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The role of climate factors on rock fall occurrence in the Central Italian Alps

G. Sala, C. Lanfranconi, A. Valagussa, P. Frattini & G.B. Crosta

Università degli Studi di Milano-Bicocca, Dept. Earth and Environmental Sciences, Milano, Italy

g.sala39@campus.unimib.it

Abstract

The climate in European Alps results from a complex interaction between the Alpine belt and the atmospheric circulation. Recent studies demonstrate that in this area the temperature warmed at a rate more than twice the global average in the last century, and the precipitation increased in the northern sub-region while decreased in the southern sub-region. Changes in climate and weather trends modify the magnitude, intensity, and frequency of climatic events that can trigger landslides and the precursory factors for landslides.

In this paper, we apply a statistically base methodology aimed at the identification of a correlation between climate factors and rock fall triggering. The approach is based on the use of two specific climatic factors: the temperature and the rainfall, with different temporal scales. We consider the data in a period ranging from 15 years up to the date of each rock fall event, with the purpose to identify anomalies of the selected climatic factors in the day of occurrence of each slope failure. To assess the presence of anomalies, non-exceedance probability for each climatic factor has been calculated.

The methodology has been applied to 50 rock fall events occurred at elevations below 2000 meters. These events have been extracted from a database of more than 300 rock fall events in the Central Italian Alps, from 2009 to 2018. Our results on the whole dataset suggest that the most important triggering factor is the daily rainfall. The dataset has been further divided in different subsets to understand a possible correlation with other site-specific parameters such as elevation, lithology and rock fall volume. Our results confirmed the role of temperature on slope failures with elevation. Foliated rocks seem to be most prone to rock fall occurrence in presence of rainfall anomalies at different temporal scales. Finally, we found that rock fall with a volume larger than $5m^3$ show a strong correlation with the cumulative rainfall of the day of each event.

1 INTRODUCTION

Changes in climate and weather trends are expected to modify the magnitude, intensity, and frequency of climatic events that can trigger landslides (Coe, 2017) and the precursory factors for landslide events (e.g. antecedent precipitation, freeze–thaws cylces, Ho et al., 2017). Climate in the European Alps results from a complex interaction between the Alpine belt and the atmospheric circulation. Recent studies demonstrate that in this area the temperature warmed at a rate more than twice the global average in the last century (Beniston 2006; Auer et al. 2007), with important effects on the amount and distribution of rainfall and rainfall extremes along the Alps (Gobiet et al, 2014).

Landslides may be affected by climate change in different ways. The increase of temperature may be a potential trigger of slope instability, especially in high-altitudes regions (Gruber et al. 2004; Huggel et al. 2010; Fischer et al. 2013; Allen and Huggel, 2013) for different types of phenomena, such as debris flows (Jomelli et al. 2004, Paranunzio et al., 2015), snow/ice avalanches (Jomelli et al. 2007, Paranunzio et al., 2015), shallow spring landslides (Saez et al. 2013), rock avalanche (Paranunzio et al., 2015) and rock falls (Paranunzio et al., 2016). The increase of average rainfall or rainfall extremes may also boost landslides in different environmental settings. This has been mainly observed for shallow slides and debris flows (e.g. Berti and Simoni 2005; Melchiorre and Frattini, 2012; Gariano and Guzzetti, 2016).

For rock falls, the relationship between their occurrence and weather condition is less clear with respect to other landslide typologies, even if some works have attempted to define such relationships (Luckman, 1976, Douglas, 1980, Pierson et al., 1990, Wieczorek and Jäger 1996, Frayssines and Hantz 2006, Higgins and Andrew 2012, Delonca et al., 2014, Maciotta et al., 2015, and Maciotta et al., 2017). In particular, Paranunzio et al. (2015, 2016) proposed a method to characterize the possible relationships between different climate variables and the triggering of slope failures by analysing climate anomalies associated to the events. They tested their method on few slope instabilities occurred in the Western Italian Alps at high elevation (larger than 1500/2000 m a.s.l.).

In this paper, we applied this methodology to large a database of rock fall events occurred in Central Alps at lower and mid-elevation (< 2000 m a.s.l.) to assess the role of climate factors in this area.

2 ROCK FALL CATALOGUE

The compiled rock fall catalogue consists of 330 historical rock fall events reported in the literature and newspapers articles in Lombardy Region (Fig. 1). Starting from this database, 50 rock fall events have been selected based on the availability of data required to perform the analysis.

The selected rock falls have a volume ranging from 1 m^3 to 5,000 m^3, and they occurred between 2009 and 2018.

The selected rock falls took place within three different lithological domains: limestones and dolostones, foliated rocks, and crystalline rocks (reclassified after Montrasio et al., 1990; table 1, Figure 2).

The elevation at which these rock-fall events occurred range from about 200 m to 1,700 m a.s.l (Figure 2)., and it has been derived from a DEM with a cell resolution of 5 m.

Table 1. Lithologies present in the three lithological classes

Lithological class	Lithology
Limestone and Dolostones	Marl Limestones Arenaceous limestones Dolostones
Crystalline rocks	Diorite Rhyolite Gabbro Dacite Quartzite Paragneiss
Foliated rocks	Phyllite Schist

3 METHODS

The analysis proposed in this paper is based on the methodology developed by Paranunzio et al. (2015 and 2016), with some differences concerning the selected predictors and the performed analysis. These differences are presented in the following.

The approach considers the same steps proposed by Paranunzio et al. (2015):

1. Choose the climatic predictor to be examined (table 2);
2. Select the level of temporal aggregation (table 2);

3. Identify the weather stations for collecting data in the study area and selection of the most representative station whose data can be transposed to the rock fall site;
4. Select the pre-event data as standard for the comparison;
5. Identification of potential triggering factors based on anomalies associated to the events.

In this research, we consider as predictors the cumulative rainfall (mm), the temperature (°C) and the temperature variation (°C). The analysis has been performed at different temporal scales, to investigate whether the occurence of rock falls is controlled by fast or slow temporal evolution.

Rainfall and temperature data have been retrieved from meteorological stations available on the Reional Enviromental Agency website (*https://www.arpalombardia.it*). Only those station with a record of more than 15 years have been considered. For each event, the nearest station in terms of distance and/or elevation from the rock-fall site has been chosen.

As a standard for comparison, we considered the 15 years before the events. This period is relatively short for climate analysis, but the available metereological data in the mountain area of Regionel Lomnbaria did not allow to consider a longer period, which could have been better for the statistical analysis.

Based on the data, a value Vi of the time-aggregated variable has been associated for the event day, and for the 15-year time serie.

Table 2. List of the climatic predictors and relative temporal scale (daily, weekly, monthly and quarterly scale).

Variable	Temporal aggregation	Unit
T	1 day	°C
T_7	7 days	°C
T_{30}	30 days	°C
T_{90}	90 days	°C
R	1 day	mm
R_7	7 days	mm
R_{30}	30 days	mm
R_{90}	90 days	mm
ΔT	1 day	°C
ΔT_3	3 day	°C
ΔT_6	6 day	°C

Hence, each rock fall will have n values of V_i (with i from 1 to n) associated to the different years, where i is the index of the position occupied by the i-*th* value V_i in the sample ranked in ascending order.

By ranking the sample population for each variable (temperature and rainfall for different time intervals), a probability value, $P(V_i)$, is therefore estimated for all the values of each climatic parameter, by dividing the i-*th* position (rank) by the sample size ($P(V_i)=i/n$). This differs from the original methodology of Paranunzio et al., (2015) where the probability, is obtained by dividing by the variable position for the sample length plus one ($P(V_i)=i/n+1$). This difference is due to the limited number of years considered in the analysis.

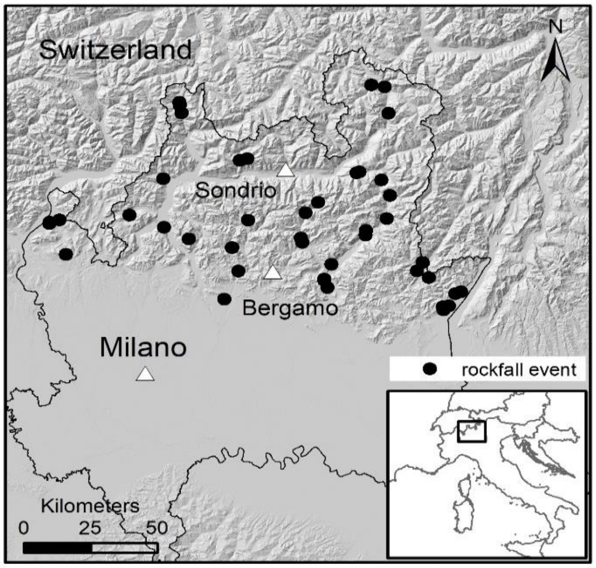

Figure 1. Map of the 50 rock falls events extracted from the historical rock-fall database. Lombardy region is outlined in the figure.

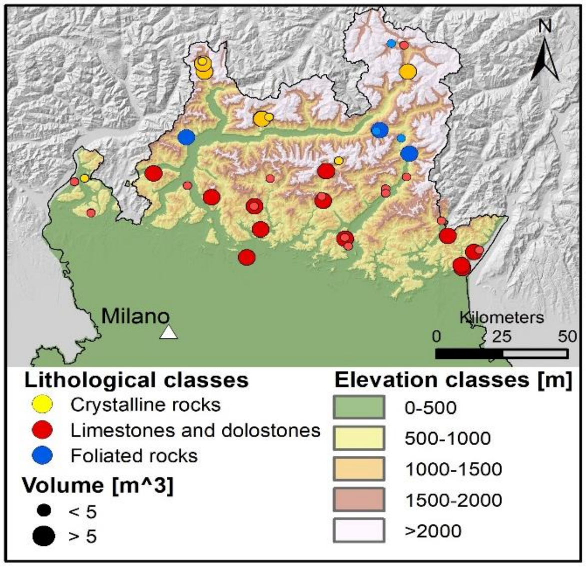

Figure 2. Map of the events and the relative lithological, volume and elevation information.

Another difference between the two approaches is related to some of the variables involved in the analysis. In our methodology, we compare the event's value of each variable with the value of same exact date of the previous years, while Paranunzio et al., (2015) also consider a time windows of 90 days (centered on the event date for each year of the time serie) for rainfall and temperature variation.

The event probability of occurrence is obtained without using any parametric distribution hypothesis, the probability corresponding to the non-exceeding probability associated with the V_i variable. If the variable V_i associated with the rock-fall event is V^*, then its non-exceedance probability will be $P(V^*)$.

Depending on the $P(V^*)$, it is possible to recognize if there is any relationship between climatic variable and rock fall occurrence. This relationship is verified if the $P(V^*)$ lies at one of the extreme values of the ordered sample. The extreme values represent a positive anomaly if corresponding to the higher value. A negative anomaly occurs in the opposite case. This is another difference with the original methodology. In fact, Paranunzio et al. (2015) consider as anomalous all the P(V*) values larger than 1-α/2 (positive anomalies) or smaller than α/2 (negative anomalies); where α corresponds to the significant level set to 0.10. Again, the modified methodology is related to the small sample available for the climatic variables. In particular, the threshold fixed by Paranunzio et al. (2015) does not allow, in our case, the identification of negative anomalies being the minimum non-exceedance probability value equal to 0.06 (i.e. larger than $\alpha/2 = 0.05$).

The analysis has been performed for the whole rock fall dataset, in order to underline a common behaviour inside the study area, and for sub-samples of the dataset based on elevation (4 classes), lithology (3 classes) and rock-fall volume (2 classes) .

4 RESULTS

The box and whiskers plot in figure 3 shows the non-exceedance probability associated with the 50 analysed rock fall events for all the eleven variables ($P(T)$, $P(T_7)$, $P(T_{30})$, $P(T_{90})$, $P(R)$, $P(R_7)$, $P(R_{30})$, $P(R_{90})$, $P(\Delta T)$, $P(\Delta T_3)$ and $P(\Delta T_6)$).

If the boxplot associated to a specific variable is near to the maximum or minimum non-exceedance probability, it is possible to conclude that the variable shows and anomalous behaviour, suggesting a relationship between the rock fall occurrence and the considered climate variable.

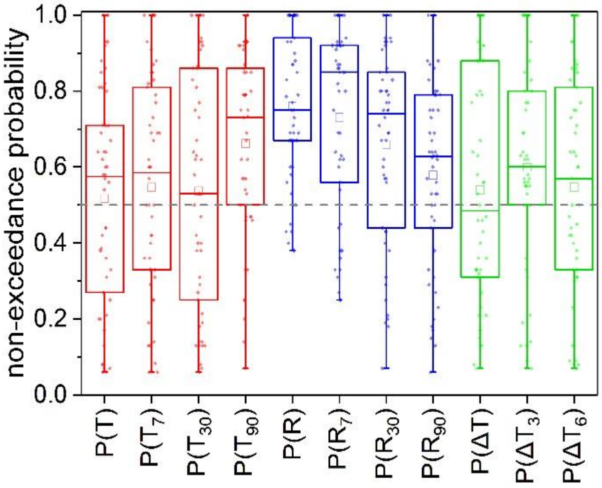

Figure 3. Non-exceedance probability associated with the 50 analyzed rock fall events for each considered variable (see Table 1). The position occupied by the boxplot define if there is a relationship between one variable and the rock fall. The dashed gray line represents a non-exceedance probability equal to 0.5.

All the variables probabilities show an average value greater than 0.5, but only the rainfall probability associated to the day of event occurrence, P(R), shows a clear distribution toward the maximum non-exceeding probability. For this variable, the 90% of case studies display a P(R) greater than 0.5 (Fig. 3). This clear positive anomaly of the daily rainfall suggests that it is a major control in the triggering of rock falls.

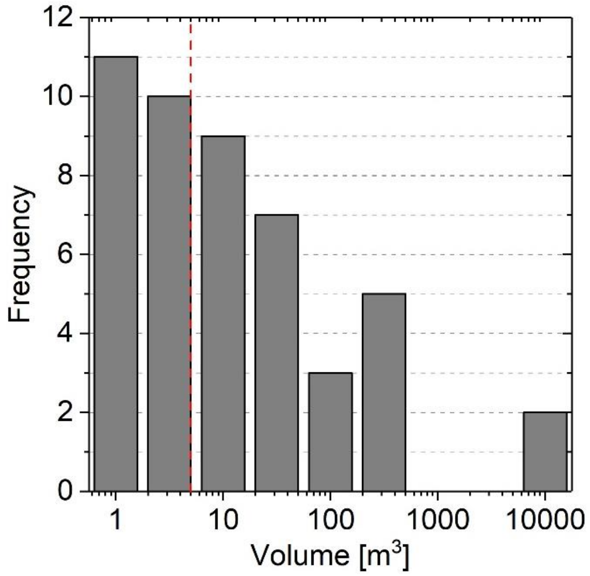

Figure 4. Frequency distribution of the volume associated to the 47 rock fall events analized. The red dashed line indicates the volume of 5 m^3, that has been used as volume threshold for the anlaysis.

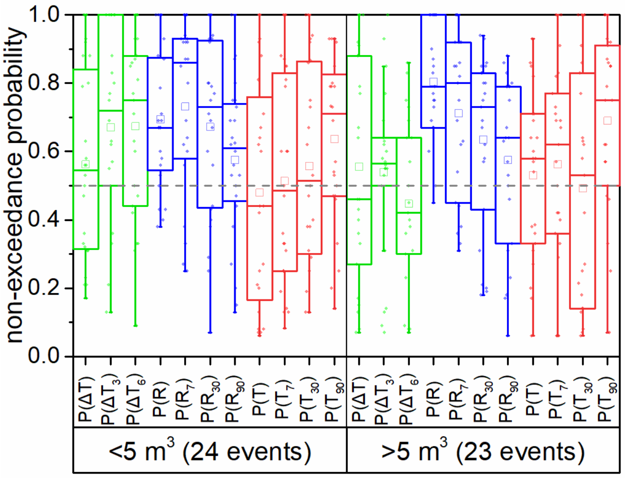

Figure 5. Non-exceedance probability associated with all rock fall events for each considered variables divided by rock fall volume, based on a threshold of 5 m^3.

To understand a possible effect of the rock-fall volume in the climate factors controlling rock-fall triggering, the dataset has been divided in two classes with a 5m^3 threshold value (Figs. 4 and 5). In this analysis 47 of the 50 rock fall events were used, due to missing volume information for 3 case studies. Figure 4 shows the frequency distribution of the rock fall volume. As commonly observed in the literature (Dussauge et al., 2003; Malamud et al., 2004), the distribution shows a larger frequency of small rock fall volumes with respect to large volumes.

Figure 5 shows the non-exceedance probability associated with the 47 analysed rock fall events for all the eleven variables. No clear relationship between the climatic variables and the volumes smaller than 5 m^3 is evident. For volumes beyond this threshold, the role of the rainfall associated to the day of occurrence, P(R), is observed (Fig. 5), similarly to what has been observed for the entire dataset.

To verify the relationship with elevation, the rock fall source elevation has been reclassified in four classes with a bin of 500 m a.s.l. The plot in figure 6a shows a high degree of correlation for the daily rainfall P(R), at elevations higher than 500 m a.s.l., and for $P(R_{90})$ for the 1000-1500 meters interval. A possible correlation is found also for two temperature variables: T_{90} for the second elevation class and T_{30} for the last elevation class.

To identify possible lithological controls on rock-fall occurrence, three classes of lithology of have been assigned to each event. The plot in figure 6b shows a good degree of correlation for rainfall at the day of the event P(R) especially for crystalline and foliated rocks.

Foliated rocks show a high correlation with most of the rainfall variables (P(R), P(R7), and P(R90) higher than 0.5). A good correlation is observed also for the temperature at the day of the event P(T) and the temperature variation between the day of the event and the third day before the events itself, $P(\Delta T_3)$.

Crystalline rocks show a good correlation with the cumulative rainfall of the seven days before the event, $P(R_7)$, and the temperature variation among the third day before the event, $P(\Delta T_3)$.

5 DISCUSSION

The analysis presented in this paper has been developed starting from the methodological approach proposed by Paranunzio et al., (2015, 2016). The main difference with respect to the above cited research is associated with the fact that we focus our attention on rock falls occurred at lower elevations. This is aimed to characterize the role of climate factors on rock fall occurrence in residential areas in proximity of strategic lifelines.

The results show that the most important variable controlling rock-fall occurrence is the rainfall associated to the day of the event, more than the temperature variables.

This is probably related to a decrease of the rock strength associate to an increase of the pore pressure during the rainfall event and to the smaller annual and daily temperature oscillation typically of lower elevation areas.

Considering the lithology in which the rock falls are triggered, we found that the foliated rocks are the most sensitive to rainfall events, either short- and long-term. For this lithology, it seems that the combined effect of specific climatic condition in terms of heavy rainfall and low temperature at the day of the event could significantly increase the occurrence probability of rockfall.

For the other lithologies, some variables appear to control rock fall occurrence, but the role is less clear (e.g. daily rainfall for crystalline rocks). In accordance with Paranunzio et al. (2016), we found a possible correlation with temperature with increasing elevation. In particular, we observe that at middle elevations there is a positive relationship with larger than average temperatures. At higher elevations the relationship is with lower than average temperatures. However, we can expect that the temperature may exert a stronger control in paraglacial environments at higher elevations.

Finally, considering the rock-fall volume, the analysis suggests small rock falls (< 5 m^3) do not show a specific relationship with climatic condition. However, it may be possible that such small rockfall are sensitive to very short-term rainfall (hourly events) that are not analysed in this paper.

In contrast, for volumes larger than 5 m^3, a clear correlation with rainfall is found. In particular, the daily rainfall events seem to have a strong control on rock fall occurrence.

Even if the results of the presented analysis are significant for the understanding of climatic variables which influence the occurrence of rock falls at lower elevation, it should be necessary to increase the dataset to provide more reliable statistics. In some cases, the separation of the original dataset led to a low number of case studies in each subset, making the analysis statistically poor. For example, in the lithological analysis, only four events occurred in the foliated rocks class. The same number of events are contained inside the elevation class ranging between 1500 and 2000 m a.s.l.

Moreover, rock fall susceptibility is the result of multiple controlling factors, such as: rock mass quality, weathering, discontinuity orientations, persistence and intersection, spacing, degree of fracturing, slope morphology, erosion and seismic activity etc. (Valagussa et al., 2014, Collins and Stock, 2016, Maciotta et al., 2017). Then, detachment of a rock fall could be related to the interaction between some of these factors, which can increase the role of temperature and/or rainfall on rock fall triggering.

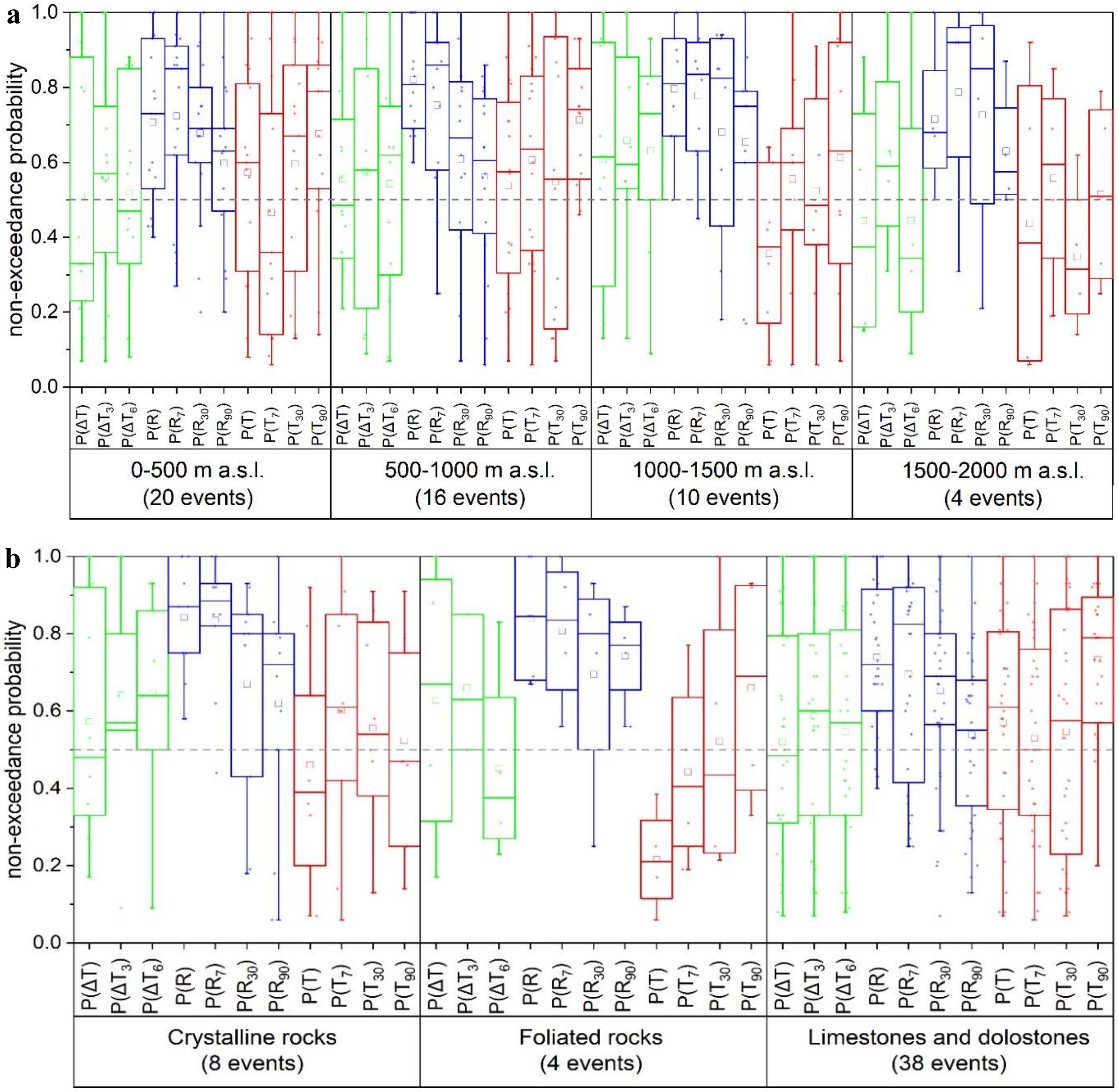

Figure 6. Non-exceedance probability associated with the analyzed rock fall events for each considered variables divided by (**a**) elevation with a bin of 500 m, and (**b**) lithological classes reclassified from Montrasio et al., (1990).

6 CONCLUSIONS

In this work we present a modified approach based on the one proposed by Paranunzio et al. (2015, 2016) for rock falls occurring at high elevation where the slope failure trigger is generally unknown. The approach adopts some simple climatic variables which can be more easily available. In our analysis we studied a series of rock falls occurred at low elevation (less than 2000 m a.s.l.) to search for a possible correlation between rock fall occurrence and the climatic parameters.

The methodological approach is based on the comparison of temperature, rainfall and temperature variations, aggregated at different temporal scales, and associated with the rock fall occurrence with the same variables for the previous 15 years.

The analysis was carried out on 50 rock fall events in the Central Italian Alps occurred between 2009 and 2018. In addition, the dataset has been divided into different subsets based on three parameters (i.e. rock fall volume, elevation and lithology of rock fall occurrence).

As a result, we found that the most relevant controlling parameter is the daily rainfall at the day of the event. In some elevation condition, we could find a correlation between rock fall events and the temperature, as suggested by Paranunzio et al. (2016), but such effect is expected to be much stronger in paraglacial environmens not analysed in this work.

Regarding the lithology, we found that some classes (i.e. foliated rocks) seems to be more prone to rock falling in response to the analysed climatic variables with respect to others.

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