

# Statistical correlation between meteorological and rockfall databases

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## **Abstract**

Rockfalls are major and essentially unpredictable sources of danger, particularly along transportation routes (roads and railways). Thus, the assessment of their probability of occurrence is a major challenge for risk management. From a qualitative perspective, it is known that rockfalls occur mainly during periods of rain, snowmelt, or freeze-thaw. Nevertheless, from a quantitative perspective, these generally assumed correlations between rockfalls and their possible meteorological triggering events are often difficult to identify because i) rockfalls are too rare for the use of classical statistical analysis techniques and ii) all intensities of triggering factors do not have the same probability. In this study, we propose a new approach to investigate the correlation of rockfalls with rain, freezing periods, and strong temperature variations. This approach is tested on three French rockfall databases, the first of which exhibits a high frequency of rockfalls (approximately 950 events over 11 years), whereas the other two databases are more typical (approximately 140 events over 11 years). These databases come from (1) the national highway RN1 on La Réunion Island, (2) a railway in the Bourgogne region, and (3) a railway in the Auvergne region. Whereas a basic correlation analysis is only able to highlight an already obvious correlation in the case of the “rich” database, the newly suggested method appears to detect correlations even in “poor” databases. Indeed, the use of this method confirms the positive correlation between rainfalls and rockfalls in the La Réunion database. This method highlights a correlation between cumulative rainfalls and rockfalls in the Bourgogne region, and it detects a correlation between the daily minimum temperature and rockfalls in the Auvergne database. This new approach is easy to use and also serves to determine the conditional probability of rockfall according to a given meteorological factor. The approach will help to optimize risk management in the studied areas based on their meteorological conditions.

Keywords: Rockfall; Hazard assessment; Database; Triggering factor

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# 1 1 Introduction

2 Rockfall hazard is defined as the probability that a rockfall of a given volume occurs in a  
3 given area within a specified time interval (Varnes, 1984). This definition considers three  
4 different components of hazard: space, time (rockfall frequency), and the intensity (volume)  
5 of the event. Numerous studies on hazard mapping (*e.g.*, Baillifard *et al.*, 2003; Jaboyedoff *et*  
6 *al.*, 2005) and rockfall frequency (*e.g.*, Brunetti *et al.*, 2009; Dussauge *et al.*, 2003) are  
7 available in the literature, but little work has been conducted to quantify the influence of  
8 meteorological factors on rockfall frequency.

9 Temporal probability can be estimated through the study of triggering factors, which are  
10 external causes that are principally climatic in origin. These factors, which appear only at  
11 discrete times, induce changes in the forces acting on rock blocks (Hoek, 2007) and cause the  
12 blocks to fall. The most common triggering factors are intense rainfall episodes (André, 1997;  
13 Berti *et al.*, 2012; Ilinca, 2008; Rapp, 1960), the freeze and thaw of water-filled fractures  
14 (Ilinca, 2008; Matsuoka and Sakai, 1999), and repeated rock surface temperature variations  
15 (Frayssines and Hantz, 2006; Gunzburger *et al.*, 2005; Luckman, 1976). Furthermore, seismic  
16 activity has been shown to influence rockfall events (Bull *et al.*, 1994; Vidrih *et al.*, 2001;  
17 Zellmer, 1987).

18 Rockfall inventories can be used to quantify the statistical correlation between rockfall events  
19 and their triggering factors (Chau *et al.*, 2003; Helmstetter and Garambois, 2010). However, it  
20 is generally difficult to identify such a correlation because: i) rockfalls are too rare for the use  
21 of classical statistical analysis techniques and ii) all intensities of triggering factors do not  
22 have the same probability. More precisely, as the occurrence or action of a triggering factor  
23 does not necessarily result in a rockfall, it is necessary to distinguish the rockfall probability  
24 itself from the frequency of its potential triggering factors.

25 In this paper, we present a new approach to investigate the correlation of rockfalls with rain,  
26 freezing periods, and strong temperature variations. This approach is tested on three French  
27 rockfall databases, the first of which exhibits a high rockfall frequency (approximately 950  
28 events over 11 years). The two other databases contain approximately 140 events over 11  
29 years. The three databases came from the following sources: (1) national highway RN1 on La  
30 Réunion Island (Indian Ocean), (2) a railway in the Bourgogne region, and (3) a railway in the  
31 Auvergne region, France (Figure 1 and Table 1). The spatial location and intensity of the  
32 events are not studied in this paper; only the number of rockfalls during the period of

1 monitoring is considered. However, the volume range and the mean height of the source rock  
2 walls are given for each sector (cf. Part 2).

3 The classical time series approach (Helmstetter and Garambois, 2010) is able to highlight an  
4 already obvious correlation only in the case of the “rich” database. The newly suggested  
5 method also appears to detect correlations in the “poor” databases. This approach will help to  
6 optimize risk management in the areas considered in terms of the meteorological conditions.

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## 1 **2 Rockfall databases**

2 There is a significant difference between the three databases: for La Réunion Island, 13% of  
3 the days have at least one rockfall (529 days out of 4,008 days in the entire database),  
4 compared with 3% for the Auvergne and Bourgogne databases. The high frequency of events  
5 makes the first database particularly unique. Rockfall databases typically have an event  
6 frequency of approximately 3% (Hungry et al., 1999; Jeannin, 2001; RTM Isère, 1996;  
7 Wieczorek et al., 1992).

8 The daily rockfall hazard, which is the probability of a fall on each day, regardless of the  
9 meteorological factors, is similar to these frequencies under the assumption of spatial and  
10 temporal homogeneity.

11

### 12 **2.1 Highway RN1 on La Réunion Island**

13 National Road #1 (RN1) on La Réunion Island (Indian Ocean, latitude: 21°10 S, longitude:  
14 55°30 E) runs along the coast at the base of a 10-km long and up to 200-m high cliff  
15 composed of basaltic lava strata alternating with pyroclastic layers. This region has a tropical  
16 climate. In the studied area, the precipitation can reach 372 mm in one day, and temperatures  
17 typically vary from 16°C to 35°C over the year, with an average amplitude of 9.2°C in one  
18 day.

19 Daily rockfall data are available due to the regular patrols conducted by the local Public  
20 Works authorities (DDE). A total of 949 rockfalls were recorded within the 11-year span  
21 between 1998 and 2009. The volumes of the rockfalls range between  $2 \cdot 10^{-3}$  and  $27 \cdot 10^3 \text{ m}^3$ .  
22 Previous studies (Durville, 2004; Rat, 2006) that considered only a portion of the database  
23 (352 rockfalls recorded between 1998 and 2002) have shown that rockfalls are mainly  
24 correlated with intense rainfall episodes. We repeated this study with a more exhaustive  
25 database and also evaluated the influence of temperature on rockfalls.

### 26 **2.2 Railway in the Bourgogne region, France**

27 The altitude of the study area is between 300 and 400 m. It consists of limestone – marl  
28 alternations. Its climate is oceanic to semi-continental. The oceanic influence is responsible  
29 for frequent rainfall in any season, with a maximum in autumn (up to 89 mm daily). The

1 semi-continental influence produces cold winters (minimum temperature down to  $-20^{\circ}\text{C}$ ) and  
2 hot summers (maximum temperature up to  $36^{\circ}\text{C}$ ). The daily temperature amplitude may be up  
3 to  $24^{\circ}\text{C}$ .

4 Technicians from the French National Railway Company (SNCF), working on the railroads to  
5 ensure their safety, are in charge of the rockfall inventory. Daily data are available, and 135  
6 rockfalls were recorded within a 13-year span (1999-2012) along the 100 km of the studied  
7 railroad. The average height of the rock walls is 20 meters. The volumes of the rockfalls range  
8 between  $8.10^{-3}$  and  $80\text{ m}^3$ .

### 9 **2.3 Railway in the Auvergne region, France**

10 The altitude of the study area is between 700 and 900 m. It consists of volcanic (basalt) and  
11 plutonic (granite) magmatic rocks. Its climate is similar to that of the Bourgogne region. The  
12 rainfall can reach 125 mm in one day. Temperatures range between  $-18^{\circ}\text{C}$  and  $36^{\circ}\text{C}$ , with a  
13 daily temperature amplitude of up to  $23^{\circ}\text{C}$ .

14 The Auvergne database provides daily data based on a rockfall inventory maintained by  
15 technicians from SNCF. Overall, 40 km of railroads are included in this database, and the  
16 mean height of the cliffs is 15 meters. The database includes 142 rockfalls, which were  
17 recorded over an 11-year span (2001-2012). The volumes of the rockfalls range between  $2.10^{-$   
18  $3$  and  $6\text{ m}^3$ .

19  
20 The following analyses were conducted for the three study sites taken separately.  
21  
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### 1 3 Preliminary analysis using a classical time-series approach

#### 2 3.1 Possible triggering factors considered in this study

3 Possible triggering factors include the following:

- 4 -  $P_{Di}$ , the amount of precipitation (or rainfall) of the considered day ( $D_0$ ), or  $n$  days  
5 before ( $D_n$ ), with  $n$  varying from 1 to 10;
- 6 -  $P_{cN}$ , the amount of precipitation (or rainfall) accumulated over  $N$  days (up to 10  
7 days):  $P_{cN} = P_{D0} + P_{D1} + \dots + P_{DN}$ ;
- 8 - The day's temperature range, indicated by the minimum temperature ( $T_{min}$ ),  
9 maximum temperature ( $T_{max}$ ), and temperature amplitude ( $T_{amp} = T_{max} - T_{min}$ );
- 10 - The daily duration of freezing. This factor was considered only for the Bourgogne  
11 and Auvergne regions because the temperatures on La Reunion Island are never  
12 below 0°C.

13 These meteorological parameters were provided by Météo France (the French National  
14 Weather Service) for each sector on a daily basis. The weather stations selected for this  
15 purpose were located no more than 30 km away from the studied area. The stations used in  
16 the study of the highway on La Réunion Island have a mean altitude of 100 meters. Those  
17 used for the Bourgogne region have a mean altitude of 310 meters, and those used for the  
18 Auvergne region have a mean altitude of 700 meters.

#### 19 3.2 Results

20 First, a qualitative analysis of the three databases was performed. Figure 2 shows the visual  
21 correlation between the rockfalls and meteorological factors over a three-year period. The  
22 graphs were obtained by calculating a 30-day moving average to smooth the data and to focus  
23 on the trend. From a purely qualitative perspective, the graphs shed light on the following:

- 24 - A good correlation between rockfalls and rainfalls and between rockfalls and  
25 minimum temperatures for La Réunion Island;
- 26 - No noticeable correlation between rockfalls and meteorological factors in the  
27 Bourgogne region;
- 28 - A low correlation between rainfalls and rockfalls in the Auvergne region but no  
29 noticeable correlation between temperatures and rockfalls.

1 Table 2 presents the distribution of the total number of rockfalls per day as a function of the  
2 daily amount of rain for the three studied areas. The maximum frequency of rockfalls occurs  
3 for the lowest daily amount of rainfall. This rainfall interval is also the most frequent. Low  
4 levels of rain are more frequent than high levels. This difference in frequency tends to conceal  
5 the effect of rain on triggering rockfall events.

6 The cross-correlation between the daily number of rockfalls ( $R$ ) and the amount of  
7 precipitation ( $P$ ), both expressed as time series, was investigated by calculating

$$8 \quad C_k(R, P) = \frac{\sum(R_t - \bar{R})(P_{t-k} - \bar{P})}{\sqrt{\sum(R_t - \bar{R})^2} \sqrt{\sum(P_t - \bar{P})^2}}, \quad (1)$$

9 with  $k$  corresponding to the time delay between the rain episode and the rockfalls that it may  
10 have triggered (Hipel and McLeod, 2005).

11 Figure 3 presents the cross-correlation function of Eq. (1) for La Réunion Island by  
12 considering various delays. A maximum value of 0.563 is reached for a delay of one day; this  
13 value is statistically significant in terms of the significance threshold applied to the data. If the  
14 cross-correlations are larger than  $1.96/\sqrt{n}$  in magnitude, with  $n$  as the number of pairs of  
15 ( $R_t, P_t$ ) available (equal to the number of days in the databases), then they are deemed  
16 significant. Similar cross-correlation analyses were performed for the other two study sites  
17 and two meteorological parameters (the daily temperature and the daily freezing duration), but  
18 none of these yielded satisfactory results (maximum value of 0.07 with a significant threshold  
19 of 0.031).

### 20 **3.3 Limitations of the classical approach**

21 The preliminary analysis presented here only confirms the visual correlation between rainfalls  
22 and rockfalls for La Réunion Island. Although meteorological factors are frequently  
23 mentioned in the literature as an explanation of rockfalls, no other correlations were identified  
24 for the two other databases.

25 This lack of significant results can be explained by the nature of databases: using only 3% of  
26 the days in the database resulted in a relatively weak time series analysis. Furthermore, these  
27 days typically contain only one event (1% of days with rockfalls are days with several events  
28 in the railway databases). These characteristics lead to a smoothing of the results and do not  
29 permit us to draw any conclusions regarding the potential correlations.

- 1 Our proposed method does not consider the delay in time, only the influence of the intensity
- 2 of the parameters on rockfalls.



## 1 4 Suggested new methodology of analysis

### 2 4.1 Principle

3 The objective of the new methodology is to weight the number of rockfalls by the probability  
4 of occurrence of the studied triggering factor (rainfall, temperatures, and freezing period). To  
5 this end, three steps are required. These steps will now be detailed for the case of rainfall.

6 First, rainfall intervals  $[P_i, P_{i+1}]$  are defined, where  $P$  designates the daily or cumulated  
7 rainfall. These intervals are defined such that i) the number of days within this rainfall  
8 interval is equal or greater to five (to avoid non-statistically significant intervals) and ii) at  
9 least one event occurs within this rainfall interval.

10 Second, the following ratio is calculated for each interval:

$$11 \quad E_i = Nr_i / Nd_i, \quad (2)$$

12 where  $Nr_i$  is the number of rockfall(s) that occurred within the given rainfall interval and  $Nd_i$   
13 is the number of days in this interval. Thus,  $E_i$  corresponds to the daily rockfall frequency for  
14 each interval.

15 Third, a linear regression analysis of the values  $E_i$  is performed with respect to  $P_i$  to search for  
16 a possible linear relationship between the magnitude of the triggering factor and the  
17 corresponding average number of rockfalls. To validate the correlation, we have considered  
18 the squared correlation coefficient  $R^2$  and the p-value of the linear regression. If the p-value  
19 was less than 0.05 (significance level), the linear model was considered satisfactory, and the  
20  $R^2$  value corresponds to the best correlation.

21

22 To test the relevance of the method, virtual rockfalls and rainfall databases were created. To  
23 confirm the importance of the number of events in the database, “rich” and “poor” databases  
24 were generated such that the correlation between the rainfall and the number of events could  
25 be determined in advance. The method was then applied to determine the correlations for  
26 different cases.

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28

## 1 4.2 Case study on virtual databases

### 2 4.2.1 Generation of virtual databases

3 For the first case study, the virtual databases were generated using Mathematica software (V9,  
4 Wolfram Research, Champaign, Illinois, USA). The following parameters were used as fixed  
5 components of the databases:

- 6 - the number of days in the entire database ( $N$ ).  $N$  is taken equal to 4,015 days (11  
7 years), similar to the real databases;
- 8 - the type of triggering meteorological factor and its distribution. The chosen factor  
9 is rainfall, which follows the same distribution as the measured rainfall of La  
10 Réunion Island (Figure 4). Overall, 43% of the days were rainy;
- 11 - the ratio between the rainfall and the number of events, which gives the number of  
12 rockfalls given the amount of rain for each day, is taken to be equal to 0.1 in the  
13 case of the virtual databases (a rainfall of 10 mm on one day is assumed to trigger  
14 one rockfall on the same day; in the case of a day without rainfall, zero rockfall  
15 occurs on this day);
- 16 -  $k$ , the time delay (in days) between a rain episode and the rockfalls that it may  
17 have triggered.  $k$  is always equal to zero in the virtual databases (because all  
18 rockfalls are assumed to occur within the same day of the rain episode).

19 Two other parameters will vary depending on the databases:

- 20 - the “correlation rate”  $C_r$  between the rainfalls and number of events. For example,  
21 a perfect correlation (correlation rate of 100%) indicates that all rainy days are  
22 days with rockfalls, in accordance with the fixed proportionality coefficient. A  
23 correlation rate of 50% means that half of the events are perfectly correlated with  
24 the rain, whereas the others are randomly distributed throughout the database;
- 25 - the proportion  $x$  of days with events. Three cases were tested: (1)  $x = 43\%$ ,  
26 corresponding to the proportion of rainy days in the La Réunion Island database;  
27 (2)  $x = 13\%$ , corresponding to the proportion of days with events in the La  
28 Réunion database; and (3)  $x = 3\%$ , corresponding to the proportion of days with  
29 events in the railway databases.

30 The cross-correlation approach and the method developed were used on the virtual databases,  
31 and the results are presented in the next section. The comparison of the results allows for the

1 detection and verification of correlations by the proposed method even in the case of the  
2 railway databases.

### 3 4.2.2 Results

4 Figure 4 shows the different cases tested and the correlations from a graphical perspective.  
5 The correlation is noticeable regardless of the proportion  $x$  of days with events if  $C_r = 100\%$ .

6 If this value decreases, the proportion of days with events has a stronger influence.

7 Table 3 presents the values of the cross-correlation function for all of the databases, obtained  
8 for a time delay  $k = 0$ . In the case of a high-frequency database ( $x = 43\%$ ), the correlation was  
9 detected for  $C_r = 50\%$ . However, the cross-correlation did not permit the establishment of a  
10 correlation between the rainfalls and rockfalls for  $C_r = 25\%$ . The same negative conclusion  
11 applies to the case of a database with 13% of days with events when  $C_r = 50\%$  and 75% for a  
12 “typical” database ( $x = 3\%$ ). Thus, by analogy, the value of the maximum of the cross-  
13 correlation function (0.563) for the La Réunion database indicated that at least 75% of the  
14 events were correlated with rain.

15 Table 4 presents the results obtained with the proposed method, allowing us to identify the  
16 correlation between the rainfalls and number of rockfalls, provided that the number of  
17 rockfalls and rainfall events are 100% correlated.

18

19 Similar tests were also performed with the rainfall distribution for the Bourgogne region  
20 (Figure 6), and the results were found to be similar to those presented here.

21

## 5 Application of the proposed method to the three real databases

Table 5 summarizes the correlations identified using the proposed method. Only the maximum correlation values are presented in the table. The new method confirms the existence of a positive correlation between rainfalls and rockfalls on La Réunion Island. This correlation exists with the daily rainfall and with the cumulative daily rainfall (Figure 7) but is more significant in the case of the accumulated rains. The method also detects a correlation between the minimum and maximum temperatures and the rockfalls in the same region, which is not surprising because the rainy season is characterized by both high temperatures and intense rainfalls. These correlations are maximal for a time delay of one day.

Whereas the classical analysis did not identify any correlation for the two other databases, the new approach detected several correlations. Indeed, the new approach detected a correlation between the accumulated rainfall and rockfalls for the Bourgogne region. More precisely, the method indicates that the occurrence of two successive days with intense rainfall is the most favorable meteorological factor, among those studied, for triggering rockfall events (Figure 8).

A correlation between the daily minimum temperature and number of rockfalls was also identified for the Auvergne database. The maximal correlation occurred for the minimum temperature recorded two days before the event ( $D_2$ ) (Figure 9). Temperatures lower than 0°C also triggered rockfall events after a delay of two days.

For the two databases, no correlation was detected between rockfalls and the daily temperature amplitude or the freezing duration. Another marker of freeze-thaw activity could be the number of freeze-thaw cycle occurrences in one day. This marker is frequently cited in the literature (Douglas, 1980; Matsuoka and Sakai, 1999) and could be used to validate or invalidate our result. Unfortunately, this marker was not available to us for the studied data.

## 1 **6 Discussion**

### 2 **6.1 Physical processes involved in each study sites**

3 The method presented in this paper highlights several statistical correlations between rockfalls  
4 and meteorological factors, depending on the geology and the climate of the studied sites.  
5 Below are several physical interpretations of these correlations.

6 On La Réunion Island, intense rainfall events, typical of the island's tropical climate, are the  
7 main triggering factor for rockfalls. Their effect is very short-term, lasting no longer than one  
8 day. It consists in a leaching of the cliff, during which already unconsolidated blocks of rock  
9 are swept along by temporary torrents flowing down the steep topography.

10 Geologically, the steep slopes in the Bourgogne region are mainly characterized by  
11 alternating layers of limestone and marl. The marls are capable of absorbing rainwater that  
12 infiltrates and causes creeping of the clay minerals contained within the substrate (Peck and  
13 Terzaghi, 1948). This process is relatively slow and is primarily related to low-intensity  
14 rainfall episodes lasting several days. Repeated water infiltrations cause the rupture of the  
15 overlying prefractured limestone layers via a fatigue effect (Pariseau and Voight, 1978).

16 The Auvergne region differs significantly from the Bourgogne region in that the rupture  
17 processes leading to block detachments are associated with different geological settings and  
18 triggering factors. The Auvergne is a region of volcanic and plutonic magmatic rocks, and the  
19 main meteorological factor observed to correlate well with rockfalls in this region is a strong  
20 negative temperature gradient occurring two days before the rockfalls. This correlation can be  
21 explained by the freeze-thaw process, inducing progressive expansion and loosening of rock  
22 fractures by repeated diurnal freezing and thawing of water-filled cavities (Coutard and  
23 Francou, 1989; Matsuoka and Sakai, 1999; Matsuoka, 1994, 2008).

### 24 **6.2 Conditional probabilities used for risk management**

25 The new approach also allows the estimation of the conditional probability of rockfall given  
26 the interval of rain ( $[P_i, P_{i+1}]$ ), to be determined as follows:

27 
$$P(\text{rockfall given the interval}) = \frac{Nrd}{Nd}, \quad (3)$$

28 where  $Nrd$  is the number of days with at least one event within the considered interval and  $Nd$   
29 is the total number of days within the considered interval.

1 Table 6 provides the conditional probabilities for (1) the accumulated rain over two days for  
2 La Réunion Island, (2) the accumulated rain over three days for the Bourgogne region, and (3)  
3 the temperature minimum for  $D_2$  for the Auvergne region. The values of the conditional  
4 probabilities ( $N_{rd}/N_d$ ) can be compared to the daily rockfall probability in each case (number  
5 of events divided by the total number of days in the database). Given the interval for the  
6 meteorological factor (e.g., the daily rainfall), the infrastructure manager can then estimate the  
7 probability of rockfall and make a risk management decision based on a rainfall forecast (a  
8 rainfall prediction provided at least a day in advance). Specifically, for both the La Réunion  
9 region and Bourgogne region, when 15 mm of cumulative rain is reached (over two and three  
10 days, respectively), the probability of a fall is doubled compared to the daily rockfall  
11 probability. For the Auvergne region, this probability is doubled when  $-5^{\circ}\text{C}$  is reached. When  
12 120 mm of rain falls in the La Réunion region, the conditional probability of rockfall reaches  
13 one, which means that the daily rockfall probability is multiplied almost by eight. In the most  
14 unfavorable case, this probability is multiplied by 5.5 for the Bourgogne region and by 3.5 for  
15 the Auvergne region.

### 16 **6.3 Advantages and drawbacks of the proposed approach**

17 The correlation between rockfalls and meteorological factors is a classical observation.  
18 However, the correlations are difficult to detect (cf. Part 3) for databases with fewer rockfalls  
19 (such as the Bourgogne and Auvergne databases) (Frayssines and Hantz, 2006). By testing the  
20 proposed method on a virtual database (cf. Table 4), it was confirmed that with a correlation  
21 rate ( $C_r$ ) of 100%, a correlation could be detected even within databases entailing very few  
22 events ( $x = 3\%$ ). By reducing the correlation rate, a correlation can still be detected for only  
23 50% of days with events completely correlated ( $C_r = 50\%$ ). In terms of the size of the  
24 intervals used in the correlation analysis, we conducted several tests using either the smallest  
25 or largest possible interval size when at least one event and five days were observed. The  
26 results, expressed in terms of the p-value, did not change significantly. However, the  $R^2$   
27 values increased slightly in the largest intervals. Our evaluation of the cross-correlation  
28 method using the virtual databases (cf. Table 3) demonstrated that no cross-correlation is  
29 detected if there are fewer than 3% of days with events. Moreover, the cross-correlation  
30 analysis appears unsuitable if only one event occurs per day (given that the cross-correlation  
31 is calculated as a function of the daily number of rockfalls).

1 For the proposed method to be applicable, the database must be as complete as possible and  
2 re-established on a daily basis, as is the case when patrolling is performed daily. The study of  
3 the correlations between the events of the day ( $D_0$ ) and the meteorological factors of the days  
4 before ( $D_n$ ) is not possible if these conditions are not met. Furthermore, the studied site should  
5 present homogeneous geological conditions to allow the statistical analyses to be relevant to  
6 the entire database. Indeed, differences in geological conditions may lead to differences in the  
7 failure mechanisms (Douglas, 1980; Fityus et al., 2013; Luckman, 1976); in such an event, it  
8 is probable that both the triggering factors and statistical conclusions will differ. To be more  
9 precise in the analysis, the Bourgogne and Auvergne databases could be divided into different  
10 parts according to the geology. However, the databases are not sufficiently “rich” to allow this  
11 partitioning.

12 Moreover, the assessment of the conditional probability of rockfall given the interval of the  
13 meteorological factor allows us to compare each of the conditional probabilities with the daily  
14 rockfall hazard, which corresponds to the proportion of days with events in the entire  
15 database.

16 At present, one of our objectives is to investigate other fields by testing this method on  
17 databases involving events other than rockfalls. This extension will permit us to examine the  
18 scope of this method, particularly in the study of slow phenomena (at least 15 days between  
19 the factor and the event).

20

## 21 **7 Conclusion**

22 The objective of this study was to identify any possible correlation between meteorological  
23 factors and rockfalls, even in the case of databases containing very few events. Preliminary  
24 statistical analyses helped to identify several correlations in the case of a “rich” database.  
25 However, no correlation was detected in the more typical “poor” databases due to the sparse  
26 representation of days with several rockfalls. The proposed method uses the probability of  
27 occurrence of the chosen triggering factor to assess the influence of this factor on the  
28 rockfalls. This approach serves to highlight the correlation between a small number of events  
29 and a meteorological factor. For a database containing only 3% of days with events, the  
30 method used to detect a correlation assessed whether approximately 50% of the events were  
31 perfectly correlated with the meteorological factor chosen. The use of this method confirms  
32 the positive correlation between rainfalls and rockfalls on La Réunion database. It highlights a

1 correlation between the cumulative rainfalls and rockfalls in the Bourgogne region, and it  
2 detects a correlation between the daily minimum temperature and rockfalls in the Auvergne  
3 database. The proposed method allowed the probability of events to be estimated given the  
4 value of the meteorological factor studied. These probabilities should be helpful in terms of  
5 risk management, e.g., for optimizing the patrolling services for each site according to the  
6 susceptibility of that site to the meteorological factors.

7

## 8 **Acknowledgments**

9 The authors acknowledge Jean-Louis Durville, from the Ministère de l'Écologie, du  
10 Développement durable, des Transports et du Logement, for providing the La Réunion Island  
11 database. We also thank him, as well as Nicolas Pollet and Florence Belut from the SNCF, for  
12 useful discussions. More generally, we acknowledge the SNCF for providing the Bourgogne  
13 and Auvergne databases and METEO FRANCE for providing the meteorological data.  
14 Finally, we would like to thank the Lorraine region for financial support.

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## 20 **Tables**

21 Table 1. Principal characteristics of the three databases

	RN1 on La Réunion Island	Bourgogne region	Auvergne region
Number of events	949	135	142
Number of days with events	529	126	122
Average number of events per day with events	1.79	1.07	1.16
Number of days in the database	4,008	4,739	4,008
Daily rockfall hazard	0.013	0.003	0.003

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1 Table 2. Number of rockfalls for various intervals of daily rainfall

RN1 on La Réunion Island			Bourgogne region			Auvergne region		
Daily rainfall interval (mm/day)	Frequency of the interval	Frequency of rockfalls in the interval	Daily rainfall interval (mm/day)	Frequency of the interval	Frequency of rockfalls in the interval	Daily rainfall interval (mm/day)	Frequency of the interval	Frequency of rockfalls in the interval
<b>0-20</b>	<b>0.97</b>	<b>0.76</b>	<b>0-5</b>	<b>0.79</b>	<b>0.6</b>	<b>0-5</b>	<b>0.88</b>	<b>0.77</b>
20-40	0.014	0.053	5-10	0.099	0.16	5-10	0.062	0.12
40-60	0.0077	0.072	10-15	0.051	0.13	10-15	0.022	0.049
60-80	0.0032	0.022	15-20	0.029	0.044	15-20	0.014	0.035
80-100	0.0014	0.02	20-25	0.014	0.022	20-25	0.0077	0.014
100-120	0.00075	0.013	25-30	0.0055	0.007	25-35	0.0072	0.007
120-140	0.00075	0.023	30-35	0.0055	0.022	35-60	0.0048	0.007
140-160	0.0005	0.022	35-50	0.0061	0.015			
160-180	0.00075	0.012						
180-220	0.00075	0.003						
220-370	0.00025	2						

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1 Table 3. Values of the cross-correlation between rainfalls and rockfalls for three virtual  
 2 databases, with a time delay of zero days. This value is compared to the significance  
 3 threshold, which is equal to 0.031 in all cases. The results presented in bold identify the non-  
 4 significant correlations (values equal to the threshold value were also considered  
 5 insignificant).

	$x = 43\%$	$x = 13\%$	$x = 3\%$
$C_r = 100\%$	Maximum value of cross-correlation = 0.65	Maximum value of cross-correlation = 0.42	Maximum value of cross-correlation = 0.23
$C_r = 75\%$	Maximum value of cross-correlation = 0.45	Maximum value of cross-correlation = 0.18	<b>Maximum value of cross-correlation = 0.031</b>
$C_r = 50\%$	Maximum value of cross-correlation = 0.23	<b>Maximum value of cross-correlation = 0.031</b>	<b>Maximum value of cross-correlation = 0.031</b>
$C_r = 25\%$	<b>Maximum value of cross-correlation = 0.031</b>	<b>Maximum value of cross-correlation = 0.030</b>	<b>Maximum value of cross-correlation = 0.026</b>

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7 Table 4.  $R^2$  and p-values of the linear regression line obtained by the proposed method for  
 8 three virtual databases.  $C_r$  corresponds to the “correlation rate” between the rainfalls and  
 9 number of events, and  $x$  corresponds to the proportion of days with events. The results shown  
 10 in bold identify non-significant correlations

	$x = 43\%$	$x = 13\%$	$x = 3\%$
$C_r = 100\%$	$R^2 = 0.98$ ; p-value $\sim 10^{-36}$	$R^2 = 0.93$ ; p-value $\sim 10^{-18}$	$R^2 = 0.73$ ; p-value $\sim 10^{-6}$
$C_r = 75\%$	$R^2 = 0.88$ ; p-value $\sim 10^{-20}$	$R^2 = 0.81$ ; p-value $\sim 10^{-12}$	$R^2 = 0.57$ ; p-value $\sim 10^{-4}$
$C_r = 50\%$	$R^2 = 0.72$ ; p-value $\sim 10^{-11}$	$R^2 = 0.71$ ; p-value $\sim 10^{-7}$	$R^2 = 0.50$ ; p-value $\sim 10^{-3}$
$C_r = 25\%$	$R^2 = 0.54$ ; p-value $\sim 10^{-6}$	$R^2 = 0.41$ ; p-value $\sim 10^{-4}$	<b><math>R^2 = 0.47</math>; p-value <math>&gt; 0.05</math></b> <b>p-value = 0.06</b>
$C_r = 10\%$	$R^2 = 0.25$ ; p-value $\sim 10^{-3}$	<b><math>R^2 = 0.18</math>; p-value <math>&gt; 0.05</math></b> <b>p-value = 0.13</b>	-

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1 Table 5. Correlations between the chosen meteorological factors and the daily number of  
 2 rockfalls; results obtained with the proposed method on the real databases. Only the  
 3 maximum correlations are presented here.

	La Réunion Island	Bourgogne region	Auvergne region
Daily precipitation ( $P$ )	For $D_1$ - $R^2 = 0.70$ p-value = $10^{-9}$ Correlation coefficient = 0.12	<b>No correlation</b>	<b>No correlation</b>
Cumulative Daily precipitation ( $P_c$ )	For $D_1$ - $R^2 = 0.74$ p-value = $10^{-13}$ Correlation coefficient = 0.10	For $D_2$ - $R^2 = 0.54$ p-value = $10^{-5}$ Correlation coefficient = 0.012	<b>No correlation</b>
Daily minimum temperature ( $T_{min}$ )	For $D_1$ - $R^2 = 0.69$ p-value = $10^{-6}$ Correlation coefficient = 0.5	<b>No correlation</b>	For $D_2$ - $R^2 = 0.34$ p-value = $10^{-5}$ Correlation coefficient = 0.05
Daily maximum temperature ( $T_{max}$ )	For $D_1$ - $R^2 = 0.60$ p-value = $10^{-5}$ Correlation coefficient = 0.8	<b>No correlation</b>	<b>No correlation</b>
Daily temperature amplitude ( $T_{amp}$ )	<b>No correlation</b>	<b>No correlation</b>	<b>No correlation</b>
Daily freezing duration	<b>No correlation</b>	<b>No correlation</b>	<b>No correlation</b>

4  $D_0$  is the day of the event(s) studied, and ( $D_n$ ) identifies the n days before, with n varying from one to 10.

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6 Table 6. Probability of having at least one event on a day falling within a given interval of  
 7 daily rainfall (La Réunion Island and Bourgogne region) and different intervals of daily  
 8 minimum temperatures (Auvergne)

La Réunion Island		Bourgogne region		Auvergne region	
Interval of cumulative daily rainfall over two days ( $D_0 + D_1$ ) (mm/day)	Probability of at least one event	Interval of cumulative daily rainfall over three days ( $D_0 + D_1 + D_2$ ) (mm/day)	Probability of at least one event	Interval of daily minimum of temperature ( $D_2$ ) (°C/day)	Probability of at least one event
<i>Daily rockfall probability:</i> <b>0.13</b>		<i>Daily rockfall probability:</i> <b>0.02</b>		<i>Daily rockfall probability:</i> <b>0.029</b>	
0-5	0.09	0-5	0.013	-20; -10	0.1
5-10	0.16	5-10	0.026	-10; -5	0.052
10-15	0.25	10-15	0.036	-5; 0	0.039
15-20	0.32	15-20	0.041	0-5	0.024
20-30	0.39	20-30	0.032	5-10	0.023
30-40	0.45	30-40	0.03	10-15	0.029
40-50	0.55	40-50	0.043	15-22	0.027
50-70	0.54	50-70	0.053		
70-90	0.64	70-136	0.111		

90-120	0.64
120-150	1
150-200	1
200-516	0.73

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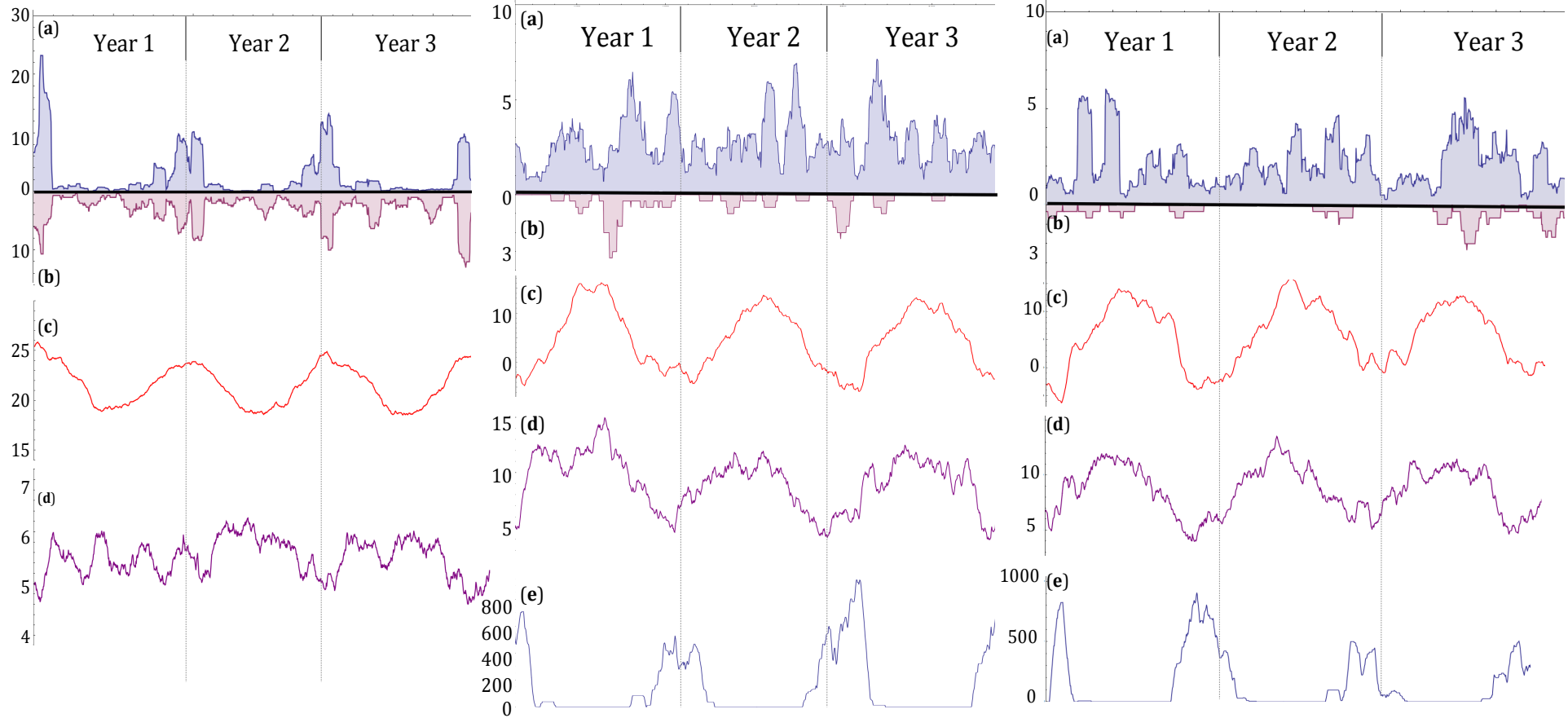
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Figure 1. Location of the three sites, corresponding to (a) the Auvergne region, (b) the Bourgogne region, and (c) Highway RN1 on La Réunion Island.

1- La Réunion Island

2- Bourgogne - France

3- Auvergne – France



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 2 Figure 2. Temperature, rainfall, and rockfall for a three-year period for the three studied sites (30-day moving average). (a) Precipitation (mm  
 3 of rain). (b) Rockfall. (c) Minimum of temperature (°C). (d) Daily temperature amplitude (°C). (e) Duration of the freezing period (min).



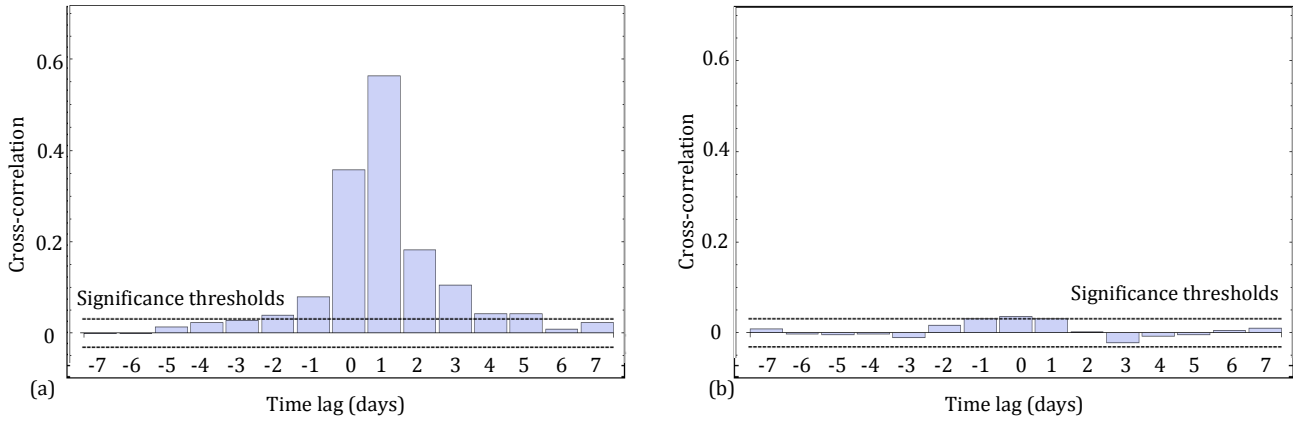
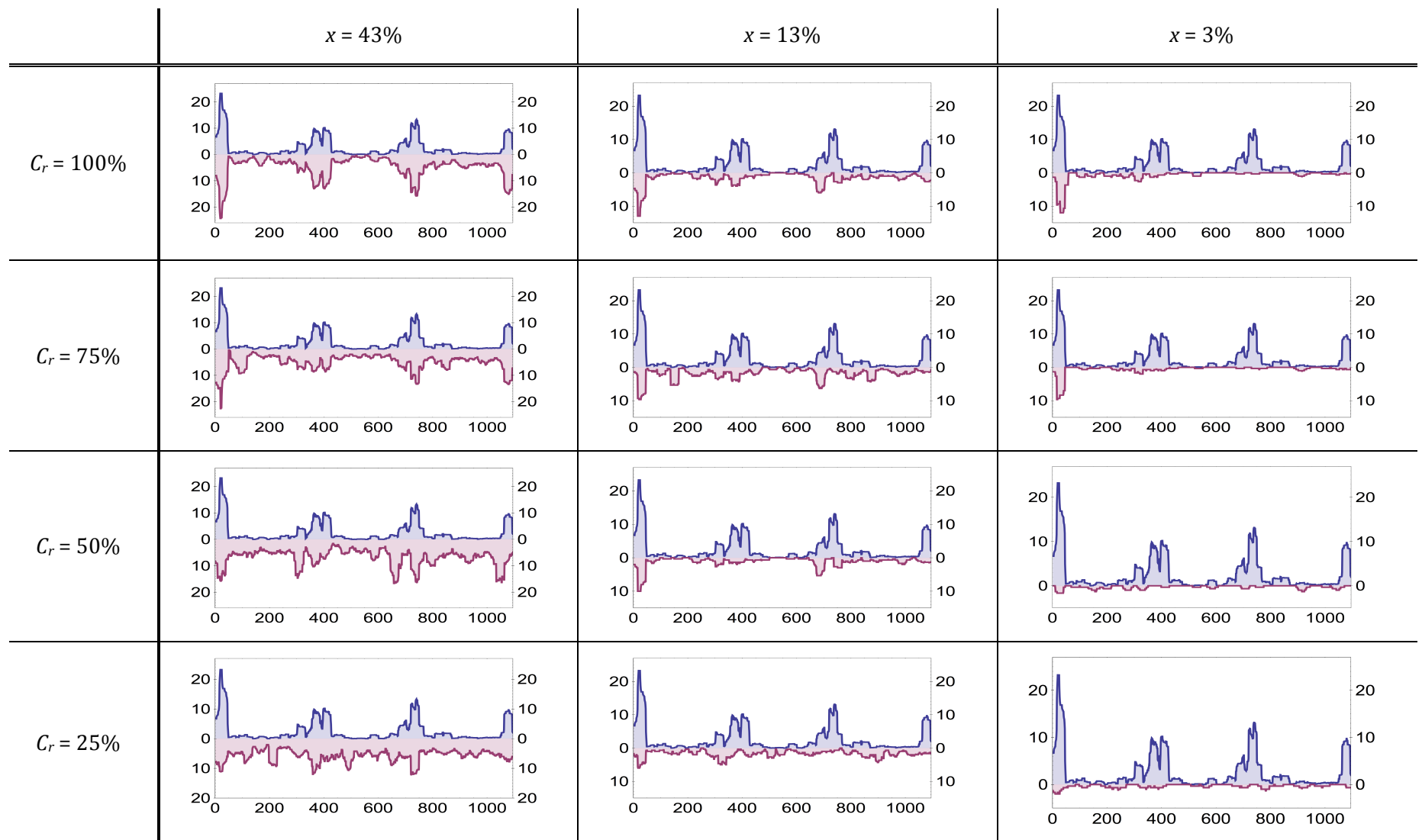
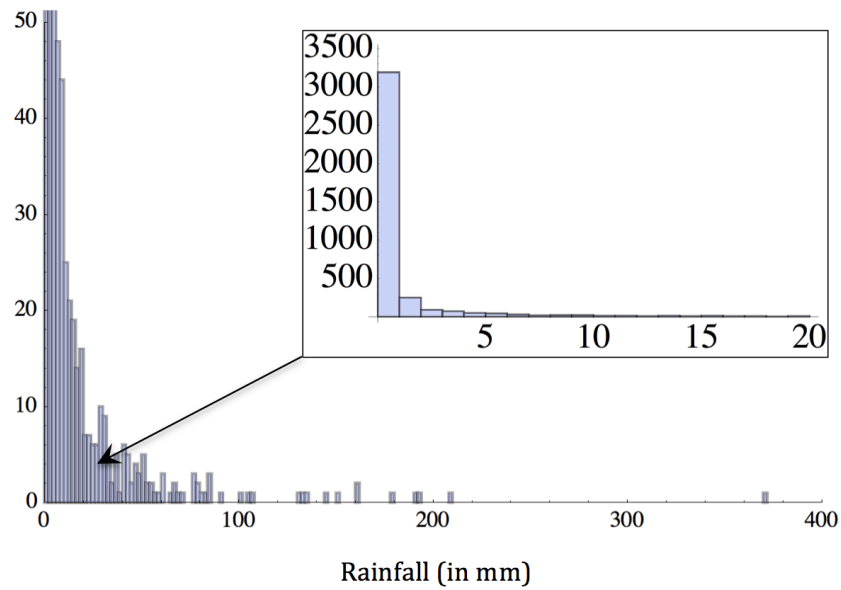


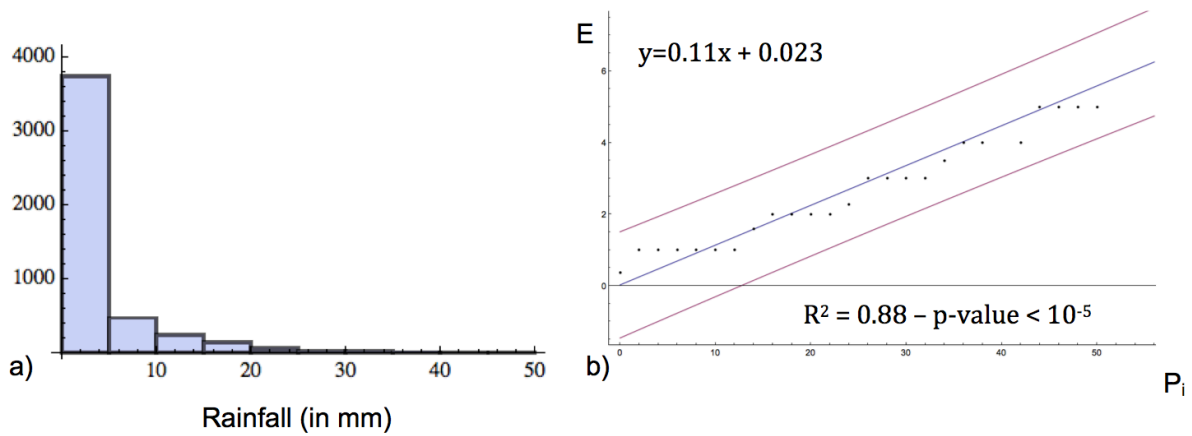
Figure 3. Cross-correlation of rockfall and rainfalls for (a) La Réunion Island and (b) the Bourgogne region. The significance threshold, equal to 0.031, is represented by the dashed lines.



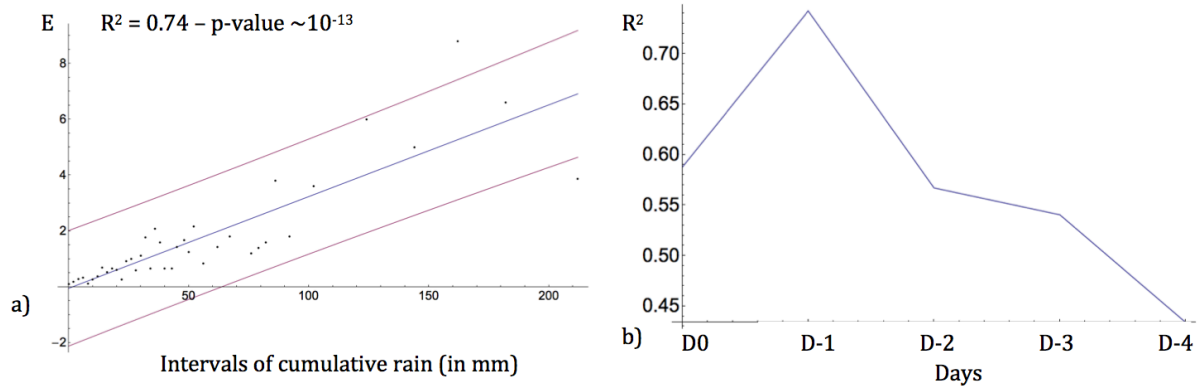
1 Figure 4. Qualitative correlation between rockfalls and rainfalls (30-day moving average) for the 12 virtual databases.  $C_r$  corresponds to the “correlation  
2 rate” between the rainfall and number of events, and  $x$  corresponds to the proportion of days with events. The x-axis corresponds to the days. The y-axis  
3 corresponds to the daily rainfall in mm (above zero) versus the number of rockfalls (below zero).



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2 Figure 5. Histogram of the rainfall for the La Réunion region.

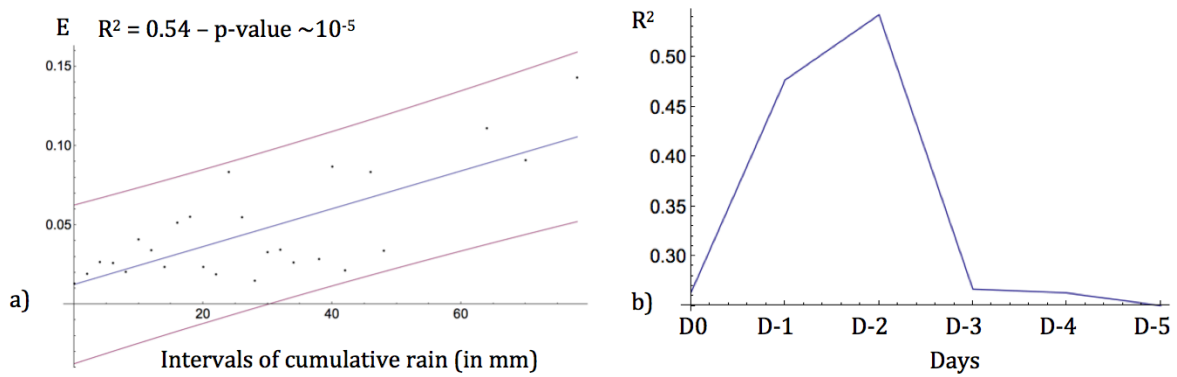


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4 Figure 6. a) Histogram of the rainfall for the Bourgogne region; b) Application of the method  
5 to a virtual database with 56% of days with events and rain that fits the empirical distribution  
6 of the Bourgogne rainfall. For these days, the rockfall and rainfall magnitudes are 100%  
7 correlated.  
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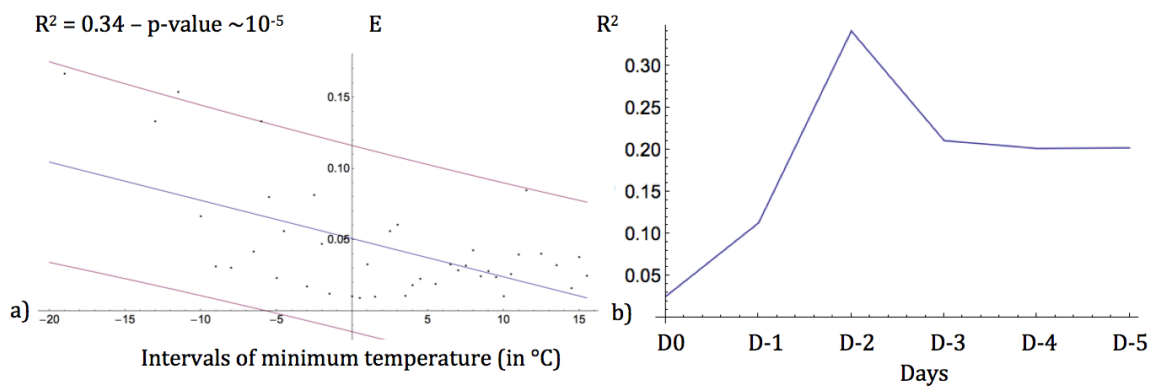
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 2 Figure 7. La Réunion Island; a) Application of the method to the cumulative rain over two  
 3 days ( $D_0 + D_1$ ); b)  $R^2$  of rockfall vs. rain accumulated over several days.

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 6 Figure 8. Same as Figure 7 for the Bourgogne region. a) Cumulative rain over three days ( $D_0$   
 7  $+ D_1 + D_2$ ).

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 10 Figure 9. Same as Figure 7 for the Auvergne region. a) Minimum temperature on  $D_2$ .

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