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Assessment of rockfall hazards using databases and considering triggering meteorological events

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Abstract

Rockfalls are major and essentially unpredictable sources of danger, particularly along transportation routes (roads and railways). Thus, assessment of their probabilities of occurrence is a major challenge for risk management. From a qualitative perspective, experience has shown 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 exhibited a high frequency of rockfalls (approximately 950 events over 11 yr), whereas the other two databases were more common (approximately 140 events over 11 yr). These databases were for (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 in the "poor" databases. This new approach, easy to use, leads to identify the conditional probability of rockfall, according to the selected meteorological factor. It will help to optimize risk management in the considered areas with respect to their meteorological conditions.

1 Introduction

Rockfall hazard is defined as the probability that a rockfall of a given volume occurs in a given area within a specified time interval (Varnes, 1984). This definition considers three different components of hazard: space, time (rockfall frequency), and the intensity of the event. Numerous publications on hazard mapping (e.g., Baillifard et al., 2003;

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Jaboyedoff et al., 2005) and rockfall intensity (e.g., Brunetti et al., 2009; Dussauge et al., 2003) are available in the literature. Temporal probability is recognized to be more difficult to assess (Hantz, 2007).

Temporal probability can be estimated through the study of triggering factors, which are external causes that are principally climatic or biological in origin. These factors, which appear only at discrete times, induce a change in the forces acting on rock blocks (Hoek, 2007) and lead to their falling. The most common triggering factors are heavy rainfall episodes (André, 1997; Berti et al., 2012; Ilinca, 2008; Rapp, 1960), freeze and thaw of water-filling fractures (Ilinca, 2008; Matsuoka and Sakai, 1999), and rock surface temperature variations (Gunzburger et al., 2005; Luckman, 1976). Furthermore, seismic activity has been shown to influence rockfall events (Bull et al., 1994; Vidrih et al., 2001; Zellmer, 1987).

Rockfall inventories can be used to quantify the statistical correlation between rockfall events and their triggering factors. However, it is typically difficult to identify such a correlation 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. More precisely, as the occurrence or action of a triggering factor does not necessarily result in a rockfall, it is necessary to distinguish the rockfall probability itself from the frequency of its potential triggering factors.

In this paper, we present a new approach to investigating 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 exhibited a high frequency of rockfalls (approximately 950 events over 11 yr). The remaining two databases are more typical (approximately 140 events over 11 yr). The databases came from the following sources: (1) the national highway RN1 on La-Réunion Island, (2) a railway in the Bourgogne region, and (3) a railway in the Auvergne region. The spatial location and intensity of the events are not considered; only the number of rockfalls during the period studied is considered.

The typically used time-series approach 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 the "poor" databases. This approach will help to optimize risk management in the considered areas with respect to the meteorological conditions.

2 Rockfall databases

As stated by Luckman (1976) or Douglas (1980), the geotechnical properties as well as morphological and geological character of the bedrock material play an important role in the rockfall process. Fortunately, each area studied in this paper have a common geological context and likely the same geotechnical properties. Therefore it is allowed to draw statistical conclusions, in each area, without taking the geological or geotechnical factors into account.

There is a significant difference between the three databases: 13 % of all days of the RN1 database were days with events (529 days with at least one event out of 4008 days in the entire database) compared to 3 % for the Auvergne and Bourgogne databases. This high incidence of events makes the RN1 database particularly unique. Databases typically have an event probability of approximately 3 % (Hungr et al., 1999; Jeannin, 2001; RTM Isère, 1996; Wieczorek et al., 1992).

The daily rockfall hazard, which is the probability of a fall on each day, independent from the meteorological factors, is close to these proportions under the assumption of spatial and temporal homogeneity.

Figure 1 presents the three areas of study, and Table 1 presents the main characteristics of the associated databases.

2.1 Highway RN1 on La-Réunion Island

The National Road #1 (RN1) on La-Réunion Island (Indian Ocean, latitude: 21°10′ S, longitude: 55°30′ E) runs along the seashore at the base of a 10 km-long and up to

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200 m-high cliff composed of basaltic lava strata alternating with pyroclastic layers. This region has a tropical climate. In the studied area, the precipitation can reach 372 mm in one day, the temperatures vary from 16 °C to 35 °C; and the temperature ranges by up to 9.2 °C in one day.

Daily rockfall data are available due to the regular patrolling service carried out by the local Public Works authorities (DDE). A total of 949 rockfalls were recorded within the 11 yr span between 1998 and 2009. A previous study (Durville, 2004; Rat, 2006) considering only a portion of the database (352 rockfalls recorded between 1998 and 2002) demonstrated that rockfalls are mainly correlated to heavy rainfall episodes. We completed this study and also evaluated the influence of temperature on rockfalls.

2.2 Railway in the Bourgogne region, France

The area is comprised of massive limestone from the Jurassic. The climate of the region is oceanic to semi-continental. Frequent rainfalls in any season, with a maximum in autumn (up to 89 mm daily), reflect the oceanic influence. The high monthly temperature amplitude (up to 31 °C), cold winters (minimum temperature down to −20 °C) and hot summers (maximum temperature up to 36 °C) reflect the semi-continental influence. The altitude of the study area is between 300 and 400 m.

Technicians from the French National Railway Company (SNCF), working on the railroads to ensure their safety, are in charge of the rockfall inventory. Daily data are available, and 135 rockfalls were recorded within a 13 yr span (1999–2012) along the 100 km of the studied railroad.

2.3 Railway in the Auvergne region, France

This area is comprised of volcanic (basalt) or plutonic (granite) magmatic rocks. The climate of the region is similar to that of the Bourgogne region. The rainfall maximum can reach 125 mm daily. Temperatures lie between −18 °C and 36 °C, with a daily temperature range of up to 23 °C. The altitude of the study area is between 700 and 900 m.

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As for the Bourgogne database, technicians from the French National Railway Company (SNCF) are in charge of the rockfall inventory and daily data are available. In total, 40 km of railroads present a rockfall hazard. The database includes 142 rockfall events, which were recorded over an 11 yr span (2001–2012).

The following analyses were realized for the three sectors taken separately.

3 Preliminary analysis using a classical time-series approach

3.1 Possible triggering factors considered in this study

Possible triggering factors included the following:

- the amount of precipitation (or rainfall) (P) of the considered day (D_0), or n days before (D_n), with n varying from one to 10;
- the amount of precipitation (or rainfall) accumulated (P_c) over several days, up to 10 days before the considered day;
- the temperatures of the day, indicated by the minimum temperature (T_{min}), maximum temperature (T_{max}), and temperature amplitude (T_{amp});
- the daily freezing duration. This factor was considered only for the Bourgogne and Auvergne regions because the temperatures on La-Réunion Island are never below zero.

These meteorological parameters were provided by Météo France (the French National Weather Service) for each sector on a daily basis. The weather stations used for this purpose were selected not to be at a distance greater than 30 km away from the studied area.

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3.2 Results

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

- a good correlation between rockfalls and rainfalls, as well as minimum temperatures for La-Réunion Island;
- no noticeable correlation between rockfalls and meteorological factors in the Bourgogne region;
- a low correlation between rainfalls and rockfalls in the Auvergne region but no noticeable correlation between temperatures and rockfalls.

Table 2 presents the distribution of the total number of rockfalls per day as a function of the daily amount of rain for the three studied areas. Surprisingly, the maximum average number of rockfalls per day occurs for the lowest amounts of daily rainfall. This result is explained by the fact that not all rainfall amounts have the same probability of occurrence. In particular, low levels of rain are more frequent than high levels, which somehow hide the effect of rain on rockfall triggering.

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

$$C_k(R,P) = \frac{\sum\left(R_\mathrm{t} - \overline{R}\right)\left(P_{\mathrm{t}-k} - \overline{P}\right)}{\sqrt{\sum\left(R_\mathrm{t} - \overline{R}\right)^2}\sqrt{\sum\left(P_\mathrm{t} - \overline{P}\right)^2}} \quad (1)$$

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

Figure 2 presents the cross-correlation function of Eq. (1) for La-Réunion Island by considering various delays. A maximum value of 0.563 is reached for a delay of one day; this value is statistically significant for the significance threshold. If the cross-correlations are larger than $1.96/\sqrt{n}$ in magnitude, with n as the number of pairs of (R_t, P_t) available (equal to the number of days in the databases), then they are deemed significant. Similar cross-correlation analyses were performed for the other two sectors and two meteorological parameters, but none of these yielded satisfactory results (maximum value of 0.07 with a significant threshold of 0.031).

3.3 Limitations of the classical approach

The preliminary analysis presented here only confirms the visual correlation between rainfalls and rockfalls for La-Réunion Island. No other correlation was identified for the two other databases even though the meteorological factors are frequently mentioned in the literature to explain rockfalls.

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

The proposed method does not consider the delay in time, only the influence of the intensity of the parameters on rockfalls.

4 Suggested new methodology of analysis

4.1 Principle

The objective of the new methodology is to weigh the number of rockfalls by the probability of occurrence of the studied triggering factor (rainfall, temperatures, and freezing

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period). To this end, three steps are required, which are presented hereafter for the case of rainfall.

First, intervals of the triggering factor intensity $[P_i, P_{i+1}[$ are defined, where P designate daily or cumulated rainfalls intervals. Theses intervals are defined such that (i) similarly to statistical fit tests, the number of days within this rainfall interval should be equal or greater to five (to avoid non-representative intervals) and (ii) there is at least one event that occurred within this rainfall interval.

Second, the following ratio is calculated for each interval:

$$E_i = \mathrm{Nr}_i / \mathrm{Nd}_i \quad (2)$$

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

Third, a linear regression analysis of the values E_i is performed with respect to P_i to search for a possible linear relationship between the triggering factor intensity and average corresponding number of rockfalls. To validate the correlation, we considered the correlation coefficient R^2 and the p value of the linear regression slope. If the p value was less than 0.05 (significance level), the linear model was considered satisfactory and the value of the R^2 yields the best correlation.

To test the relevance of the method, virtual rockfalls and rainfall databases were created such that the correlation between the rainfall and number of events could be known in advance. Then, the method was applied to determine the correlations for different cases.

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4.2 Case study on virtual databases

4.2.1 Generation of virtual databases

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

- the number of days in the entire database (N). N is taken equal to 4015 days (11 yr), similar to the real databases;
- the type of triggering meteorological factor and its distribution. The chosen factor is rainfall, which follows the same distribution as the measured rainfalls of La-Réunion Island (Fig. 3). Overall, 43 % of days were rainy;
- the proportionality coefficient between the rainfall and number of events is taken to be equal to 0.1 in the case of the virtual databases (a rainfall of 10 mm on one day is assumed to trigger one rockfall on the same day);
- k the time delay (in days) between a rain episode and the rockfalls that it may have triggered. k is always equal to zero in the virtual databases (because all rockfalls are assumed to occur within the same day of the rain episode).

Two other parameters will also vary depending to the databases:

- the "correlation rate" C_r between the rainfall and number of events. For example, a perfect correlation (correlation rate of 100 %) indicates that all rainy days are days with rockfalls, in accordance with the fixed proportionality coefficient. A correlation rate of 50 % means that half of the events are perfectly correlated with the rain, whereas the others are randomly distributed throughout the database;
- the proportion x of days with events. Three cases were tested: (1) $x = 43$ %, corresponding to the proportion of rainy days in the La-Réunion Island database; (2)

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$x = 13\,\%$, corresponding to the proportion of days with events in the La-Réunion database; and (3) $x = 3\,\%$, corresponding to the proportion of days with events in the railway databases.

Table 3 presents the different cases tested, and the correlations were detected from a qualitative perspective. The correlation was noticeable regardless of the proportion x of days with events when $C_r = 100\,\%$. The proportion of days with events is more significant as the value of C_r decreases.

The cross-correlation approach and the method developed were used on the virtual databases, and the results are presented in the next section. The comparison of the results allows for the detection and verification of correlations by the proposed method even in the case of the railway databases.

4.2.2 Results

Table 4 presents the values of the cross-correlation function for all of the databases obtained for a time delay $k = 0$. In the case of a high-frequency database ($x = 43\,\%$), the correlation was detected for a $C_r = 50\,\%$. However, the cross-correlation did not permit the establishment of a correlation between the rainfalls and rockfalls for a $C_r = 25\,\%$. The same negative conclusion applies to the case of a database with 13 % of days with events when $C_r = 50\,\%$ and 75 % for a "typical" database ($x = 3\,\%$). Thus, by analogy, the value of the maximum of the cross-correlation function (0.563) for the La-Réunion database indicated that at least 75 % of the events were correlated with rain.

Table 5 presents the results obtained with the proposed method, allowing us to identify the correlation between the rainfall and number of rockfalls even when a rockfall occurs a few days later, provided that the number of rockfalls and rainfall events are 100 % correlated.

Similar tests were also performed with the rain distribution of the Bourgogne region (Fig. 4), and the results were found to be similar to those presented here.

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5 Application of the proposed method to the three databases

Table 6 summarizes the correlations identified with 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 rainfalls and with the cumulative daily rainfalls (Fig. 5) 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 heavy rainfall. 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 some correlations. Indeed, concerning the Bourgogne region, the new approach detected a correlation between the accumulated rainfalls and rockfalls. More precisely, the method indicates that two days running with heavy rainfalls is the most favorable meteorological factor among those studied to trigger rockfall events (Fig. 6). 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 of two days before the event (D_2) (Fig. 7). Temperatures lower than 0 °C also triggered rockfall events after a delay of two days.

No correlation was identified for the two databases between the freezing duration and rockfalls. A marker of the freeze–thaw activity, which is a factor frequently cited in the literature (Douglas, 1980; Matsuoka and Sakai, 1999), could be used to validate or invalidate this result. Unfortunately such marker was not available to us on the studied data. Similarly, no correlation between rockfalls and the daily temperature amplitude was detected.

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6 Discussion

6.1 Conditional probabilities used for risk management

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

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

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

Table 7 provides the conditional probabilities for (1) the accumulated rain over two days for La-Réunion Island, (2) the accumulated rain over three days for the Bourgogne region, and (3) the temperature minimum for D_2 for the Auvergne region. The values of the conditional probabilities (Nrd/Nd) can be compared to the daily rockfall probability in each case (number of events divided by the total number of days in the database). The infrastructure manager, when informed of the interval of the meteorological factor (e.g., the daily rainfall) can then estimate the probability of rockfall and make a risk management decision. Specifically, for both the La-Réunion region and Bourgogne region, when 15 mm of cumulative rain is reached (over two and three days, respectively), the probability of a fall is doubled compared to the daily rockfall probability. For the Auvergne region, this probability is doubled when −5 °C is reached. When 120 mm of rain falls in the La-Réunion region, the conditional probability of rockfall reaches one, which means that the daily rockfall probability is multiplied almost by eight. In the most unfavorable case, this probability is multiplied by 5.5 for the Bourgogne region and by 3.5 for the Auvergne region.

The probabilities are considerably lower for databases were few rockfalls. However, the presented work is helpful in determining the meteorological factors than can trigger rockfalls in a specific area.

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6.2 Advantages and drawbacks of the proposed approach

The correlation between rockfalls and meteorological factors is a classical observation. However, the correlations are difficult to detect (cf. Sect. 3) for databases with fewer rockfalls (such as the Bourgogne and Auvergne databases) (Hantz and Frayssines, 2006). By testing the proposed method on a virtual database, it was confirmed that a correlation was able to be detected, even within databases entailing very few events ($x = 3\,\%$, $C_r = 100\,\%$). By reducing the correlation between the selected meteorological factor and number of events, a correlation can still be detected for only 25 % of days with events completely correlated ($C_r = 25\,\%$). Regarding the size of the intervals used in the correlation analysis, we conducted several tests using either the smallest or largest possible interval size when at least one event and five days were observed. The results in terms of p value did not change significantly, but the R^2 values were slightly increased in the largest intervals. Regarding the cross-correlation method, using the virtual databases, we demonstrated that no cross-correlation is detected when there are fewer than 3 % of days with events. Moreover, the cross-correlation is not helpful when there is no more than one event per day.

For the proposed method to be applicable, the database must be as complete as possible and re-established on a daily basis, as is the case when daily patrolling is undertaken. Any study of the correlations between the events of the day (D_0) and the meteorological factors of the days before (D_n) is not possible if these conditions are not met. Furthermore, the studied site should present homogeneous geological conditions for the statistical analyses to be relevant to the entire database. Indeed, differences in geological conditions may lead to differences in the failure mechanisms (Douglas, 1980; Luckman, 1976); in such an event, both the triggering factors and statistical conclusions are likely to differ.

Moreover, the assessment of the conditional probability of rockfall given the interval of the meteorological factor allows us to compare each of the conditional probabilities

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with the daily rockfall hazard, which corresponds to the proportion of days with events in the entire database.

At present, one of our objectives is to test this method on other databases outside of rockfalls to investigate other fields. This extension will permit us to examine the scope of this method, particularly in the study of slow phenomena (at least 15 days between the factor and event).

7 Conclusion

The objective of this work was to identify any possible correlation existing between meteorological factors and rockfalls, even in the case of few provided databases. Preliminary statistical analyses helped to identify some correlations in the case of a high-frequency database. However, no correlation was detected in the more typical databases due to a "background noise" effect that does not permit the data to be treated as regular, temporal, or chronic. The proposed method considers the occurrence probability of the chosen triggering factor to assess its influence on the rockfalls. This approach allows a correlation between a small number of events and a meteorological factor to be highlighted. For a database containing only 3 % of days with events, the method of detecting a correlation assessed whether approximately 50 % of the events were perfectly correlated with the meteorological factor chosen (similar assessments could be made with other combinations of the rate of correlated data and the level of correlation). The proposed method allowed the probability of events to be obtained given the value of the meteorological factor studied. These data should be helpful in terms of risk management as for optimizing the patrolling service on each site according to their susceptibility to the meteorological factors).

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Table 1. Main 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	1.79	1.07	1.16
Number of days in the database	4008	4739	4008
Daily rockfall hazard	0.013	0.0027	0.003

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^{-1})	Frequency of these intervals	Number of rockfalls in this interval	Daily rainfall interval (mm day^{-1})	Frequency of these intervals	Number of rockfalls in this interval	Daily rainfall interval (mm day^{-1})	Frequency of these intervals	Number of rockfalls in this interval
0–20	0.97	720	0–5	0.79	76	0–5	0.88	103
20–40	0.014	50	5–10	0.099	15	5–10	0.062	13
40–60	0.0077	68	10–15	0.051	14	10–15	0.022	5
60–80	0.0032	21	15–20	0.029	4	15–20	0.014	5
80–100	0.0014	19	20–25	0.014	2	20–25	0.0077	2
100–120	0.00075	12	25–30	0.0055	1	25–35	0.0072	1
120–140	0.00075	22	30–35	0.0055	3	35–60	0.0048	1
140–160	0.0005	21	35–50	0.0061	2			
160–180	0.00075	11						
180–220	0.00075	3						
220–370	0.00025	2						

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Table 3. Qualitative correlation between rockfalls and rainfalls (30 day moving average) for the 12 virtual databases. C_r corresponds to the "correlation 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 corresponds to the daily rainfalls in mm (above zero) vs. the number of rockfalls (below zero).

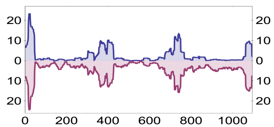
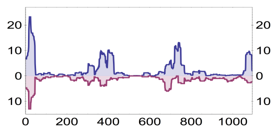
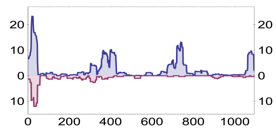
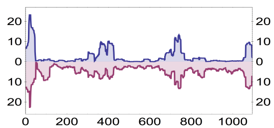
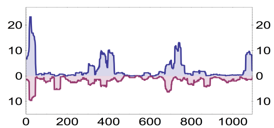
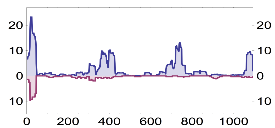
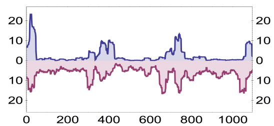
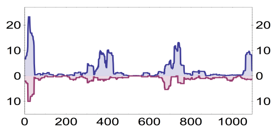
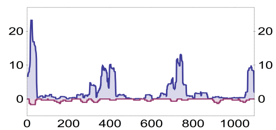
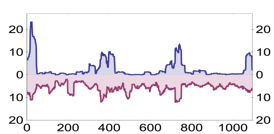
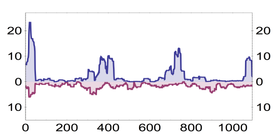
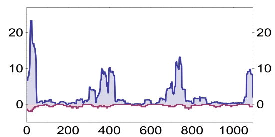
	$x = 43\,\%$	$x = 13\,\%$	$x = 3\,\%$
$C_r = 100\,\%$			
$C_r = 75\,\%$			
$C_r = 50\,\%$			
$C_r = 25\,\%$			

Table 4. Values of the amplitude obtained with a cross-correlation between rainfalls and rockfalls for three virtual databases, with a time delay of zero days. This value is compared to the significance threshold, which is equal to 0.031 in all cases. The results presented in bold identify the non-significant correlations (values very close to the threshold value were also considered 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	**Maximum value of cross-correlation = 0.032**
$C_r = 50\,\%$	Maximum value of cross-correlation = 0.23	**Maximum value of cross-correlation = 0.033**	**Maximum value of cross-correlation = 0.031**
$C_r = 25\,\%$	**Maximum value of cross-correlation = 0.031**	**Maximum value of cross-correlation = 0.030**	**Maximum value of cross-correlation = 0.026**

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Table 5. R^2 and p values of the linear regression line obtained by the proposed method for three virtual databases. C_r corresponds to the "correlation rate" between the rainfall and number of events, and x corresponds to the proportion of days with events. The results presented in bold identify the correlation, non-highlighted.

	x = 43 %	x = 13 %	x = 3 %
C_r = 100 %	R^2 = 0.98; p value ~ 10^{-36}	R^2 = 0.93; p value ~ 10^{-18}	R^2 = 0.73; p value ~ 10^{-6}
C_r = 75 %	R^2 = 0.88; p value ~ 10^{-20}	R^2 = 0.81; p value ~ 10^{-12}	R^2 = 0.57; p value ~ 10^{-4}
C_r = 50 %	R^2 = 0.72; p value ~ 10^{-11}	R^2 = 0.71; p value ~ 10^{-7}	R^2 = 0.50; p value ~ 10^{-3}
C_r = 25 %	R^2 = 0.54; p value ~ 10^{-6}	R^2 = 0.41 p value ~ 10^{-4}	**R^2 = 0.47; p value > 0.05 p value = 0.06**
C_r = 10 %	R^2 = 0.25; p value ~ 10^{-3}	**R^2 = 0.18; p value > 0.05 p value = 0.13**	–

Table 6. Correlations between the chosen meteorological factors and the number of rockfalls; results obtained with the proposed method on the real databases. Only the maximum correlations are presented here.

	La-Réunion Island	Bourgogne region	Auvergne region
Daily precipitation (P)	For $D_1 - R^2 = 0.70$ and p value $= 10^{-9}$	No correlation	No correlation
Cumulated Daily precipitation (P_c)	For $D_1 - R^2 = 0.74$ and p value $= 10^{-13}$	For $D_2 - R^2 = 0.54$ and p value $= 10^{-5}$	No correlation
Daily minimum temperature (T_{min})	For $D_1 - R^2 = 0.69$ and p value $= 10^{-6}$	No correlation	For $D_2 - R^2 = 0.34$ and p value $= 10^{-5}$
Daily maximum temperature (T_{max})	For $D_1 - R^2 = 0.60$ and p value $= 10^{-5}$	No correlation	No correlation
Daily temperature amplitude (T_{amp})	No correlation	No correlation	No correlation
Daily freezing duration	No correlation	No correlation	No correlation

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

La-Réunion Island		Bourgogne region		Auvergne region	
Interval of cumulated daily rainfall over two days ($D_0 + D_1$) (mm day^{-1})	Probability of at least one event	Interval of cumulated daily rainfall over three days ($D_0 + D_1 + D_3$) (mm day^{-1})	Probability of at least one event	Interval of daily minimum of temperature (°C day^{-1})	Probability of at least one event
Daily rockfall probability: 0.13		Daily rockfall probability: 0.02		Daily rockfall probability: 0.029	
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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Fig. 1. Location of the three sites, corresponding to **(a)** the Auvergne region, **(b)** the Bourgogne region, and **(c)** the Highway RN1 on La-Réunion Island.

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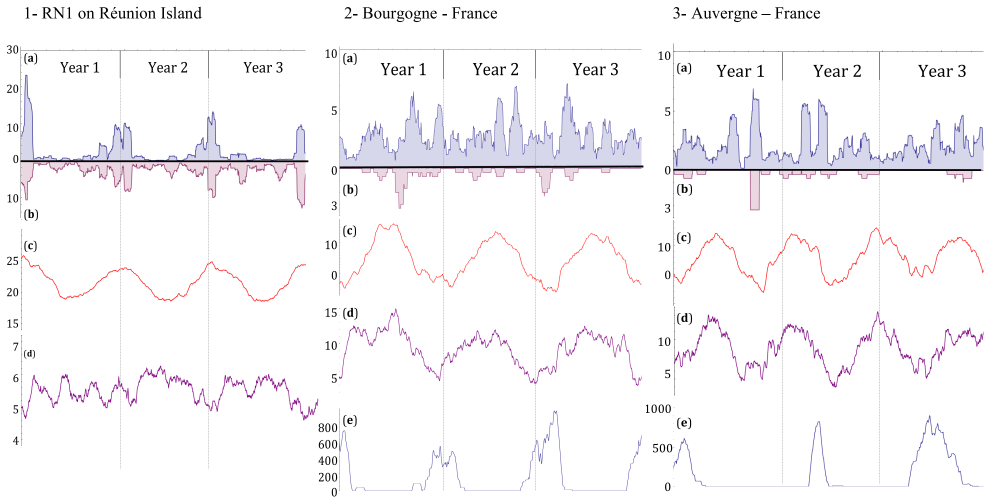

Fig. 2. Temperature, rainfall, and rockfall for a three-year period for the three studied sites (30 day moving average). **(a)** Precipitation (mm of rain). **(b)** Rockfall. **(c)** Minimum of temperature (°C). **(d)** Daily temperature amplitude (°C). **(e)** Duration of the freezing period (min).

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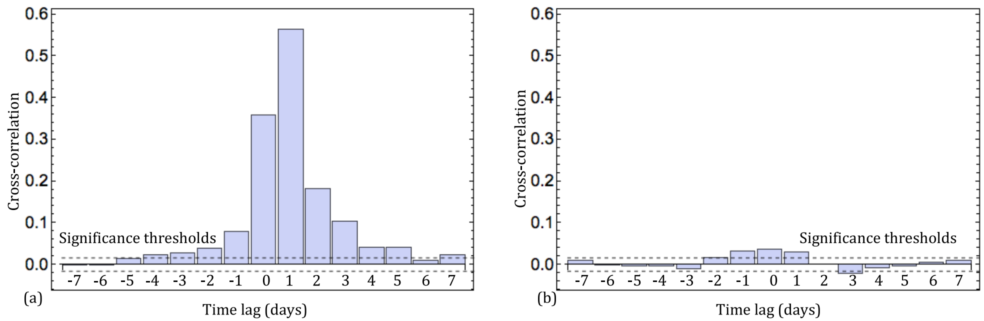

Fig. 3. Cross-correlation of rockfalls and rainfalls on the cases of **(a)** La-Réunion Island and **(b)** the Bourgogne region. The significance threshold, equal to 0.031, is represented by the dashed lines.

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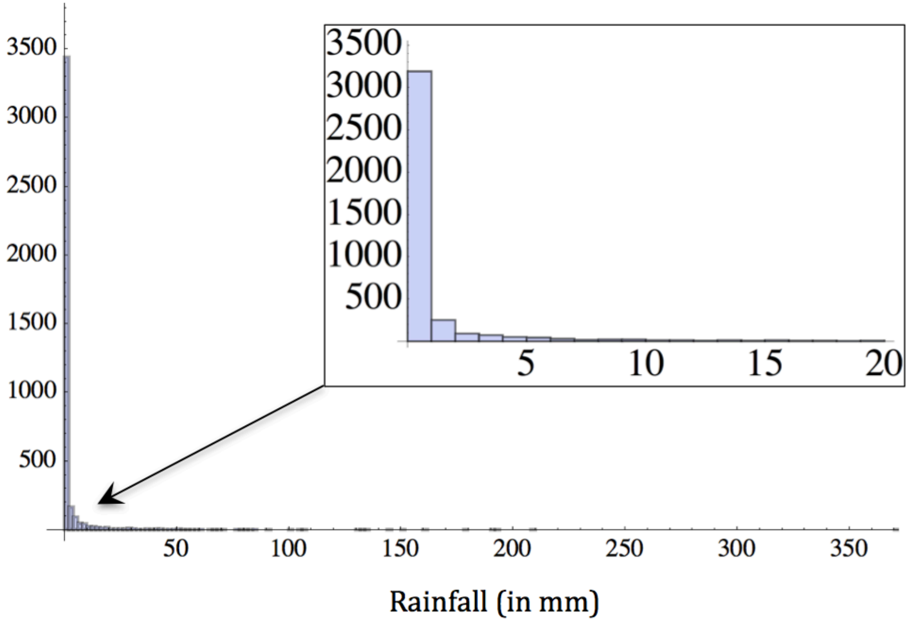

Fig. 4. Histogram of the rain for the La-Réunion region.

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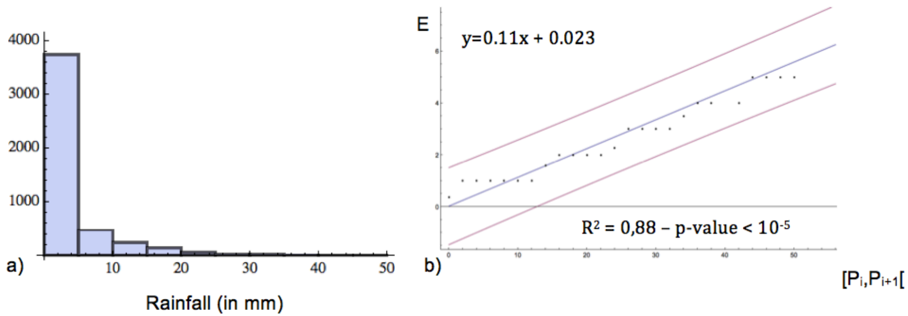

Fig. 5. (a) Histogram of the rain for the Bourgogne region; **(b)** application of the method to a virtual database with 56 % of days with events and rain that fits the empirical distribution of the Bourgogne rainfalls. For these days, the rockfall and rainfall magnitudes are 100 % correlated.

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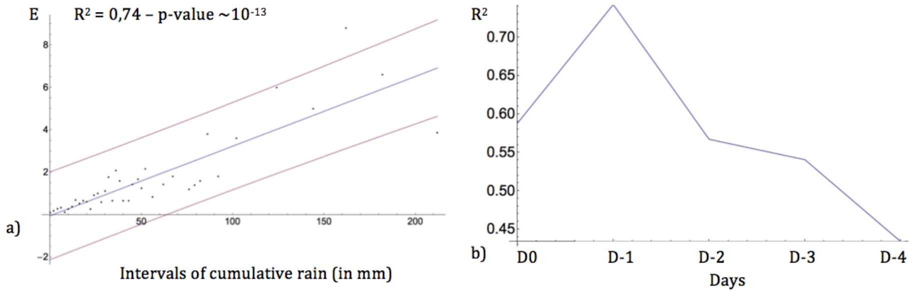

Fig. 6. La-Réunion Island; **(a)** application of the method for the cumulated rain over two days ($D_0 + D_1$); **(b)** R^2 of rockfalls vs. rains accumulated over several days.

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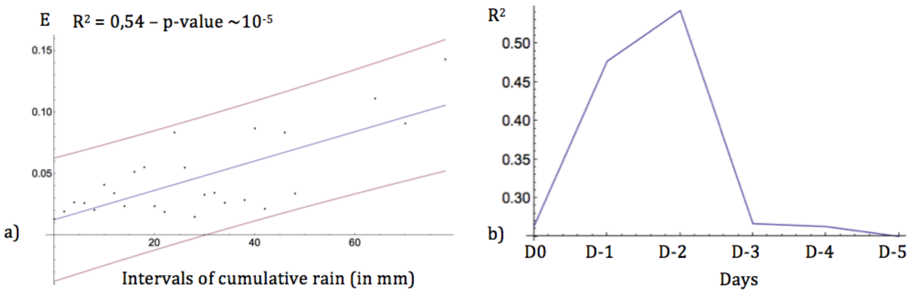

Fig. 7. Same as Fig. 6 for the Bourgogne region. **(a)** Cumulated rain over three days ($D_0 + D_1 + D_3$).

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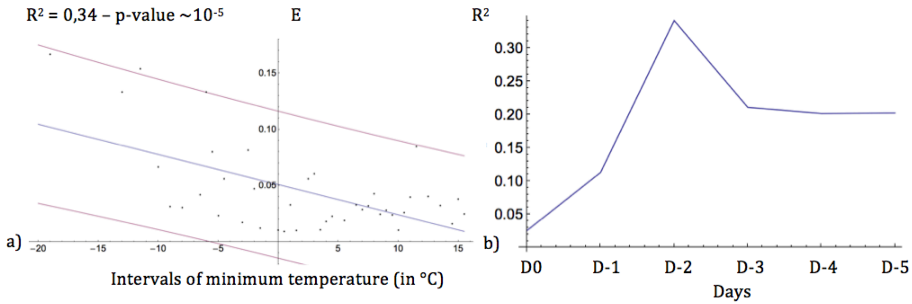

Fig. 8. Same as Fig. 6 for the Auvergne region. **(a)** Minimum temperature of D_2.

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