

Editor comments

Dear colleagues,

I am pleased to announce, that both reviewers agreed on the suitability of your manuscript for NHESS following minor revisions.

I kindly ask you to follow strictly the reviewers comments as you already pointed out in your respective responses and to resubmit the revised manuscript as soon as possible.

I am looking forward to receiving your revised contribution.

R: Dear Editor,

thank you very much for your support in reviewing the manuscript. In the following we attach a point-by-point response to the reviews, including all relevant changes made in the manuscript, and a marked-up manuscript version.

Reviewer #1

Nice study. Nicely and well written. Everything's fine.

R: we thank Reviewer #1 for his/her kind comments.

Very small comments:

- The first two lines in both abstract and introduction theoretically could be left out. These sentences are found in almost every rockfall publication.

R: We thank for this comment. Nevertheless, we would prefer to leave these generic statements to introduce the topic and the potential hazard of rockfalls in the wider framework of rainfall-induced mass movements.

- Line 88: you could add a reference to Fig. 1 here as well.

R: Done.

- Section 3.2: how were the occurrence times of the rockfalls been detected? Was it the date of the road inspection? How often took the inspection place? etc.

R: We thank the reviewer for the question that allowed us to clarify the item. We added now the following text in Section 3.2: *"After a rockfall occurrence, a quick action is required by local authorities to remove boulders from road, and to repair the damage. The average response time for these emergencies is down to one day, and therefore the date of the rockfall occurrence is the same of the road inspection."*

Apart from scheduled inspections, a survey is carried out whenever a rockfall occurrence is reported.

- Section 5: is there a reasonable approach to see rainfall intensity changing due to climate change and therefore to use this study to predict rockfall activity?

R: This is an interesting topic, indeed. Following the indications of the World Meteorological Organization, which reads: "a 30-year period is long enough to filter out any inter annual variation or anomalies, but also short enough to be able to show longer climatic trends", we believe that the number of years available to us to assess a reliable climatic trend is inadequate.

- References: You could add Contino et al, NHESS 17(12), 2017.

R: Done.

Reviewer #2

This manuscript applies the ED rainfall threshold on rockfall and discusses the link between the change of seasonal rainfall amount and the occurrence of rockfall through great amounts of rockfall cases and rainfall data. The contents, figures, tables are all well-organized. The results also provide a new insight for the early warning of rockfall. Here are some suggestions for the authors that may take into account.

R: We thank the Reviewer #2 for his/her kind comments.

1. Since there are lots of rockfall records in GC and TEN, is it possible to discuss the influence of geology and geomorphology on rainfall threshold? Besides, the relationship between the volume of rockfall and the cumulated event rainfall may also be discussed.

R: We thank the Reviewer #2 for the interesting suggestion, but from the geological point of view, all Canary Islands are located inside the Africa Plate, in the transitional zone between the Continental Crust and the Oceanic Crust, and are characterized by the volcanic origin that is still active. As a consequence, there aren't significant differences in the geology. Moreover, rockfalls in our catalogue occurred on the road network of GC and TEN, and therefore the dependence of the thresholds on the geology and geomorphology is likely not relevant here.

Regarding the second question, besides a qualitative classification in small, medium, and large boulders provided by the Civil Protection Authorities, the volume associated to each rockfall is unfortunately unavailable. We agree with the Reviewer that this relationship would have been very useful in defining the magnitude of the event as a function of the rainfall.

2. [Section 2.2, Line 128~130] Comparing to the last paragraph in section 2.1, the information of average annual rainfall in TEN is missed.

R: We now added the required information for TEN, and we corrected the upper average annual rainfall.

3. [Figure 4 & Line 227] There are 29 cases with hourly rainfall data in GC, but they are not analyzed in Figure 4 c and d. Too less to be analyzed?

R: The Reviewer #2 is right. The low number of cases precludes the calculation of rainfall thresholds. We now added this statement in the text.

4. It is suggested to add some representative pictures of these rockfalls in order to make readers understand the environment of study area more.

R: We thank Reviewer #2 for this suggestion. We now added two pictures of rockfalls on GC-200 road and on a road in Tenerife (shown below).



Minor issues:

[Line 219~220] "light green dots in Fig. 2" These are no green dots in Figure 2. Is it Figure 4?

R: Light green dots are in Fig.1 We corrected the citation.

[Figure 2 and Figure 3] The Y-axis of Fig. 2 c, d and Fig. 3 d, e, f should be “Rockfall” instead of “Rock fall.”

R: We thank Reviewer, and we noticed that the same error was also in Fig. 1. We corrected it.

1 RAINFALL AND ROCKFALLS IN THE CANARY ISLANDS: ASSESSING A SEASONAL
2 LINK

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14

15 **Abstract**

16 Rockfalls are frequent and harmful phenomena occurring in mountain ranges, coastal cliffs and slope
17 cuts. Albeit several natural processes concur in their formation and triggering, rainfall is one of the
18 most common causes. The prediction of rock failures is of social significance for civil protection
19 purposes and can rely on the statistical analysis of past rainfall conditions that caused the failures.
20 The paper describes the analysis of information on rainfall-induced rockfalls in Gran Canaria and
21 Tenerife, Canary Islands (Spain). An analysis of the monthly rainfall versus the monthly distribution
22 of rockfalls reveals that they are correlated for most of the year, except in summer, when other triggers
23 act to induce collapses. National and regional catalogues with hourly and daily rainfall measurements
24 are used to reconstruct the cumulated amount (E) and the duration (D) of the rainfall responsible for
25 the rock failures. Adopting a consolidated statistical approach, new ED rainfall thresholds for possible
26 rockfall occurrence and the associated uncertainties are calculated for the two test sites. As far as is
27 known, this is the first attempt to predict this type of failure using the threshold approach. Using the
28 rainfall information, a map of the mean annual rainfall is obtained for Gran Canaria and Tenerife, and
29 it is used to assess the differences between the thresholds. The results of is study are expected to
30 improve the ability to forecast rockfalls in the Canary Islands, in view of implementing an early
31 warning system to mitigate the rockfall hazard and reduce the associated risk.

32

33 **Keywords:** Rockfall, rainfall threshold, Canary Islands.

34

35 1 Introduction

36 Rockfalls are instability processes affecting mountainous regions, coastal cliffs and slope cuts. Being
37 very rapid, they are extremely dangerous and life-threatening, especially when they occur in
38 populated areas, along roads and railways. The most frequent triggering factors of rockfalls are
39 rainfall, cycling thermal stress, and seismic activity (Wieckzorek and Jaeger, 1996; Keefer, 2002;
40 Mateos, 2016; Ansari et al., 2015; Collins and Stock, 2016; Contino et al., 2017; Sarro et al., 2018;
41 Saroglou, 2019; González de Vallejo et al., 2020). At regional and global scales, empirical approaches
42 to forecast the occurrence of rockfalls may contribute reducing risk. Generally, for rainfall-induced
43 slope failures the forecast can rely upon the definition of rainfall thresholds, i.e. the rainfall conditions
44 that when reached or exceeded are likely to trigger the failure. Rainfall thresholds are calculated
45 through the statistical analysis of historical rainfall conditions that have resulted in landslides (e.g.,
46 Guzzetti et al., 2007, 2008; Cepeda et al. 2010; Sengupta et al., 2010; Ruiz-Villanueva et al. 2011;
47 Berti et al., 2012; Staley et al., 2013; Zêzere et al., 2015; Palenzuela et al., 2016; Rosi et al., 2016;
48 Peruccacci et al., 2017; Segoni et al., 2018; Valenzuela et al., 2018, 2019). The definition of reliable
49 empirical rainfall thresholds relies on the use of objective procedures for (i) the reconstruction of the
50 rainfall events responsible for the failures and (ii) the calculation of the thresholds. For the purpose,
51 Melillo et al. (2018) have proposed an algorithm that reconstructs rainfall events, identifies the
52 rainfall conditions that have resulted in slope failures, and calculates probabilistic cumulated event
53 rainfall-rainfall duration (ED) thresholds at different non-exceeding probabilities and their associated
54 uncertainties (Peruccacci et al., 2012). The obtained thresholds are a set of parallel power-law curves
55 in a log-log (D,E) plane, which are characterized by a slope and an intercept, the last being a function
56 of the non-exceeding probability value (Brunetti et al., 2010).

57 In this work, a relationship between the amount of rainfall and the occurrence of rockfalls is assessed
58 and empirical rainfall thresholds are defined for two test sites in Gran Canaria and Tenerife, Canary
59 Islands (Spain). The possible prediction of rainfall-induced rock failures is of fundamental importance
60 primarily for the safety of the inhabitants and for preserving infrastructures such as roads and
61 buildings. An increasing level of safety against this type of hazard is also important for the local
62 economy, one third of which is based on tourism. As far as is known, this is the first attempt to predict
63 rock failures triggered by rain using the threshold approach. Recently, in Italy it has been observed
64 that the slope of the power-law curve is dependent on the mean annual rainfall (MAR). In particular,
65 the higher is the MAR the steeper is the threshold (Peruccacci et al., 2017). This relationship is
66 explained assuming that where the landscape has been shaped over long time periods by landslides

67 triggered by a given minimum amount of rainfall, it is likely necessary at least as much rainfall to
68 trigger the next landslides (Chen, 2015). For improving the discussion of the results, it has been
69 considered worthwhile producing a map of the MAR for the islands of Gran Canaria and Tenerife
70 using the available rainfall data sets.

71 The manuscript is organized as follows. After a description in Section 2 of the general settings of the
72 two test sites, Section 3 describes the rainfall and rockfall datasets, and the methods used to determine
73 *ED* rainfall thresholds and the map of the MAR. Section 4 illustrates in detail the relationship between
74 the rainfall regime and the occurrence of rock failures, and presents the rainfall thresholds for the
75 possible rockfall occurrence in the two test sites. Finally, in Section 5, the main findings of the work
76 are summarised and discussed.

77 **2 Test site description**

78 The Canary Islands (Spain) are one of the major volcanic chain in the oceans. The archipelago
79 consists of eight islands in the Atlantic Ocean, aligned along a W-SW to E-NE direction: El Hierro,
80 La Palma, La Gomera, Tenerife, Gran Canaria, Fuerteventura, La Graciosa and Lanzarote. The
81 geological origin of the Canary archipelago (800 km in length) is still under debate, but it has been
82 traditionally interpreted as a hotspot track (Fullea et al., 2015).

83 The steep topography and the geological complexity of the archipelago influence the activation of an
84 intense slope failures activity. Rockfalls are the most frequent landslide type in the Canary Islands,
85 causing damage on built-up areas and communication networks.

86 Two test sites are selected for assessing the relationship between the rainfall and the occurrence of
87 rockfalls. The first site (GC) is located in the north-western part of Gran Canaria island, and the
88 second site (TEN) is the entire Tenerife island (Fig. 1).

89 **2.1 Gran Canaria Island (GC-200 road)**

90 Gran Canaria is the third island in size of the Canarian archipelago. With an area of 1560 km² and a
91 maximum altitude of 1956 m a.s.l., the island is approximately circular in shape (Fig. 1). The origin
92 of Gran Canaria can be dated about 15 million years ago (Miocene) with the first submarine building
93 stages of the Gran Canaria Volcano. From the geological point of view, the island presents the greatest
94 variability of igneous rocks of the entire archipelago. Besides the distinctive lavas of the basanite
95 basalt to trachyte phonolite series, Gran Canaria presents also other types of magma, such as tholeiitic

96 basalts and rhyolites (Troll and Carracedo, 2016). Massive flank failures and erosion give place to
97 chaotic deposits that cover large areas.

98 The test site is the GC-200 road located in the north-western extreme of Gran Canaria, and specifically
99 between the localities of Agaete and Aldea. The road constitutes the main transportation corridor
100 between the two localities. With a length of 34 km, the road path is very tortuous following the
101 contour of the coast, a very step coastline with some of the highest cliffs in Europe. The road has
102 heavy traffic estimated on average at 1500 vehicles per day. The geology of the test site area is within
103 the domain of the basaltic shield stage, Middle Miocene in age. Along the road, an alternance of
104 alkaline basaltic deposits and piroclastic flows can be observed. In some parts, gravitational deposits
105 (mainly colluvial) also outcrop covering wide areas.

106 Regarding climatological conditions, Gran Canaria is located in a transitional zone between temperate
107 and tropical conditions. The conical morphology of Gran Canaria retains the humidity of the
108 predominant N-NE trade winds of the subtropical Azores anticyclone on the north side of the island.
109 As a result, the northern flanks are humid and vegetation is vigorous, while the south part of the island
110 is very dry and the conditions are very arid and desert-like. Annual rainfall ranges between 100 and
111 900 mm on average, increasing with altitude. In the test site the climate is very dry, with low average
112 annual rainfall (< 100 mm) and high average annual temperature (~ 20°C).

113 **2.2 Tenerife island**

114 Tenerife (Fig. 1) is the largest (2057 km²) and the most populated (950,000 inhabitants and 13.2
115 million visitors in 2019) island of the archipelago. It is home to the third largest volcano in the world
116 (Pico del Teide, 3718 m a.s.l.).

117 From a geological point of view, Tenerife was constructed via Miocene–Pliocene shields that now
118 form the vertices of the island. The shields were unified into a single edifice by later volcanism that
119 continued in central Tenerife from approximately 12 to 8 million years ago and was followed by a
120 period of dormancy. Rejuvenation at approximately 3.5 Ma is recorded by the central Las Cañadas
121 Volcano, and long residence times of magmas during this period favoured magmatic differentiation
122 processes to produce an episode of felsic and highly explosive felsic volcanism (Troll and Carracedo,
123 2016).

124 The steep orography of the island and the climate variety have resulted in a diversity of landscapes
125 and geographical formations. Very impressive coastal cliffs (till 500 m in height) are present in the

126 northern corner of Tenerife. This area is also characterized by narrow and deep ravines which
127 determine an intense slope activity.

128 The climate of Tenerife is subtropical oceanic; the minimum and maximum annual average
129 temperatures are about 15°C in winter and 24°C in summer. **Similarly to Gran Canaria, annual rainfall**
130 **ranges between 100 and 900 mm.** Tenerife offers a large variety of micro-climate zones controlled
131 by the altitude and the winds.

132 **3 Data and methods**

133 The availability of rainfall measurements and landslide information is fundamental to define reliable
134 rainfall thresholds. For the selection of the rain gauges, the data quality and the location of the rain
135 gauges are assessed, given that these features are crucial to characterize the spatial-temporal variation
136 of the precipitations. Similarly, the calculation of the MAR relies on the availability of sufficiently
137 long rainfall series (at least 30 years). This is difficult to achieve for a dense network of rain gauges,
138 where sensors may exhibit different operating time periods. The World Meteorological Organization
139 (WMO) guidelines on the calculation of the annual standard normal, specifically the MAR,
140 recommend at least 10 years to define at least provisional MAR maps (WMO, 1989). This is the case
141 in the test sites, where a lot of rainfall information is limited to short time periods (the average is 15.6
142 years), thus hampering the calculation of the MAR with a detailed space resolution.

143 **3.1 Rainfall data**

144 In the GC test site, hourly rainfall data (purple triangles in Fig. 1) from the Spanish National
145 Meteorological Service (AEMET) network (in total 25 stations among which 4 are close to the study
146 area) are used for the calculation of rainfall thresholds. Moreover, daily rainfall data (orange triangles
147 in Fig.1) are provided from the *Consejo Insular de Aguas de Gran Canaria* (CIAGC) regional rain
148 gauge network (13 stations) and from AEMET (92 stations, among which 7 are close to the study
149 area). Some of the sensors of the AEMET network provide both hourly and daily rainfall, in different
150 time periods. Details of the rainfall series are reported in Table 1.

151 For the TEN test site, rainfall measurements are provided by AEMET with the contribution of
152 regional networks. As for the GC test site, the rainfall analysis is performed using both hourly and
153 daily data. The two networks in the TEN test site are composed by 34 rain gauges recording hourly
154 data (purple triangles in Fig. 1) and 66 rain gauges recording daily data (orange triangles in Fig. 1).

155 To calculate the MAR for the two test sites, yearly and monthly rainfall data provided by AEMET
156 and by *Sistema de Información Agroclimático y de Regadíos* (SIAR), respectively, are used (Table
157 1). In particular, in order to obtain homogeneous maps, data recorded in the 20-year period from
158 January 2000 to December 2019 in both test sites are selected. Following WMO guidelines (WMO,
159 1989), only stations with at least 10 years of data are included in the analysis. Overall, 72 (one every
160 22 km²) and 67 (one every 31 km²) rain gauges are used to calculate MAR in Gran Canaria and
161 Tenerife, respectively. The average number of sensors operating per year in the considered period is
162 56 (84%; one every 28 km²) in Grand Canaria and 47 (65%; one every 43 km²) in Tenerife. The used
163 rain gauges are homogeneously distributed over the test site areas.

164 Using the monthly and annual rainfall data recorded by the 103 rain gauges in the two islands, the
165 MAR for the period 2000-2019 was calculated for each station. Moreover, the coefficient of variation
166 of the MAR is calculated by dividing its standard deviation by the MAR. This coefficient represents
167 the variability of the MAR in the considered time interval. The map of the MAR and of its coefficient
168 of variation are calculated using the tension spline tool in ESRI ArcMAP 10.7.1.

169 **3.2 Rockfall data**

170 The information on the rockfalls was collected **by the Road Maintenance Service in the GC test site**
171 **and by the Canarian Civil Protection Authorities in the TEN test site. After a rockfall occurrence, a**
172 **quick action is required by local authorities to remove boulders from road, and to repair the damage.**
173 **The average response time for these emergencies is down to one day, and therefore the date of the**
174 **rockfall occurrence is the same of the road inspection. Figure 2 portrays an example of rockfalls**
175 **occurred in GC and TEN test sites.**

176 For the GC test site a total of 8174 rockfall events occurred from January 2010 to March 2016 was
177 documented. A catalogue was prepared defining accurately the location of each impact along the road
178 using orthophotos available for the region and technical reports. The information for each event
179 includes kilometre point, number of events, date, and boulder size. In GC only 535 rockfalls
180 characterized by medium to large size are included in the analysis for the thresholds, whereas small
181 and very small rockfalls (< 10⁻³ m³) are discarded. Analogously, a catalogue of 1898 rockfalls that
182 impacted along Tenerife roads from January 2010 to November 2017 was prepared. For each event,
183 the information includes rockfall localization, geographic accuracy, occurrence day, month, year, and
184 time (if available), and temporal accuracy.

185 The influence of the rainfall on the occurrence of rockfalls is assessed analysing the distribution of
186 monthly rainfall (Figs. 3a,b) and monthly number of rockfalls (Figs. 3c,d) on the two test sites. As
187 expected, an increase of the rainfall in the autumn-winter period, between October and March, is
188 observed in both islands, with a maximum in November.

189 The monthly distribution of rockfalls in Gran Canaria (Fig. 3c) is coherent with the rainfall values in
190 the period January-April, with a maximum in February (~ 130; Fig. 3a). For the remaining dry (May
191 to September) and wet (October to December) months the number of rock failures decreases and
192 becomes almost flat (below 50). This behaviour suggests the presence of triggering mechanisms other
193 than the rainfall. For the TEN test site, the number of rockfalls per month (Fig. 3b) is similar to the
194 rainfall distribution, confirming anyway the presence of one or more additional triggers as evidenced
195 by the abundance of failures between May and September (Fig. 3d) when the rainfall is irrelevant.

196 **3.3 Empirical rainfall thresholds**

197 Empirical *ED* thresholds are represented by the following power law curve:

$$198 \quad E = (\alpha \pm \Delta\alpha) \times D^{(\gamma \pm \Delta\gamma)} \quad (1)$$

199 where *E* is the cumulated event rainfall (in mm), *D* is the duration of the rainfall event (in hours or in
200 days), α and γ are the intercept and the slope of the curve, respectively, and $\Delta\alpha$ and $\Delta\gamma$ are the
201 uncertainties associated with them. Thresholds at different non-exceedance probabilities are
202 calculated adopting the frequentist approach and the bootstrap nonparametric statistical technique
203 (Brunetti et al., 2010; Peruccacci et al., 2012), using 5000 randomly selected synthetic series of *DE*
204 pairs. A threshold at 5% non-exceedance probability should leave 5% of the empirical *DE* pairs below
205 itself. The parameter uncertainties depend mostly on the number and the distribution of the rainfall
206 conditions. The minimum number of *DE* pairs needed for having stable mean values of the parameters
207 α and γ (i.e. reliable thresholds) depends on the distribution and dispersion of the empirical data points
208 in the *DE* domain.

209 **3.4 The CTRL-T algorithm for threshold calculation**

210 The quantitative identification of the rainfall responsible for slope failures and the definition of
211 reliable thresholds are fundamental steps towards a well-founded event prediction (Peruccacci et al.,
212 2017; Melillo et al., 2018). The use of standardized procedures for the reconstruction of the rainfall
213 conditions able to trigger past failures and for the definition of thresholds is necessary for enhancing

214 the objectivity and reproducibility of the curves. The tool named CTRL-T (Calculation of Thresholds
215 for Rainfall-induced Landslides - Tool) proposed by Melillo et al. (2018) is exploited to calculate ED
216 thresholds for the two test sites. CTRL-T reconstructs rainfall events starting from continuous rainfall
217 series. For each rockfall, the algorithm: 1) identifies automatically the representative rain gauge; 2)
218 identifies multiple (D,E) rainfall conditions responsible for the failure; 3) selects among them the
219 maximum probability rainfall conditions (MPRCs). Then, analysing the distribution of the MPRCs it
220 calculates probabilistic rainfall thresholds at different non-exceeding probabilities and their
221 associated uncertainties. In order to avoid using wrong temporal information (i.e., incorrect dates for
222 the occurrence of rockfalls) in the definition of the thresholds, the rainfall conditions having a delay
223 longer than 48 hours between the rainfall ending time and the rockfall occurrence are discarded.

224 Using CTRL-T, 82 rockfalls occurred between 2012 and 2016 in GC test site and 626 rockfalls
225 occurred between 2010 and 2016 in the TEN test site are selected (light green dots in Fig. 1). The
226 remaining records are discarded due to the: 1) absence of rainfall data in the period including the
227 collapse occurrence time; 2) absence of rain gauges within a buffer of 15 km radius centred on the
228 rockfall; 3) lack of an evident correlation with the rainfall. The definition of rainfall thresholds relies
229 only upon rainfall conditions that triggered the first failure in each event. As a consequence, numerous
230 rockfalls (106, 39% in GC and 271, 30% in TEN) which occurred at the same date and in the same
231 location, and which are associated with the same rainfall event are discarded. In GC among the
232 remaining rockfalls 53 are analysed with daily and 29 with hourly rainfall data, respectively. The low
233 number of rock failures associated to hourly-based rain gauges is to be ascribed to the low density of
234 the sensors in the area, **and precludes the definition of rainfall thresholds**. In TEN 245 rockfalls are
235 reconstructed with hourly data and 381 with daily rainfall data. Note that for 83 failures it was possible
236 reconstructing the rainfall conditions using sensors from both the two rain gauge networks. As a
237 consequence, the reconstructed (D,E) rainfall conditions have different temporal resolutions and are
238 used to define both hourly-based and daily-based rainfall thresholds.

239 **4 Results**

240 A correlation between the rainfall and the observed failures is confirmed by the comparison between
241 the monthly rainfall and the corresponding number of rockfalls both in GC and in TEN (Fig. 4).
242 Figures 4a,b,c show the boxplots of cumulated monthly rainfall based on the data recorded in rain
243 gauges used to reconstruct the rainfall responsible for rockfalls for GC and TEN test sites. Inspection
244 of these figures reveals that the rainfall pattern in the two test sites is typically Mediterranean, with a
245 maximum in winter (but also in October and November) and a minimum in summer, with practically

246 no rain in the warmest months. Analysing data from seven daily-based rain gauges in GC (GC-d), it
247 turns out that the rainiest months are February and November with an average rainfall of 52.2 mm
248 and 55.7 mm, a highest rainfall of 98.6 mm and 133.9 mm, and a median rainfall of 42.3 mm and
249 39.8 mm, respectively (Fig. 4a). A similar trend is found for Tenerife using both daily and hourly
250 data. Data from 40 daily-based rain gauges in TEN (TEN-d) are analysed finding an average rainfall
251 of 64.6 mm and 86.4 mm, a highest rainfall of 183.5 mm and 183.6 mm, and a median rainfall of 56.1
252 mm and 93.2 mm for February and November, respectively (Fig. 4b). Data from 21 hourly-based rain
253 gauges in TEN (TEN-h) are analysed finding an average rainfall of 88.8 mm and 82.0 mm, a highest
254 rainfall of 169.8 mm and 190.8 mm, and a median rainfall of 97.5 mm and 66.4 mm for February and
255 November, respectively (Fig. 4c).

256 Figures 4d,e,f portray the monthly number of rockfalls associated with rainfall events for GC-d, TEN-
257 d and TEN-h. The GC catalogue lists 53 collapses occurred in the period from November 2012 to
258 October 2016, with the majority of the failures in 2015 (22). The month with the largest number of
259 rockfalls (14) is February, followed by January (8) and November (7). The least number of failures
260 is reported in September (1) and no rainfall-induced rockfalls are reported in May and July (Fig. 4d).
261 The 245 rock failures in the TEN-d catalogue cover the period from September 2010 to February
262 2016, with the majority of records in 2014 (66). The month with the largest number of rockfalls (80)
263 is November, followed by October (37) and December (36). The least number of failures is reported
264 in May (1) and no rainfall-induced rockfalls are reported in June and July (Fig. 4e). The TEN-h
265 catalogue lists 381 rockfalls occurred in the period from September 2010 to November 2016, with
266 the majority of the failures in 2014 (90). The month with the largest number of rockfalls (115) is
267 November, followed by December (72) and October (64). The least number of failures is reported in
268 May (1) and no collapses are reported in July (Fig. 4f).

269 The rainfall that triggered the rockfalls is classified according to the method proposed by Alpert et al.
270 (2002), based on six daily rainfall (E_d) categories from “light” to “torrential” over the Mediterranean
271 (Table 2). Using the procedure adopted by Melillo et al. (2016), each rainfall condition responsible
272 for rock failures (MPRC) is attributed to a specific category. In particular, for events lasting less than
273 24 hours, a category based on the total cumulated rainfall of the event is assigned. For events lasting
274 more than 24 hours, the maximum value of the cumulated rainfall in 24 hours in a moving window is
275 used. In GC, over 40% of the MPRCs responsible for the collapses are classified as moderate-high
276 (MH); in TEN, approximately 30% as high (H) and high-torrential (HT). No MPRCs are found in the
277 lowest Alpert’s category (light, Table 2). Figures 4g,h,i show the cumulated percentage of rainfall
278 events per month grouped according to Alpert’s classification. In GC-d, in February (Fig. 4g) 6

279 rockfalls (43%) are triggered by a rainfall classified as H, 3 (21%) as torrential (H), 3 (22%) as MH,
 280 and 1 as light-moderate (LM) and HT each (14%). In TEN-d, in November, 29 rockfalls (36%) are
 281 triggered by a rainfall classified as HT, 26 (33%) as MH, 22 (28%) as H, 2 (2%) as LM, and 1 (1%)
 282 as T (Fig. 4h). In TEN-h, in November, 5 (4%), 26 (23%), 26 (23%), 31 (27%) and 27 (23%) rockfall
 283 are triggered by a rainfall classified as LM, MH, H, HT and T, respectively (Fig. 4i).

284 Using the catalogues of rainfall events with rockfalls described above and the CTRL-T tool, *ED*
 285 thresholds, and their associated uncertainties are calculated for GC and TEN test sites. Table 3 lists
 286 the number of MPRC used to define the thresholds, the equations of the power law curves, and the
 287 range of validity for the thresholds, expressed in hours or days. Note that *D* must be expressed in days
 288 in the equations for the thresholds calculated with daily data, and in hours in the equations for the
 289 thresholds calculated with hourly data (Gariano et al., 2020).

290 Figure 5a shows, in logarithmic coordinates, the distribution of the (*D,E*) rainfall conditions,
 291 reconstructed with daily data, that have caused rockfalls in GC (53 blue dots) and in TEN (245 green
 292 dots). In particular, the 53 daily rainfall conditions responsible for the rockfalls in GC have durations
 293 in the range $1 \leq D \leq 11$ days (with an average value of 2 days) and cumulated rainfall in the range
 294 $16.5 \leq E \leq 219.9$ mm (average value 51.6 mm). All the conditions were recorded in rain gauges
 295 located at a maximum distance of 5.7 km from the failures, with a mean value of 2.8 km. The 245
 296 daily-based rainfall conditions associated with the collapses in TEN have durations ranging from one
 297 to 15 days, with a mean value of two days. The cumulated rainfall ranges from 15.4 to 235.0 mm,
 298 with an average of 71.5 mm. The average distance between the rockfalls and their representative rain
 299 gauges is 2.2 km, with a maximum distance of 5 km. Figure 5a portrays also the 5% *ED* thresholds
 300 for GC ($T_{5,GC-d}$, blue curve) and TEN ($T_{5,TEN-d}$, green curve). The shaded areas around the threshold
 301 lines show the uncertainty regions associated to the thresholds (Table 3). Figure 5b portrays the same
 302 $T_{5,GC-d}$ and $T_{5,TEN-d}$, in linear coordinates, in the range $1 \leq D \leq 7$ days.

303 Figure 5c shows, in logarithmic coordinates, the distribution of the (*D,E*) rainfall conditions,
 304 reconstructed with hourly data, that have triggered rock failures in TEN (381 purple dots). The hourly
 305 rainfall conditions associated to rockfalls have durations ranging from 2 to 712 hours and mean value
 306 of 111 hours. The cumulated rainfall ranges from 10.6 to 433.9 mm, with an average of 105.6 mm.
 307 The average distance between the rockfalls and the representative rain gauges is 6.7 km, with a
 308 maximum distance of 14.9 km. In the log-log plot the purple curve is the 5% threshold for TEN
 309 ($T_{5,TEN-h}$) obtained with hourly data. Figure 5d portrays the same $T_{5,TEN-h}$, in linear coordinates, in the

310 range $1 \leq D \leq 120$ hours. The uncertainty associated with the threshold (purple shaded area in Figs.
311 5c,d) is also shown.

312 The difference between the $T_{5,GC-d}$ and $T_{5,TEN-d}$ thresholds can be ascribed to the different MAR in the
313 two test sites. Figure 6 portrays the maps of the MAR and of its coefficient of variation, which is the
314 percentual variability (standard deviation) of the MAR in the considered time interval. The
315 geographical distribution of the MAR values exhibits the highest values in the northern parts of both
316 islands, where it overcomes 800 mm (Fig. 6a). On the contrary, the highest values of the coefficient
317 of variation (i.e. an index of the MAR variability) are localized in the southern part of the islands,
318 where the rain gauge density is lower (Fig. 6b).

319 **5 Discussion and conclusions**

320 In Canary Island rainfall is the most important triggering factor for rockfalls (Fig. 3). Nevertheless,
321 there are other factors that predispose directly or indirectly the trigger of the failure (Temiño et al.,
322 2013a). Factors that greatly accentuate this hazard in the two test sites are wind, geomorphological
323 characteristics (e.g., slope, aspect), type of soil and seismic activity. Regarding the wind many
324 collapses are caused by strong gusts of wind that affect the northern side of Tenerife Island and the
325 road GC-200 from Agaete to Aldea in Gran Canaria. (Temiño et al., 2013b). Regarding the
326 geomorphology, the existence of many sections of road running through the old basaltic massifs with
327 significant sub-vertical jointing, makes the area very susceptible to rock failures. In addition, the
328 action of the trade winds on the higher altitude areas, produces an increase in the relative humidity,
329 as large masses of water vapor are retained by steep slopes resulting in an intense weathering (and
330 weakening) of the rock masses. Finally, the large flank instability of the two test sites (especially in
331 the northwest sector of the Gran Canaria island) could be related to structural control and to seismic
332 activity connected to the dynamic geologic condition that characterizes them. (Masson et al., 2002;
333 Temiño et al. 2013b; Urgeles et al., 2001).

334 By selecting the subset of rockfalls triggered by rainfall it can be observed that their monthly
335 frequency is linked to the monthly distribution of the rainfall measured in nearby rain gauges (Figs.
336 4a-f). For GC-d (Figs. 4a,d) the correlation is apparently weaker in fall than in winter, but this could
337 be ascribed to a statistical fluctuation and should be confirmed by increasing the number of events.
338 Conversely, for TEN-d (Figs. 4b,e) the monthly number of rock failures well reflects the monthly
339 rainfall amount, suggesting that rainfall is the only triggering cause. Hourly rainfall data in TEN-h

340 (Figs. 4c,f) confirm partially this outcome, since even with a median lower amount of rainfall, a
341 higher number of rock failures is expected to occur from October to December than in February.

342 The number of rockfalls for which it has been possible to reconstruct the rainfall conditions (MPRCs)
343 using daily and hourly data in the TEN test site (Figs. 4e,f) is different. This is mostly due to the worst
344 temporal resolution of the TEN-d dataset.

345 In the two test sites, the majority of the rainfall responsible for rockfalls belongs to the Alpert's MH
346 category (Figs. 4g,i). In TEN-h, 31 events belong to the most severe category T, whereas in TEN-d
347 only one event is found in the T category. This result could be ascribed to the time step of the moving
348 window used to assign the Alpert's category. For a rainfall event lasting more than one day, the
349 Alpert's category varies depending on the data temporal resolution, since the time step is one hour or
350 one day for the hourly and daily data, respectively. In TEN-d, the total amount of rainfall responsible
351 for the failure is shared in two or more consecutive days, causing a lowering of the Alpert's category,
352 as confirmed by the paucity of T events in TEN-d.

353 Figure 5 shows that $T_{5,TEN-d}$ is higher and steeper than $T_{5,GC-d}$. This means that, at increasing values
354 of D , a smaller amount of rainfall (E) is necessary to trigger the collapses in GC than in TEN.
355 Comparing Figures 1 and 5, the recorded rockfalls in the TEN test site are localized in areas including
356 several classes of MAR (ranging from 100 to 800 mm), while in GC test site they fall in the area
357 characterized by the lowest class of MAR (≤ 100 mm). The different ranges of MAR values in the
358 two test sites are able to explain the observed differences in the two daily ED thresholds (Fig. 5a).
359 This finding confirms that where the MAR is higher, the minimum rainfall conditions able to trigger
360 a failure, specifically a rockfall, are also higher.

361 Moreover, the threshold defined for the TEN test site has an uncertainty smaller than the threshold
362 for GC test site. Peruccacci et al. (2012) observed that the parameter uncertainty reduces as the
363 number of MPRC used to calculate the threshold increases. In particular, as derived from Table 3, the
364 relative uncertainty of the intercept, $\Delta\alpha/\alpha$ is 9.8% for $T_{5,GC-d}$ and 4.9% for $T_{5,TEN-d}$. Regarding the
365 slope of the curves, $\Delta\gamma/\gamma$ is 16.1% for $T_{5,GC-d}$ and 6.7% for $T_{5,TEN-d}$. Given the lower uncertainty range
366 and relative uncertainties of both parameters, $T_{5,TEN-d}$ has a reliability higher than that of $T_{5,GC-d}$. The
367 same analysis for the $T_{5,TEN-h}$ threshold gives $\Delta\alpha/\alpha = 9.3\%$ and $\Delta\gamma/\gamma = 4.2$. Thresholds with an hourly
368 temporal resolution and having relative uncertainties of the parameters α and γ lower than 10% could
369 be implemented in an operative system for the prediction of rainfall-induced failures (Peruccacci et
370 al., 2012; 2017). The thresholds for different non-exceedance probabilities obtained for TEN test site

371 using hourly rainfall data are suited for the design of probabilistic schemes for the operative prediction
372 of rainfall-induced rockfalls. An improvement in the number of rain gauges providing hourly
373 measurements, as well as in the number of recorded rock failures, would be necessary in GC test site
374 in order to reduce the uncertainty of the threshold.

375 Currently, neither prototype nor operative early warning systems for rainfall-induced failures are
376 present in the Canary Islands (Guzzetti et al. 2020). The findings of this work can contribute to the
377 understanding of the rainfall conditions that can trigger rainfall-induced rockfalls in Tenerife and in
378 the western part of Gran Canaria, and their relationship with mean annual rainfall regime. These
379 findings have scientific and social implications given that in both test sites also spring and autumn
380 are characterized by a moderately occurrence of rock failures, with relevant impacts on the
381 population, tourism activities, and local economy. As long as a sufficient amount of empirical data
382 will be available in both test sites (and also in other islands of the archipelago), the method adopted
383 in this work for the definition of reliable rainfall thresholds can be replicated, and the results can be
384 implemented in a prototype early warning system.

385 **6 Code availability**

386 The code of CTRL-T was written using the R open-source software and can be freely downloaded at:
387 [http://geomorphology.irpi.cnr.it/tools/rainfall-events-and-landslides-thresholds/ctrl-t-algorithm/ctrl-](http://geomorphology.irpi.cnr.it/tools/rainfall-events-and-landslides-thresholds/ctrl-t-algorithm/ctrl-code/ctrl_t_code.r/view)
388 [code/ctrl_t_code.r/view](http://geomorphology.irpi.cnr.it/tools/rainfall-events-and-landslides-thresholds/ctrl-t-algorithm/ctrl_t_code.r/view). An example of the input files required by the algorithm can be freely
389 downloaded at: [http://geomorphology.irpi.cnr.it/tools/rainfall-events-and-landslides-thresholds/ctrl-](http://geomorphology.irpi.cnr.it/tools/rainfall-events-and-landslides-thresholds/ctrl-t-algorithm/input-demo/INPUT.zip/view)
390 [t-algorithm/input-demo/INPUT.zip/view](http://geomorphology.irpi.cnr.it/tools/rainfall-events-and-landslides-thresholds/ctrl-t-algorithm/input-demo/INPUT.zip/view).

391 **7 Author contribution**

392 All authors designed the experiment and carried it out. M.M., S.P. and M.T.B. developed the model
393 code, R.S. and R.M.M. provided the data, and M.M. and S.L.G. performed the simulations. All
394 authors analyzed the results and prepared the manuscript.

395 **8 Competing interests**

396 The authors declare that they have no conflict of interest.

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404 Islands Government.

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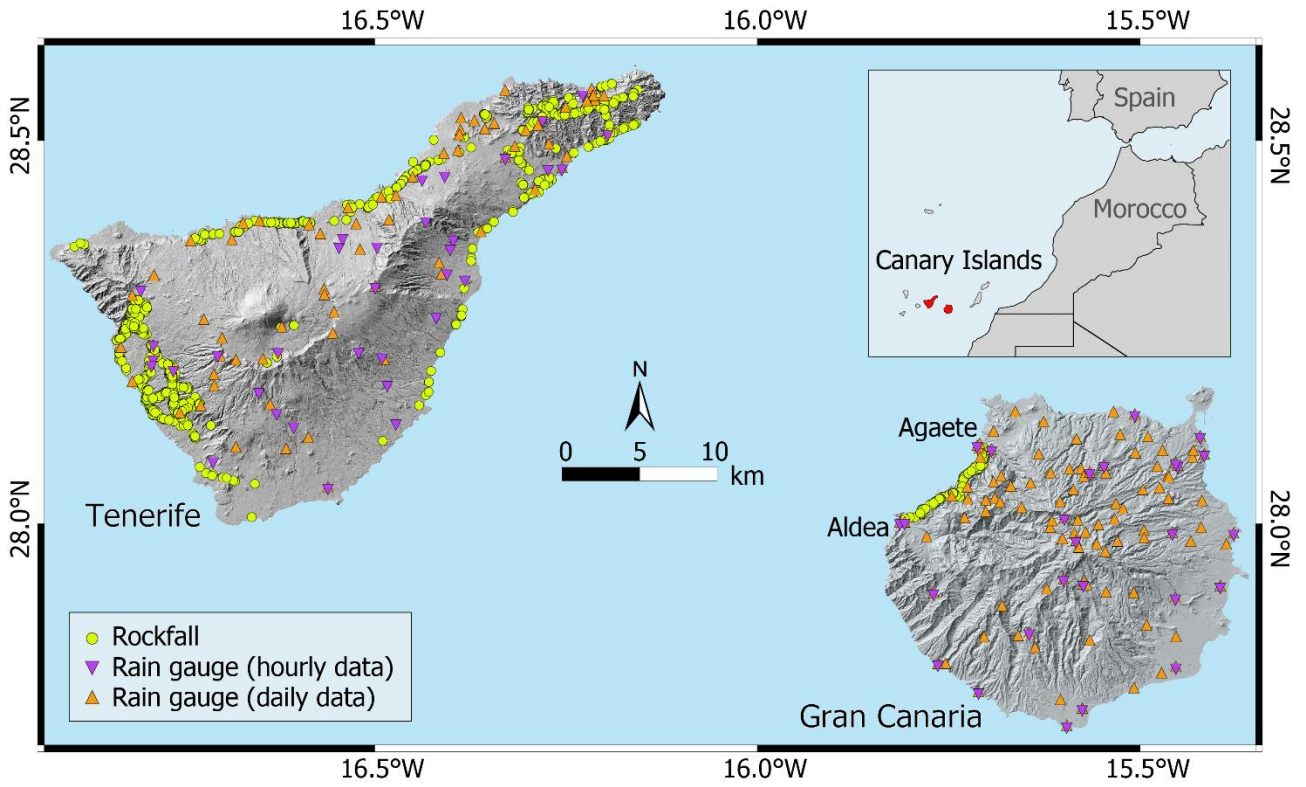
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522

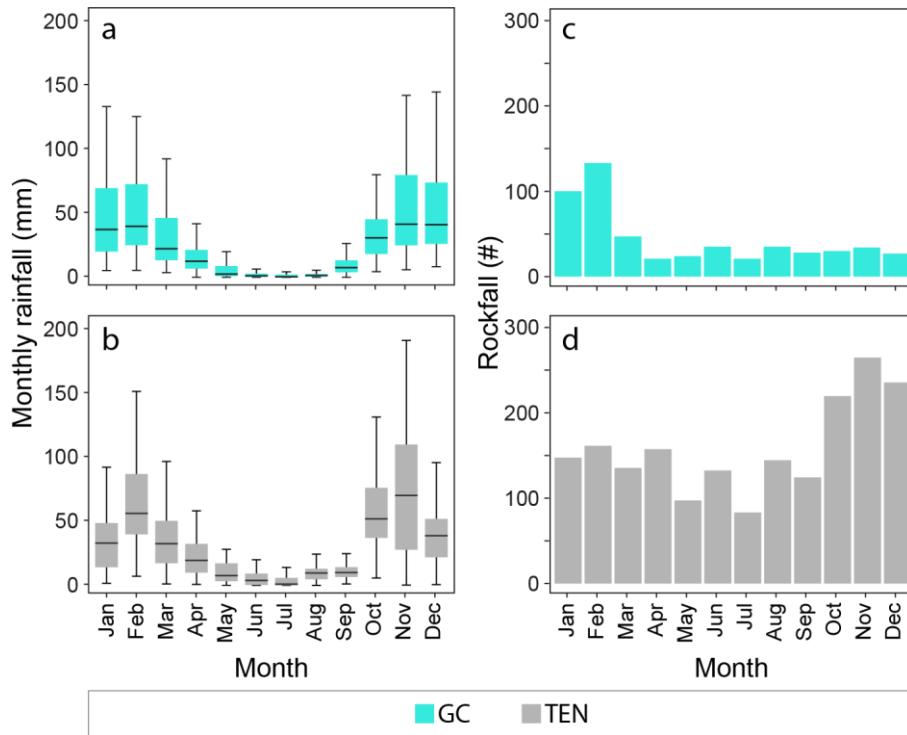
523 Figure 1. GC and TEN test sites. Location of the rain gauges providing hourly (purple triangles) and daily
524 (orange triangles) rainfall measurements, and of rockfalls used for threshold calculations (light green dots).
525 Hillshade derived from MDT05 2009 CC-BY 4.0 scene.es.



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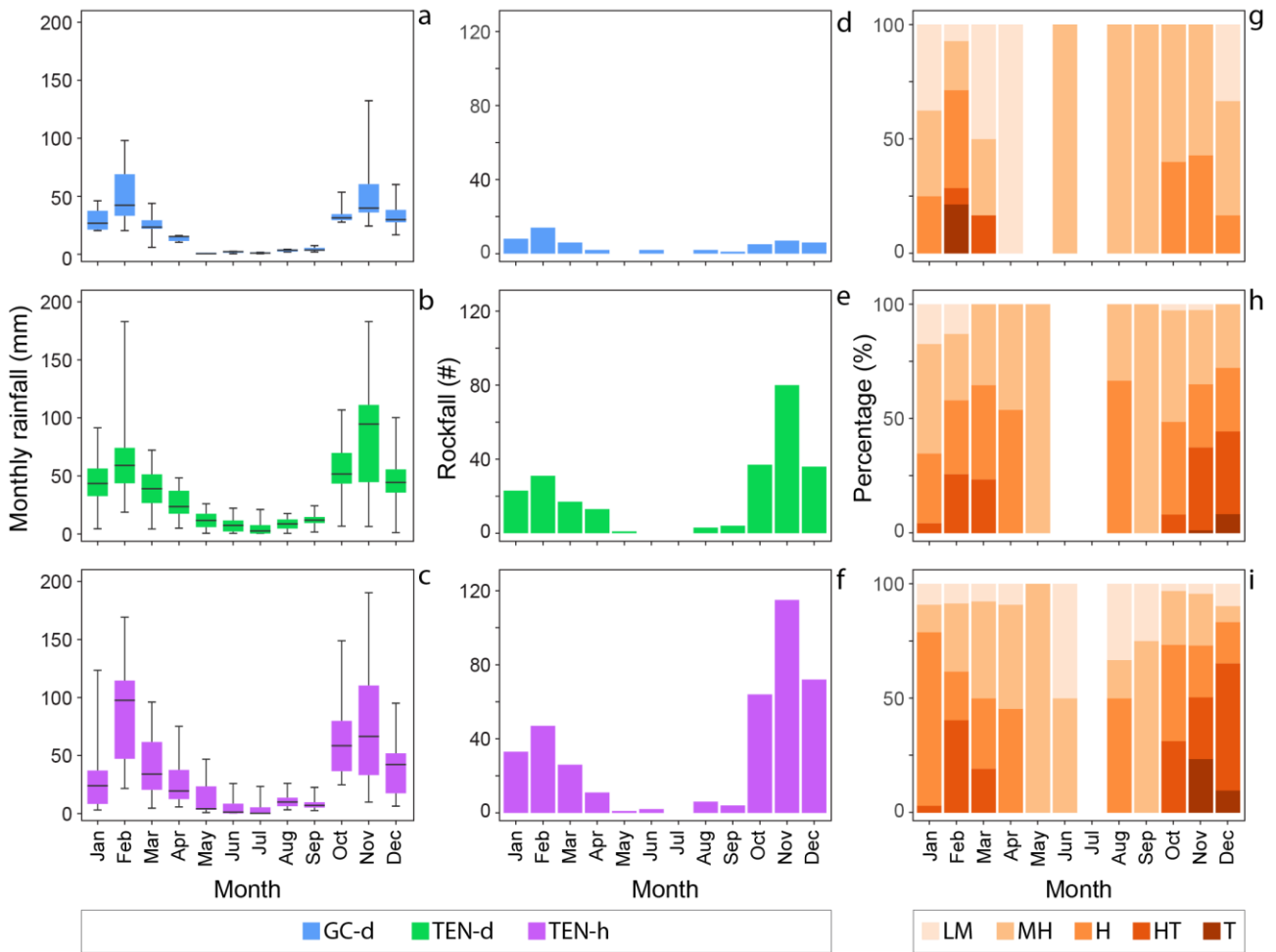
527 **Figure 2. Photos of rockfalls in GC (a) and TEN (b) test sites (credits R.M. Mateos and S. Leyva Campos).**

528



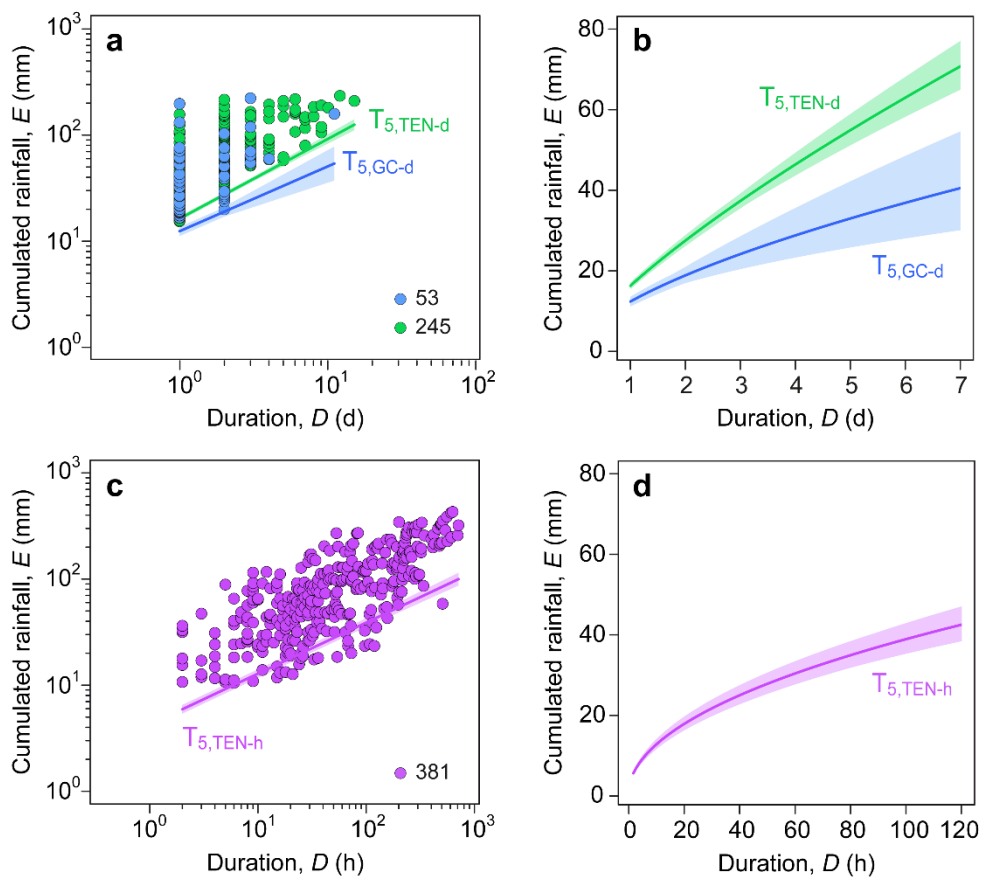
529

530 Figure 3. Comparison between monthly rainfall and rockfall occurrence. (a, b) Annual variation of monthly
 531 rainfall measures in GC (cyan) and TEN (grey). The whiskers show 1.5 times the interquartile range. (c, d)
 532 Number of rockfalls per month in the two test sites.



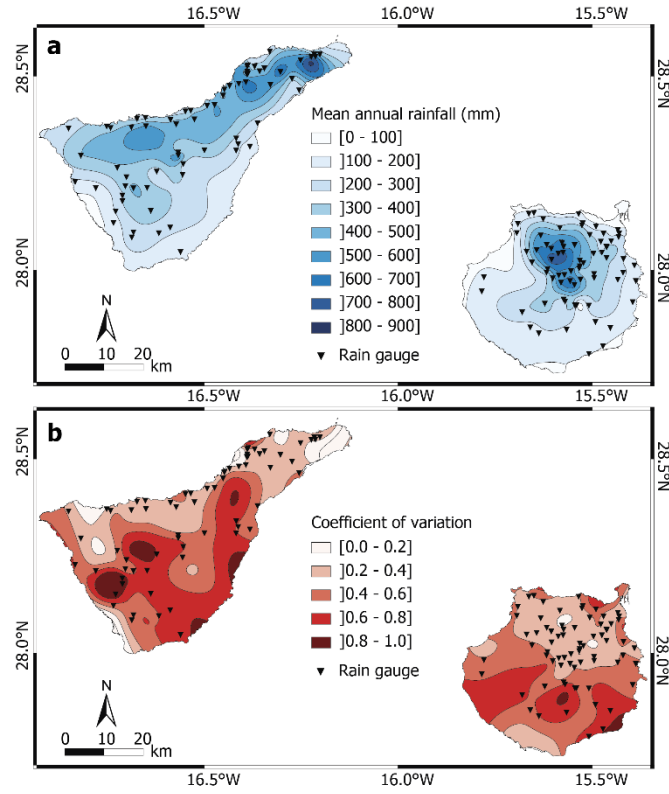
533

534 Figure 4. Comparison between monthly rainfall and rainfall-induced rockfalls and Alpert classification. (a, b,
 535 c) Annual variation of monthly rainfall measures in the test sites. Legend: GC-d, daily rainfall data in GC test
 536 site; TEN-d, daily rainfall data in the TEN test site; TEN-h, hourly rainfall data in TEN test site. (d, e, f)
 537 Number of rainfall-induced rockfalls per month. (g, h, i) Cumulated percentage of rainfall events per month
 538 classified according to Alpert et al. (2002). Legend: LM, light-moderate ($4 < E_d \leq 16$ mm); MH, moderate-
 539 heavy ($16 < E_d \leq 32$ mm); H, heavy ($32 < E_d \leq 64$ mm); HT, heavy-torrential ($64 < E_d \leq 128$ mm); T, torrential
 540 ($E_d > 128$ mm).



541

542 Figure 5. Rainfall thresholds for the possible rockfall occurrence in the two test sites. (a) Rainfall duration D
 543 (x-axis, in days) and cumulated event rainfall E (y-axis, in mm) conditions that have produced rockfalls in GC
 544 (53 blue dots) and TEN (245 green dots) test sites, respectively. Green and blue curves are the 5% power law
 545 thresholds ($T_{5,TEN-d}$, $T_{5,GC-d}$). (b) 5% daily ED thresholds for GC and TEN in linear coordinates, in the range of
 546 durations $1 \leq D \leq 7$ days. (c) Rainfall duration D (x-axis, in hours) and cumulated event rainfall E (y-axis, in
 547 mm) conditions that have produced rockfalls in TEN (381 purple dots) test site. Purple curve is the 5% power
 548 law threshold ($T_{5,TEN-h}$). (d) 5% hourly ED thresholds for GC and TEN in linear coordinates, in the range of
 549 durations $1 \leq D \leq 120$ hours.



550

551 Figure 6. Maps of (a) mean annual rainfall and (b) of its coefficient of variation. The rain gauges used for these
552 analysis (cf. Table 1) are also shown.

553 Table 1. Summary of the three available rain gauge networks (CIAGC, AEMET, SIAR) in the two test sites
 554 (GC and TEN) i.e., network name, network operating time period, temporal resolution, test site, number of
 555 used rain gauges, their average operating time, and the use of data.

Network	Period	Temporal resolution	Test site	Rain gauges (#)	Average operating time (year)	Data application
CIAGC	Jan 2010 - Dec 2017	daily	GC	13	8.0	Thresholds
	Jan 1951 - May 2019			92	41.8	
AEMET	Oct 1997 - May 2019	hourly	GC	25	16.5	
	Jan 2010 - Mar 2018		TEN	34	5.5	
	Jan 2010 - May 2018	daily	TEN	66	8.2	
	Jan 2000 - Dec 2019	yearly	GC	67	15.2	
TEN			58	13.8		
SIAR	Jan 1999 - Dec 2019	monthly	GC	5	18.2	MAR
			TEN	9	15.1	

556

557 Table 2. Summary of the number (#) and percentage (%) of MPRC in the categories proposed by Alpert et al.
 558 (2002), in the two test sites.

Category	E_d (mm)	GC-d		TEN-d		TEN-h	
		#	%	#	%	#	%
Light (L)	$E_d \leq 4$	0	0	0	0	0	0
Light-moderate (LM)	$4 < E_d \leq 16$	11	20.7	11	4.5	28	7.3
Moderate-heavy (MH)	$16 < E_d \leq 32$	23	43.4	92	37.5	86	22.6
Heavy (H)	$32 < E_d \leq 64$	14	26.4	80	32.7	117	30.7
Heavy-torrential (HT)	$64 < E_d \leq 128$	2	3.8	58	23.7	116	30.5
Torrential (T)	$E_d > 128$	3	5.7	4	1.6	34	8.9

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561 Table 3. *ED* rainfall thresholds at different non-exceedance probabilities (1%, 5%, 10%, 20%, 35% and 50%)
 562 for the GC and TEN test sites. The number of MPRC and the duration range of each threshold are also reported.

Threshold name	Number of MPRC	Threshold equation	Duration range
T _{1,GC-d}	53	$E = (8.3 \pm 1.0) \times D^{(0.62 \pm 0.10)}$	1-11 days
T _{5,GC-d}		$E = (12.3 \pm 1.2) \times D^{(0.62 \pm 0.10)}$	
T _{10,GC-d}		$E = (15.1 \pm 1.4) \times D^{(0.62 \pm 0.10)}$	
T _{20,GC-d}		$E = (19.5 \pm 1.8) \times D^{(0.62 \pm 0.10)}$	
T _{35,GC-d}		$E = (25.5 \pm 2.5) \times D^{(0.62 \pm 0.10)}$	
T _{50,GC-d}		$E = (31.9 \pm 3.6) \times D^{(0.62 \pm 0.10)}$	
T _{1,TEN-d}	245	$E = (11.6 \pm 0.6) \times D^{(0.75 \pm 0.05)}$	1-15 days
T _{5,TEN-d}		$E = (16.3 \pm 0.8) \times D^{(0.75 \pm 0.05)}$	
T _{10,TEN-d}		$E = (19.6 \pm 0.8) \times D^{(0.75 \pm 0.05)}$	
T _{20,TEN-d}		$E = (24.4 \pm 1.0) \times D^{(0.75 \pm 0.05)}$	
T _{35,TEN-d}		$E = (30.6 \pm 1.4) \times D^{(0.75 \pm 0.05)}$	
T _{50,TEN-d}		$E = (37.1 \pm 1.8) \times D^{(0.75 \pm 0.05)}$	
T _{1,TEN-h}	381	$E = (2.8 \pm 0.3) \times D^{(0.48 \pm 0.02)}$	2-712 hours
T _{5,TEN-h}		$E = (4.3 \pm 0.4) \times D^{(0.48 \pm 0.02)}$	
T _{10,TEN-h}		$E = (5.3 \pm 0.5) \times D^{(0.48 \pm 0.02)}$	
T _{20,TEN-h}		$E = (6.9 \pm 0.6) \times D^{(0.48 \pm 0.02)}$	
T _{35,TEN-h}		$E = (9.1 \pm 0.7) \times D^{(0.48 \pm 0.02)}$	
T _{50,TEN-h}		$E = (11.4 \pm 1.0) \times D^{(0.48 \pm 0.02)}$	

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