may be associated with multi-decadal natural climate variability and  
438 not with a long-term climate trend. These projected changes are consistent with the  
439 trends in the changes of *PRC95p* as discussed for the A1B scenario (Fig. 3).

440 Finally, it is important to underline that projected changes in the size of the building  
441 storm-water drainage systems are statistical significant at the 99% level in all cases  
442 except in the 6 cases (17%) identified by a dagger in Table 2 and for the station of Pega  
443 in the first 30-year period of the A1B scenario. It is important to underline that  
444 projected changes in all cases of rainfall region A are statistical significant (99%) and  
445 that statistical significance is higher in the end of the XXI century.

446

## 447 **Conclusions**

448 This study aimed at discussing the current status of the *IDF* curves adopted by the  
449 Portuguese Law and investigate the possible influence of projected changes in extreme  
450 precipitation in the current designing of building storm-water drainage systems. Patterns  
451 of spatial distribution of annual maximum daily rainfall and extreme precipitation  
452 indices, obtained from both observed and simulated data for recent past conditions,  
453 exhibit considerable variability and suggest the necessity to revise the results of Matos  
454 and Silva (1986) included in the legislation (DR 1995), which divide Continental  
455 Portugal in three homogeneous rainfall regions. This is the case even assuming the  
456 long-term stationarity of current precipitation regime.

457 The developed methodology to assess the impacts of projected climate change is well  
458 grounded in literature and ensures the robustness and statistical significance of the  
459 results. The comparison of the design carried out with the *IDF* curves outlined for future  
460 scenarios with the curves obtained by Portuguese law allowed estimating an average  
461 increase of the gutter section and the rainwater pipe that is higher for region A (21% and  
462 11%, respectively) than for region B (13% and 7%) and region C (7% and 4%).  
463 Regarding the uncertainty for the three regions, estimated as the range between the two  
464 stations, estimates were similar for region C, with maximum increases of 16% for the  
465 gutter and 9% for the rainwater pipe. For region B, the estimates for gutter design varies  
466 between 18% and 39% and, for the rainwater pipe range between 10% and 21%. For  
467 region A, estimates are larger for southern Portugal (São Manços) – of 40% for the  
468 gutter and 20% for the rainwater pipe – than for Northern Portugal (Ponte da Barca),  
469 with 20% and 11% for the gutter and rainwater pipe, respectively. In spite of these  
470 uncertainties, the sign of the trends are very consistent between regions and stations.

471 These tendencies are in line with the projected long-term changes of the 95th percentile  
472 (*PRC95p*) and other extreme precipitation indices for under future climate conditions  
473 which exhibit similar spatial patterns to the annual maximum daily rainfall. These  
474 results, together with the spatial distribution of rainfall and extreme precipitation indices  
475 seem to reinforce the suggested need to evaluate the precipitation regime classification  
476 performed in Matos and Silva (1986).

477 Most cases studies discussed above (cf. Tab. 2) identified statistically significant  
478 differences between the dimensions of the building storm-water drainage systems  
479 estimated for recent and future climate conditions. This is also the case for the near-  
480 future period of 2011 – 2041 and for the entire rainfall region A, which covers by far the  
481 largest part of the mainland area.

482 In summary, the impact of projected climate change should be reflected in the overall  
483 increase in the design of drainage storm-water drainage systems based on *IDF* curves as  
484 defined in Portuguese law for all scenarios and future periods analysed. Projected  
485 changes are typically larger and increasingly statistical significant for the end of the 21<sup>st</sup>  
486 century, and the magnitude of the changes is larger for the scenario A1B than for  
487 scenario B1. Current laws and regulations relating to the design and management of  
488 hydraulic works may become out of date in the short term, given the increase in the  
489 frequency and intensity of extreme precipitation events. Therefore, the design of new  
490 building storm-water drainage systems for Continental Portugal should be modified to  
491 larger dimensions to mitigate the projected changes in extreme precipitation

492

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## Tables

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Table 1 – Weather stations used in this study. Characterization includes the code, name, abbreviation, altitude (H), geographical coordinates (latitude, longitude), cover period (P) and percentage of hourly precipitation missing values (MV).

Code	Name	Altitude (m)	Latitude (° N)	Longitude (° W)
03G/02C	Ponte da Barca, PB	39	41.80	-8.42
23K/01UG	São Manços, SM	190	38.46	-7.75
07O/05UG	Castelo Melhor, CM	286	41.01	-7.06
04R/02G	Pinelo, PI	607	41.63	-6.55
12L/03G	Covilhã, CO	719	40.28	-7.51
11O/01G	Pega, PE	770	40.43	-7.14

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Code	Name	Alt (m)	Lat (° N)	Lon (° W)	P	MV (%)
03G/02C	Ponte da Barca, PB	39	41.80	-8.42	01/2003-09/2012	4.9
23K/01UG	São Manços, SM	190	38.46	-7.75	02/2001-03/2012	1.1
07O/05UG	Castelo Melhor, CM	286	41.01	-7.06	10/2001-12/2009	0.0
04R/02G	Pinelo, PI	607	41.63	-6.55	02/2003-01/2012	3.8
12L/03G	Covilhã, CO	719	40.28	-7.51	05/1998-05/2010	11.8
11O/01G	Pega, PE	770	40.43	-7.14	10/2001-03/2012	8.6

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712 Table 2 – Projected changes in the dimension of the drainage systems. Height of the Gutter (H) and  
713 diameter of the rainwater Pipe (D) designed for weather stations located in the three pre-defined rainfall  
714 regions, using the precipitation intensity estimated by Portuguese law (DR 1995) and with data simulated  
715 by COSMO-CLM, for three periods of thirty years of the two future scenarios (A1B and B1) as well as  
716 the relative differences between these dimensions ( $\Delta H$  and  $\Delta D$ ). Projected changes are statistical  
717 significant at 99% level except for the cases identified by superscript lowercase letter (<sup>a</sup>). Arithmetic  
718 averages of  $\Delta H$  and  $\Delta D$  for each weather station ( $\overline{\Delta H}_w$  and  $\overline{\Delta D}_w$ ) and region and scenario ( $\overline{\Delta H}_s$  and  $\overline{\Delta D}_s$ )  
719 are also shown. The former values are calculated over different periods to obtain an average value  
720 representative for the mid-21<sup>st</sup> century, thus sampling decadal variability. The latter are derived to obtain  
721 values representative for each region considering scenario uncertainty.

Station	Scenario	Period	Gutter				Rainwater pipe			
			H (cm)	$\Delta H$ (%)	$\overline{\Delta H}_s$ (%)	$\overline{\Delta H}_w$ (%)	D (cm)	$\Delta D$ (%)	$\overline{\Delta D}_s$ (%)	$\overline{\Delta D}_w$ (%)
Region A	Ponte da Barca	DR n°23/95	4.51				96.60			
		A1B	2011-2040	4.92	9%	9%	101.48	5%	5%	11%
			2041-2070	4.79	6%		99.94	3%		
			2071-2100	5.01	11%		102.57	6%		
		B1	2011-2040	5.28	17%	17%	105.50	9%	9%	
			2041-2070	5.39	20%		106.81	11%		
	2071-2100		5.14	14%	103.90		8%			
	São Manços	DRn°23/95		4.51			21%	96.60		
		A1B	2011-2040	5.84	30%	33%	111.67	16%	17%	
			2041-2070	5.91	31%		112.38	16%		
			2071-2100	6.26	39%		116.00	20%		
		B1	2011-2040	6.17	37%	26%	115.06	19%	14%	
2041-2070			5.61	24%	109.13		13%			
2071-2100	5.28		17%	105.57	9%					
Region B	Castelo Melhor	DRn°23/95		3.89			88.80			
		A1B	2011-2040	4.50	16%	22%	96.52	9%	12%	
			2041-2070	4.33	11%		94.34	6%		
			2071-2100	5.41	39%		107.04	21%		
		B1	2011-2040	4.47	15%	18%	96.18	8%	10%	
			2041-2070	4.36	12%		94.76	7%		
	2071-2100		4.99	28%	102.31		15%			
	Pinelo	DRn°23/95		3.89			12%	88.80		7%
		A1B	2011-2040	3.63	-7%	4%	85.34	-4%	2%	
			2041-2070 <sup>a</sup>	3.91	1%		89.01	0%		
			2071-2100	4.57	18%		97.38	10%		
		B1	2011-2040 <sup>a</sup>	4.01	3%	5%	90.38	2%	3%	
2041-2070 <sup>a</sup>			4.00	3%	90.26		2%			
2071-2100	4.27		10%	93.74	6%					
Region C	Covilhã	DRn°23/95		5.09			103.44			
		A1B	2011-2040 <sup>a</sup>	5.25	3%	8%	105.22	2%	4%	
			2041-2070	5.37	5%		106.58	3%		
			2071-2100	5.89	16%		112.09	8%		
		B1	2011-2040	5.38	6%	6%	106.68	3%	3%	
			2041-2070	5.53	9%		108.32	5%		
	2071-2100 <sup>a</sup>		5.24	3%	105.03		2%			
	Pega	DRn°23/95		5.09			7%	103.44		4%
		A1B	2011-2040 <sup>b</sup>	5.29	4%	9%	105.64	2%	5%	
			2041-2070	5.45	7%		107.48	4%		
			2071-2100	5.93	16%		112.53	9%		
		B1	2011-2040 <sup>a</sup>	5.24	3%	5%	105.09	2%	3%	
2041-2070			5.39	6%	106.76		3%			
2071-2100	5.38		6%	106.63	3%					

722 <sup>a</sup> change is not statistically significant (p-values>0.05).

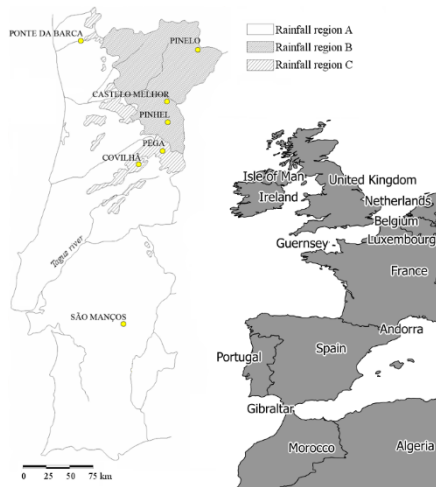
723 <sup>b</sup> change is statistically significant at 95% level

## Figures

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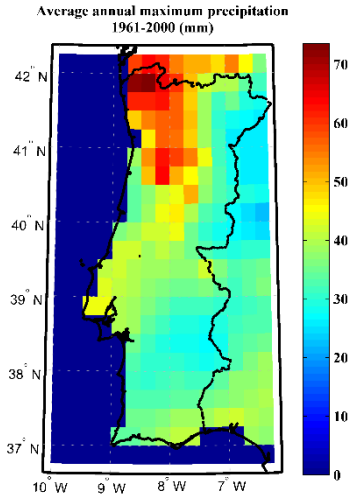
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Figure 1 – Rainfall regions defined in the Portuguese Law (DR 1995), including the geographical location of the weather stations used in this study (left panel) and the geographical location of Continental Portugal in Western Europe (right panel).



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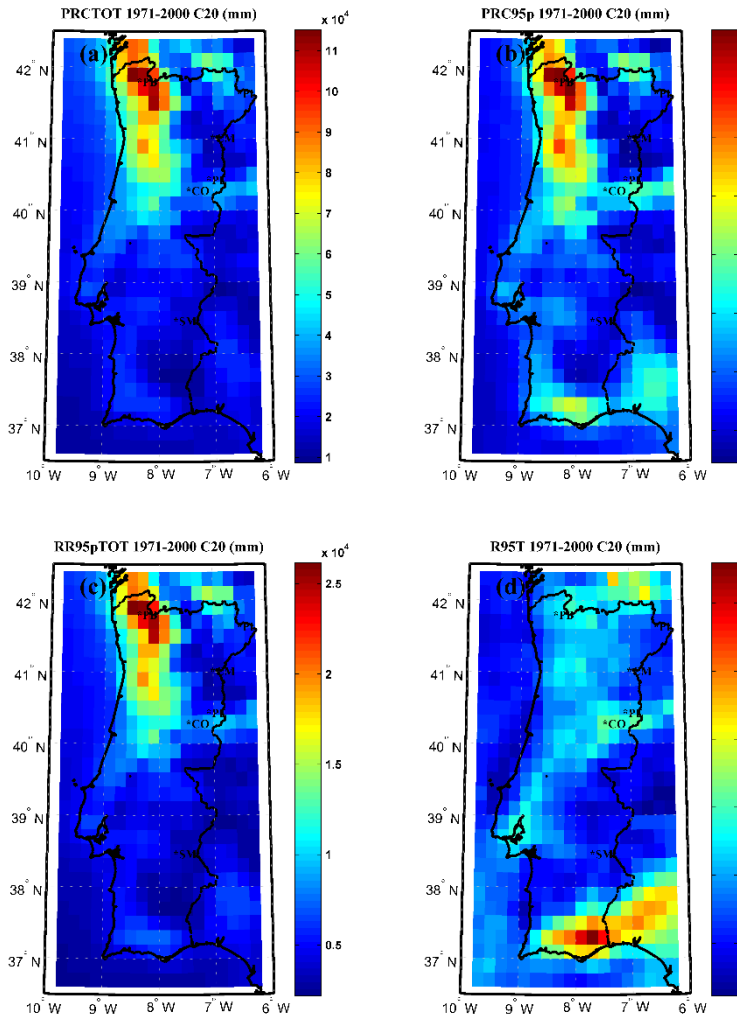
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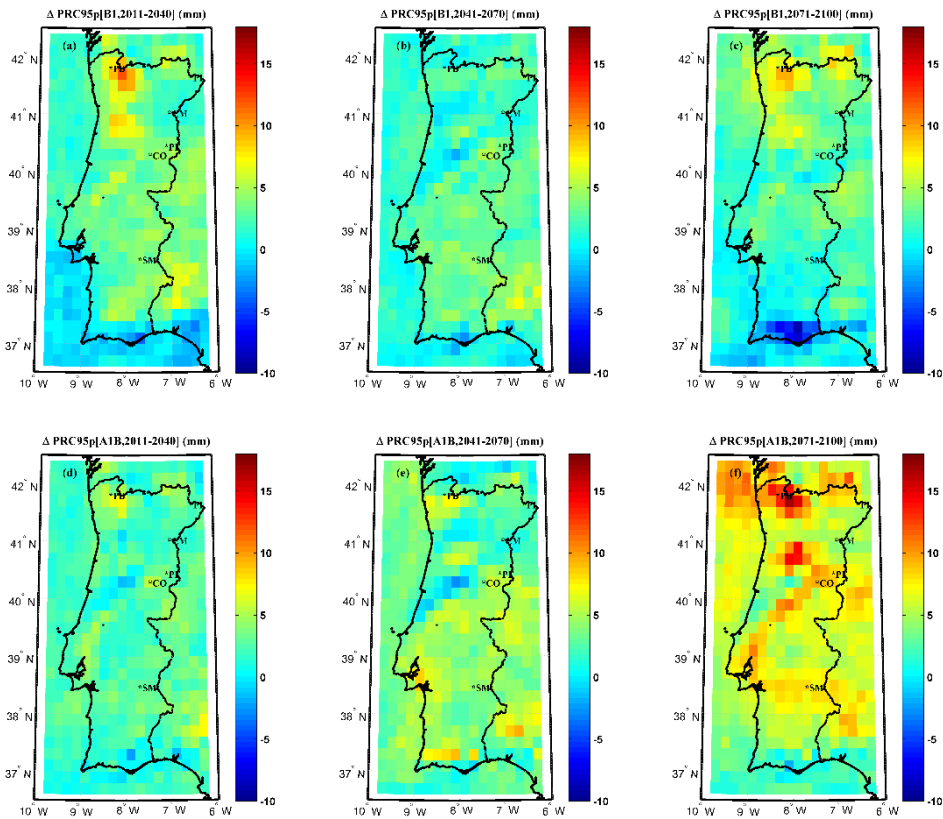
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Figure 2 – The long-term (1961-2000) arithmetic average of the annual maximum daily precipitation. Values were evaluated with ECAD precipitation dataset (E-OBS v8.0, 0.25 degree regular lat-lon grid) over Continental Portugal.



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 745 Figure 3 – Extreme Precipitation indices for Continental Portugal. Values of the (a) long-term 95th  
 746 percentile ( $PRC95p$ ), (b) total precipitation ( $PRCTOT$ ), (c) total precipitation falling in days with daily  
 747 precipitation amounts greater than the corresponding  $PRC95p$  ( $RR95pTOT$ ) and (d) the ratio between  
 748  $RR95pTOT$  and  $PRCPTOT$  ( $R95T$ ) evaluated for daily precipitation simulated by the COSMO-CLM  
 749 model, for recent–past climate conditions (C20 scenario, 1971 – 2000).  
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Figure 4 – Trends in long-term 95th percentile  $PRC95p$  over continental Portugal. Differences between of the long-term 95th percentile ( $\Delta PRC95p$ ) evaluated for future climate conditions under the B1 (top panel) and A1B (bottom panel) SRES scenarios and three 30-year periods 2011 – 2040 (left panels), 2041 – 2070 (middle panels) and 2071 – 2100 (right panels) in relation to recent–past climate conditions (C20 scenario, 1971 – 2000).