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Discussions

Regional-scale analysis of weather-related rockfall triggering mechanisms in Norway, and its sensitivity to climate change.

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Abstract. This paper evaluates the relation between rockfall events and weather conditions for two regions in Norway – Romsdalen and Gudbrandsdalen and explores how rockfall frequency might change with future climate conditions. Our analysis focuses on understanding the relationship between rockfall occurrence and effective water inputs, including rainfall and snow melt, and temperature oscillations both in cold conditions (freeze-thaw cycles) and in warm conditions (hot-cold cycles). To accomplish this, regional weather data and rockfall information in the Norwegian Mass Movement Database have been employed. Our results indicate that temperature oscillations might be better suited than effective water input to depict the occurrence of rockfalls in the two study areas in Norway. Freeze-thaw cycles are most frequent during winter and spring, and hot-cold cycles are most frequent during summer. Climate change will affect rockfall seasonality and the frequency in which freeze-thaw cycles and hot-cold cycles are observed. Thus, altering the exposure of population and infrastructures to rockfalls.

Keywords: Rockfalls, climate, triggering mechanisms, climate change, Norway

1 Introduction

In Norway, rockfalls constitute a significant hazard, accounting for almost 50% of the Norwegian National Mass Movements Database entries (Jaedicke et al. 2009). Rockfalls commonly impact the functioning of infrastructure assets such as roads and railways and occasionally damage buildings or result in fatalities.

Rockfall-triggering mechanisms are complex. Rockfall occurrence strongly depends on intrinsic factors such as the weathering of the rock mass and the orientation, spacing and continuity of the rock joints. Rockfalls are often triggered by external factors such as biological and human activity (Paterson 1996) and earthquakes (Keefer 1984; Marzorati et al. 2002) and multiple meteorological conditions. Numerous examples in the literature emphasize the importance of climate conditions on the initiation of rockfalls and rockslides. Rockfall activity during summer is generally associated with heavy rainfall (Mateos et al. 2007; Delonca et al. 2014; Melillo et al. 2020). Rainfall and snowmelt infiltration increases the rock joint's water pressure and reduces shear strength. Additionally, water percolation within the rock joints can cause a loss of cohesion by removing clayey material and facilitating the dissolution of minerals. Several authors argue that rockfalls are more frequent when temperatures oscillate around 0 ºC (Mateos et al. 2012; D'Amato et al. 2016; Matsuoka 2019; Hales and Roering 2007). This fact is usually attributed to the formation and melting of ice in rock joints and its subsequent expansion, leading to failure.

Recently, several studies have highlighted the importance of cyclic thermal stressing in the initiation of rockfall. Cyclic temperature oscillations within the rock lead to deformation, work cycles, and stresses that can fracture the rock mass (Gunzburger et al. 2005; Gunzburger and Merrien-Soukatchoff 2011; Collins and Stock 2016; Collins et al. 2018; Gasc-Barbier et al. 2021).

Current practice for risk reduction relating to rockfall hazards is almost entirely reliant on structural mitigation. Structural mitigation of rockfall hazards at regional scales is costly and impractical. Early warning systems are tools to depict the time and location of future hazard events so that emergency managers and other stakeholders can act to evacuate persons in advance. Thus, early warning systems can constitute a suitable alternative to structural interventions and mitigate risk by reducing exposure. For the case of shallow landslides and debris flows regional-scale early warning systems have been widely adopted to predict occurrence of future landslide events (NOAA-USGS Debris Flow Task Force 2005; Kirschbaum and Stanley 2018; Segoni et al. 2018; Park et al. 2019; Palau et al. 2020). Such systems generally employ rainfall thresholds to distinguish between the weather conditions prone to triggering landslides and those that are not (Caine 1980; Guzzetti et al. 2008; Abancó et al. 2016; Gariano et al. 2020; Oorthuis et al. 2023).

Due to the diversity of rockfall climate triggers, determining thresholds relating climate variables and rockfall occurrence that can be applied for regional-scale rockfall warning is more complex. To date, only a few authors have explored this possibility. Delonca et al. (2014) analysed the correlation between rockfall occurrence, precipitation and temperature in Réunion, Burgundy and Auvergne. Melillo et al. (2020) obtained rainfall thresholds to determine the possible occurrence of rockfall in the Canary Islands (Spain). In the Aosta Valley, Bajni et al. (2021) analysed multiple meteorological factors, including rainfall, freeze-thaw cycles, and wet-dry cycles, to find correlations between such and rockfall occurrence. Nissen et al. (2022) used a logistic regression to quantify rockfall probability in response to changes in pore water content and freeze-thaw cycles. In Norway, Sandersen et al. (1996) and Jaedicke et al. (2008) analysed the rainfall conditions before rockfall events. However, although they were able to identify a clear correlation between rainfall and rockslides, they could not identify any clear correlation between rockfalls and rainfall events.

Climate change predictions suggest that Norway will experience more extreme weather events. This includes an increased number of severe rainfall events, an increase in the average temperature, a reduction of snow-cover days (Hanssen-Bauer et al. 2017), and the consequent reduction of permafrost areas (e.g. Gisnås et al. 2013). Thus, to assess the frequency of future rockfall events at a national level, it is essential to understand the relation between rockfall-triggering mechanisms and climate. The objectives of this study are: (i) to understand the relationship between rockfall initiation and climate in two study regions in Norway (ii) to explore the possibility of using climate data to establish thresholds for rockfall early-warning at a regional-scale, and (iii) to discuss how climate change will influence the future occurrence of rockfalls.

The results of this study will be valuable for both academic research and practical applications in rockfall risk management in Norway and other mountainous regions with similar climatic conditions. Additionally, the findings of this study will contribute to the development of early warning systems and risk management strategies at a national level in Norway.

2 Description of the study areas

For the analysis of the climate conditions prior to rockfall events we have focused on two study areas in Norway (Figure 1): (i) Romsdalen and (ii) Gudbrandsdalen.

The Romsdalen area is located on Norway's west coast, and usually experiences weather systems originating from the north Atlantic. According to the Köppen-Geiger climate classification system (Köppen 1884; Beck et al. 2018) Romsdalen area experiences an oceanic climate, characterized by substantial annual precipitation (exceeding 2500 mm) and moderate daily and yearly temperature variations. September, October, November and December are the months during which the largest precipitation amounts are recorded. The bedrock lithology in Romsdalen area mainly consists of granite and granitic gneisses.

Gudbrandsdalen is a major north-south valley in the Innlandet County, central southern Norway. The region landscape presents a glacial morphology with large floodplains along the river and steep valley sides covered by till deposits and outcropping heavily weathered schists that act as a source for rockfalls. The climate in the Gudbrandsdalen area is relatively dry and according to the Köppen-Geiger climate classification system (Köppen 1884; Beck et al. 2018) it can be defined as continental. The average annual precipitation recorded varies over the region, but some areas receive less than 300 mm/year. June, July and August are the months with the highest precipitation with a monthly average exceeding 50 mm.

Due to its location the Gudbrandsdalen area is an important node of communication. The E-6 road that link Oslo and Trondheim, the Rv-15 road linking the East and the West of Norway, and the county roads Fv-418, Fv-435 and Fv-436 cross the area and are in some sections highly exposed to rockfall events. Similarly, the E-136 road which crosses the Romsdalen area from West to East, and the popular scenic county road 63 are also very exposed to rockfalls.

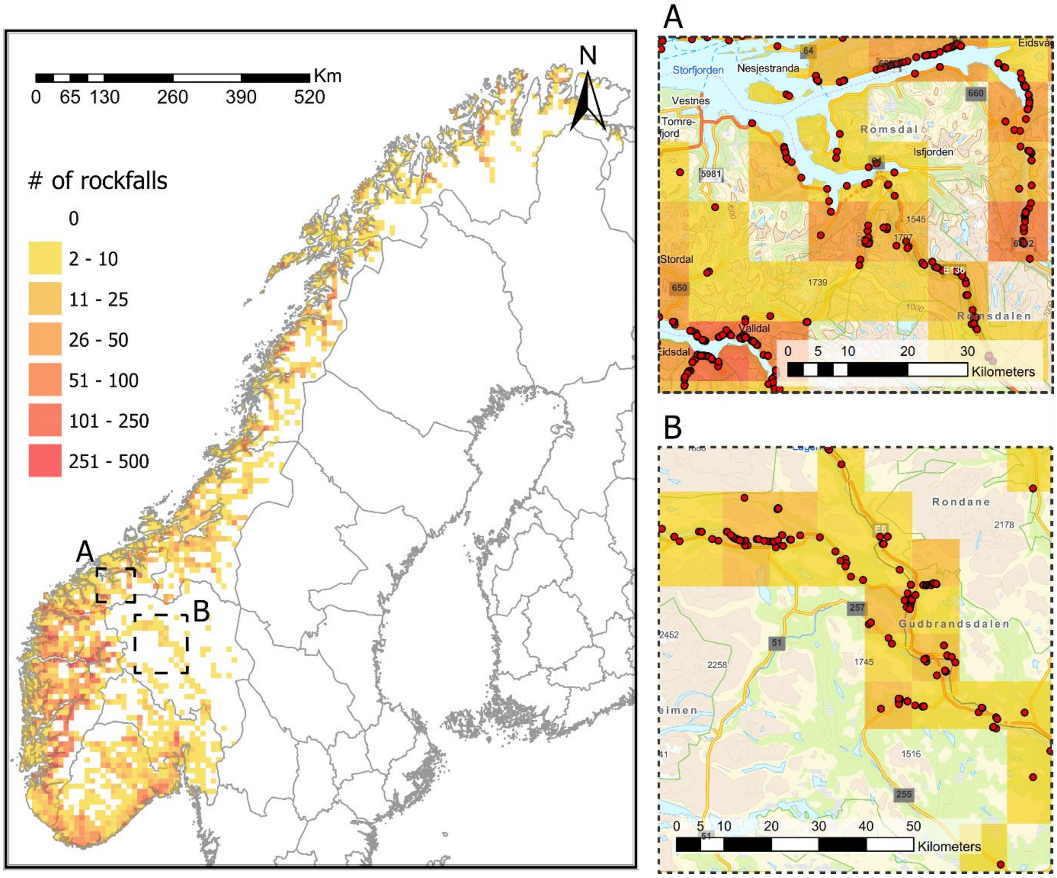

Figure 1 Intensity map showing the number of rockfalls in 10 km^2 grid-cells and zoom into the location of the two study areas (A) Romsdalen and (B) Gudbrandsdalen. The red circles represent the rockfall events included in the Norwegian National Database. N50 dataset (Kartverket 2023) is used as a background map in boxes (A) and (B).

3 Data

3.1 Meteorological data

Daily gridded rainfall and snowmelt information and 3-hourly temperature data, at 1 km resolution (Lussana et al. 2019; Lussana et al. 2019) for the period 2013-2022 have been provided by the Norwegian Meteorological Institute (MET Norway) and The Norwegian Water Resources and Energy Directorate (NVE).

Both rainfall and temperature products result from the interpolation of observations at weather stations using a method based on optimal interpolation (Gandin and Hardin 1965). The interpolation of precipitation combines rain-gage measurements with numerical weather predictions to obtain an improved description of the rainfall field over Norway (Lussana et al. 2019; Lussana et al. 2019).

Regarding the temperature product, temperature measurements at weather stations are first projected to sea level. Then, residual kriging is applied for the spatial interpolation of the temperatures. Finally, the estimated temperatures are readjusted to terrain topography by using a 1 km resolution Digital Elevation Model (DEM) to apply altitude temperature lapse rates (ATLR) (Tveito et al., 2000).

However, rockfalls are usually detached from steep slopes which are not well represented in 1 km resolution DEM. We have benefited from the information contained in a 10 m resolution DEM (*DTM 10 - Geonorge Register*, n.d.) and further adjusted the temperature estimates using a constant lapse rate of 0.0063 ºC/m. It is known that several other factors influence the bedrock temperature on a local scale, the most important being aspect (Hipp et al. 2014). However, in our regional analysis temperature has not been adjusted to slope orientation.

The adjusted air temperature time-series has been compared to the measured rock wall temperature time-series at the Marstein site, in the Romsdalen area, which was instrumented by the University of Oslo (Magnin et al. 2019). Generally, both the adjusted air temperature and the measured rock wall temperature show a similar trend. However, the rock wall temperature is generally lower than the air temperature during the winter months, and often higher than the air temperature during summer.

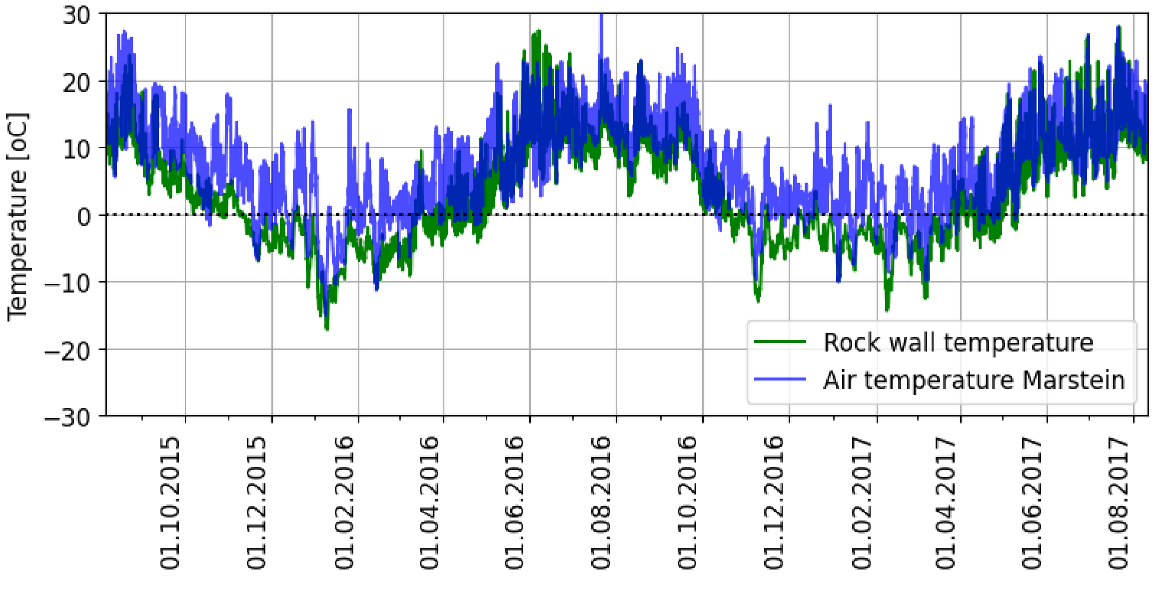

Figure 2 Comparison of the rock wall temperature measured by monitoring at the Marstein rock wall, and the adjusted air temperature during the period 2015- 2017.

The used snowmelt information is the output of the GBW snow model (Saloranta 2012; Saloranta 2016). The GBW snow model is based on the snowpack water valance from the HBV hydrological model (Sælthun 1996) and applies daily mean temperature and 24 h rainfall accumulations as input parameters.

Table 1Summary of the input datasets used for the study.

Temperature	Grided 1x1 km 3-hour resolution Interpolation of readings at meteorological stations
Rain	Gridded 1x1 km Daily resolution Interpolation of readings at meteorological stations and output of numerical weather models
Snowmelt	Gridded 1x1 km Daily resolution Hydrological model
Inventory of 2 areas	**Romsdalen**: 311 events from 2013-2021 **Gudbrandsdalen**: 190 events from 2013-2021

3.2 Rockfall inventory

The Norwegian National Mass Movements Database gathers information of historic rockfalls, rock avalanches, landslides, debris flows, snow avalanches and icefalls that have happened in Norway. The database is managed by NVE and collects the information from various sources such as historical records, the NVE archives, citizen reports, and field observations by experts and infrastructure operators (Ekker et al. 2013).

The Norwegian National Mass Movements Database includes 6352 historic rockfalls and rock avalanches over the entire Norway. For this study, we have employed the information on rockfalls triggered within the two selected study areas from 2013 to 2021. The used inventory contains 190 rockfall events in the Gudbrandsdalen area (Figure 1 a), and 311 rockfalls in the Romsdalen area (Figure 1 b).

One of the limitations of the Norwegian National Mass Movements Database is that it comprises single rockfall events. Thus, recurrent rockfall events happening at the same site are usually not recorded. Another limitation of the available inventory data is that it contains mainly rockfalls that have affected linear infrastructure (with the majority along roads) or buildings. Rockfalls happening in remote areas are usually unreported (Figure 1).

Furthermore, a third limitation of the inventory is that rockfall events are generally mapped in the deposition areas which can have a very different elevation from the release areas. To limit the spatial uncertainties on the location of rockfall events, the information contained in the Norwegian National Mass Movements Database attribute tables, aerial imagery, and slope maps have been employed to manually move each rockfall event included in the analysed inventories to the most provable release

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area. Then, a 10 m resolution digital elevation model (DEM) has been used to determine the orientation of the slopes at the rockfall release areas and its elevation.

4. Analysis of the rockfall inventory data

In the Gudbrandsdalen area, around 54 % of the rockfalls triggered during the analysed period were registered during the period between 2015 and 2020. 2020 is the year with the largest number of rockfall reports in the Gudbrandsdalen area. In the Romsdalen area around 50 % of the rockfalls were triggered between the years 2016 and 2018 (Figure 3 a).

Regarding the monthly distribution of the registered rockfall events (Figure 3 b), in the Romsdalen area rockfalls were registered with a relatively constant frequency throughout the year. However, rockfalls were observed with a higher frequency during January, February, March and October. Around 40 % of the rockfalls in the inventory of the area were recorded during those three months. In the Gudbrandsdalen area, the frequency of rockfalls during spring and autumn is significantly higher than the frequency of rockfalls triggered in summer and winter. Around 60% of the rockfalls in the Gudbrandsdalen area were triggered during February, March and April. March is the month with the highest frequency of observed rockfalls, followed by February and April.

The rockfalls in both areas were generally released from South, South-West and West facing slopes. These orientations correspond to the orientations of the slopes along the European E6 and E-136 roads, which respectively cross the Gudbrandsdalen and the Romsdalen areas from North-West to South-East, and the county roads 63, 6012 and 6020 in the Romsdalen area which have a North-South direction. These orientations can be expected, and illustrate the bias of the available rockfall inventory towards roads and railroads which have been hit by rockfalls. Damage to roads has been reported for 78% of the inventoried rockfalls in Gudbrandsdalen, and 82 % of the inventoried rockfalls in Romsdalen. Rockfall events that have not affected infrastructures or buildings are generally not reported, and therefore are not included in the Norwegian National Mass Movements Database.

The typical elevation rockfall release areas in the two regions are rather different. In Gudbrandsdalen most of the observed rockfalls were provably released from elevations ranging from 350 m a.s.l and 850 m a.s.l. In the Romsdalen area most of the recorded rockfalls were released from lower elevations, mainly ranging between 0 and 500 m a.s.l. The elevation is not directly related to any geologic feature in any of the two areas.

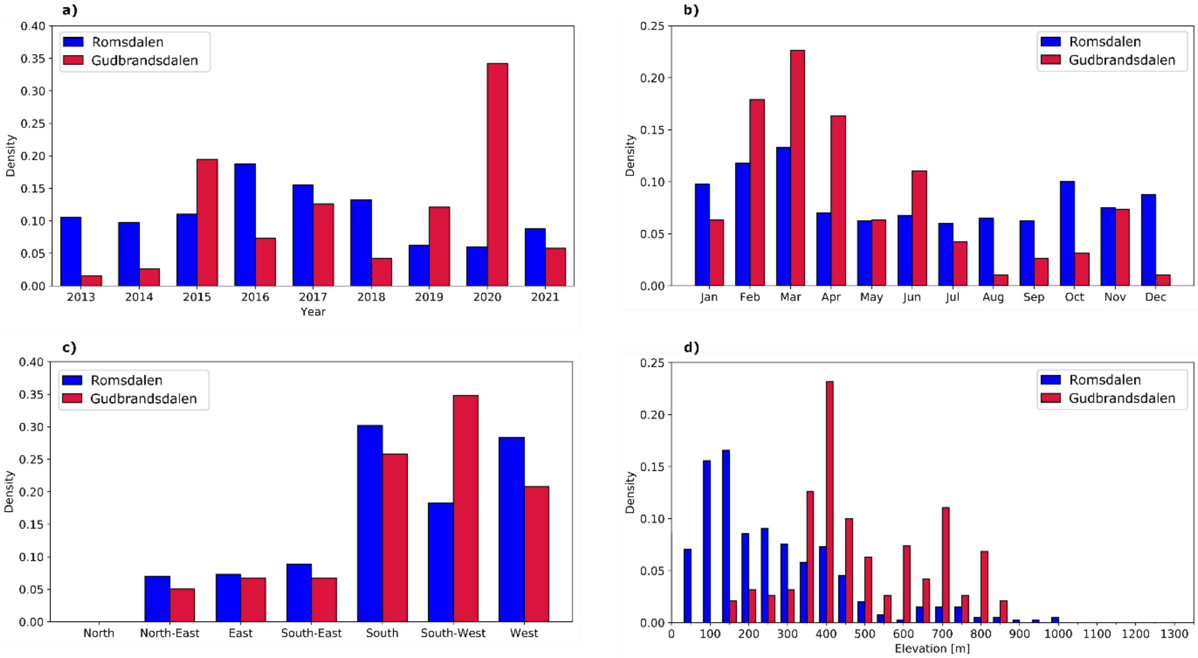


Figure 3 Histograms showing the distributuion of rockfall reports from the Norwegian National Mass Movements Database in the Romsdalen and Gudbrandsdalen areas. (a) Yearly-distribution of rockfall events, (b) monthly distribution of rockfall events, and release area (c) slope orientation, and (c) elevation.

4.1 Identification of the seasonality and relevant meteorological triggers of rockfalls in the study areas

In this section, we have focused on identifying possible relevant weather-related triggering mechanisms of rockfalls in the two study areas using the available meteorological data at a regional scale. To do so, the air temperature, and rainfall and snowmelt water accumulations (from now on, effective water inputs) time series at the location of the events in the inventory have been visually examined.

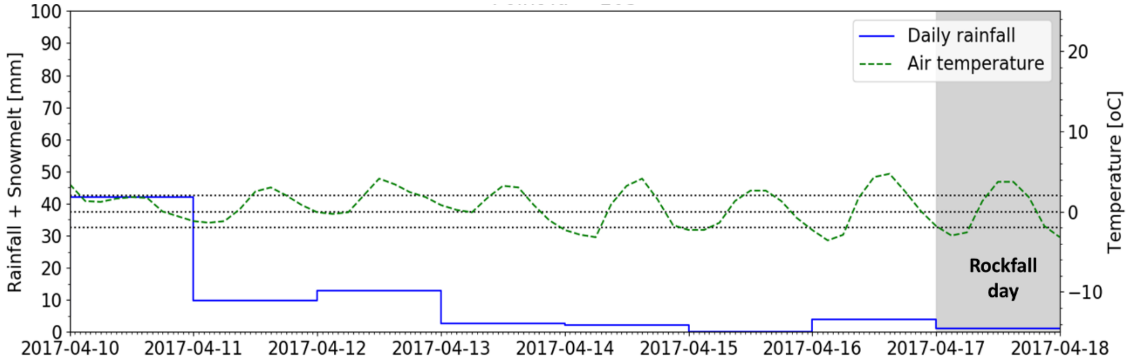


Figure 4 Example of the time-series of air temperature and rainfall and snowmelt water accumulation during the week before a rockfall event was registered.

During the week before the rockfalls were recorded, we have generally been able to observe the following patterns: (i) Temperature fluctuations around 0˚C (Figure 4) which we have associated to freeze-thaw cycles, (ii) significant temperature oscillations above 0 ˚C during summer which we have been related to hot-cold cycles, and (iii) accumulation of effective water inputs exceeding 10 mm.

The majority of rockfalls in the Gudbrandsdalen area can be attributed to one or more weather-related triggering conditions (Figure 5 a). Our analysis shows that freeze-thaw cycles are the most frequent triggering factor, identified as the trigger of 33% of rockfalls in the area. Additionally, the combination of freeze-thaw cycles and effective water inputs has been identified as the trigger of 12% of rockfalls in Gudbrandsdalen. Hot-cold cycles are also relevant and have been recognised before 14% of registered rockfalls in the area. Effective water inputs are identified as the only triggering factor for only 6% of events in the Gudbrandsdalen. Around 35% of registered rockfalls in the Gudbrandsdalen area cannot be related to any of the studied weather-related triggering factors using the available hydrometeorological data.

In the Romsdalen area, approximately 50 % of the rockfalls included in the inventory can be attributed to a weather-related triggering mechanism (Figure 5 b). In this area, both effective water inputs and freeze-thaw cycles play a relevant role in rockfall initiation. Effective water inputs have been identified as the only triggering factor for 16.5 % of the rockfalls, freeze-thaw cycles have been distinguished as the trigger of 14 % of the rockfalls in the inventory, and a combination of the two factors has been observed before 10 % of the rockfalls.

In both areas, freeze-thaw cycles have been identified as a trigger for winter, spring and autumn rockfalls (Figure 5). In Gudbrandsdalen, freeze-thaw cycles trigger the largest number of rockfalls during spring. Conversely, in Romsdalen, rockfalls triggered by freeze-thaw cycles are more common during winter. This fact can be partly explained by the different elevation of the registered rockfalls in the two areas. It can also be explained by the different climates that the two areas exhibit. As expected, hot-cold cycles have primarily been identified as the trigger of rockfalls registered during summer. Hot-cold cycles have also been observed before some rockfalls recorded during spring and autumn.

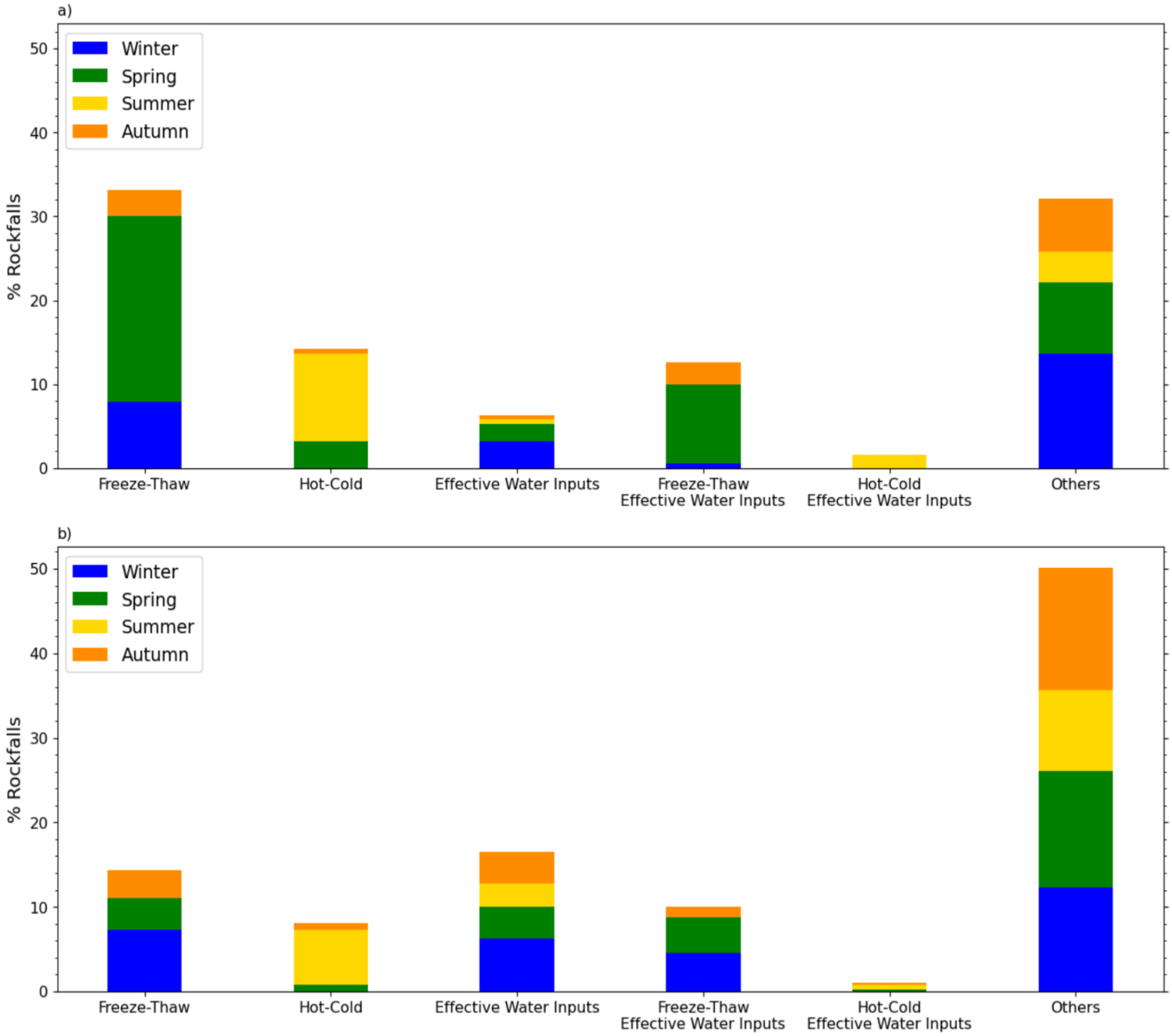


Figure 5 Identified weather-related triggering mechanisms for the rockfalls registered in (a) Gudbrandsdalen area, and (b) Romsdalen area. The different colors represent the seasonality of the events that have been attributed to each of the triggering mechanisms.

5 Analysis of the hydrometeorological conditions before rockfall events and non-events

Based on the preliminary analysis in section 4, we have qualitatively assessed how well the effective water input, number of freeze-thaw cycles, and number of hot-cold cycles, can distinguish the conditions that might lead to rockfalls and the conditions that might not in the two study areas. Additionally, we have analysed if the coupling of temperature cycles and effective water inputs would allow a better classification of the weather conditions that might result in rockfalls.

To assess the relationship between each of the analysed factors and rockfall occurrence, the inventory has been filtered to select only the rockfalls triggered by it. That is to say, to analyse the effect of freeze-thaw cycles, we have selected only the location of rockfalls for which at least two freeze-thaw cycles could be identified during the three days before the rockfall occurred. Similarly, to analyse the effect of hot-cold cycled we have selected the locations of the rockfalls for which at least two hot-cold cycle could be identified during the three days before the rockfall was triggered. Finally, for the case of rockfalls triggered by effective water inputs we have selected the location of those events where at least 10 mm of rainfall and snowmelt had been registered during the three days before the rockfall occurred. This has allowed removing the noise caused by rockfalls that were triggered by other factors.

Then for each day of the period 2013-2022, the number of freeze-thaw cycles, number of hot-cold cycles, and the daily effective water input amounts at the locations of rockfalls have been computed. Finally, the probability distributions of the different factors for rockfall event days and non-event days have been compared to qualitatively assess how well these parameters distinguish the hydrometeorological conditions leading to rockfalls and those that do not.

It is important to note that the rockfall inventory does not contain frequency information. Thus, for the studied nine-year period, at each rockfall location, we have analysed only one rockfall event day and 3276 non-event days.

Finally, in addition to the daily analysis, windows of two days, three days, four days, five days, six days, and seven days have been applied to each day from 2013 to 2022 to compute the density distribution of the different parameters.

5.1 Relation between single-hydrometeorological factors and rockfall occurrence

As expected, the number of freeze-thaw cycles registered before rockfalls events (Figure 6a and c) increases with time. Generally, more freeze-thaw cycles are observed for rockfall event days in the Gudbrandsdalen region (Figure 6a) than in the Romsdalen region (Figure 6c). 75 % of the freeze-thaw triggered rockfalls in Romsdalen were recorded after experiencing at least four freeze-thaw cycles during the seven days before the rockfall took place.

The number of freeze-thaw cycles observed for the majority of rockfall non-event days (Figure 6 c and d) is lower than the number of freeze-thaw cycles observed for the rockfall event days. The distributions of number of freeze-thaw cycles observed before rockfall non-event days are positively skewed. The results presented in Figure 6 indicate that any freeze-thaw cycle has been recorded during the week preceding 50 % of the non-rockfall event days. More than four and two freeze-thaw cycles have been observed only before 25 % of the non-event days in Romsdalen and Gudbrandsdalen respectively.

The size of the boxes in Figure 6 increases with the duration of the time windows, indicating that the variability in the number of observed freeze-thaw cycles before rockfall event days and non-event days is larger when using long durations for the assessment.

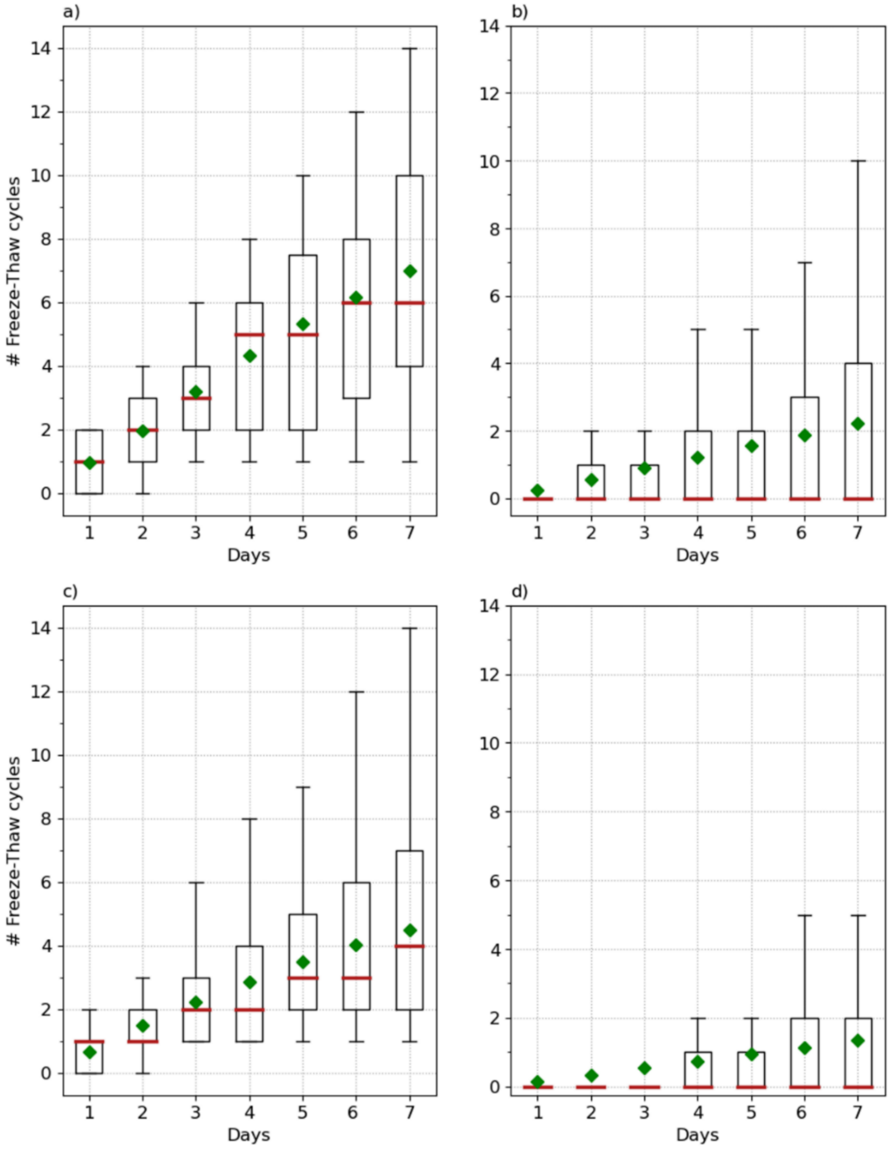


Figure 6 Box plots showing the cumulative number of freeze-thaw cycles observed for different durations before rockfall event days (a) and before no-event days (b) in Romsdalen, and before rockfall event days (c) and before no-event days (c) in Gudbrandsdalen. The red lines represent the median. Green triangles represent the mean number of cycles.

Similarly, the number of hot-cold cycles observed before landslide event days increases with the duration of the time window (Figure 7). As for the case of freeze-thaw cycles the number of registered hot-cold cycles before rockfall event days is larger in the Gudbrandsdalen area (Figure 7a) than in the Romsdalen area (Figure 7b). The variability in terms of the number of observed hot-cold cycles prior to rockfall event days is larger in the Romsdalen area than in the Gudbrandsdalen area, especially if time windows of 4 days or more are applied for the computation.

Generally, no hot-cold cycle has been registered before most of the non-event days in the two areas (Figure 7 b and d). However, in the Romsdalen, around 25 % of the no-event days experience a significant number of freeze-thaw cycles when employing the longer time windows (5, 6 and 7 days). Since the inventory only includes single occurrence of rockfalls, it is possible that some rockfalls which have not been included in the inventory have been triggered during some of the no-event days.

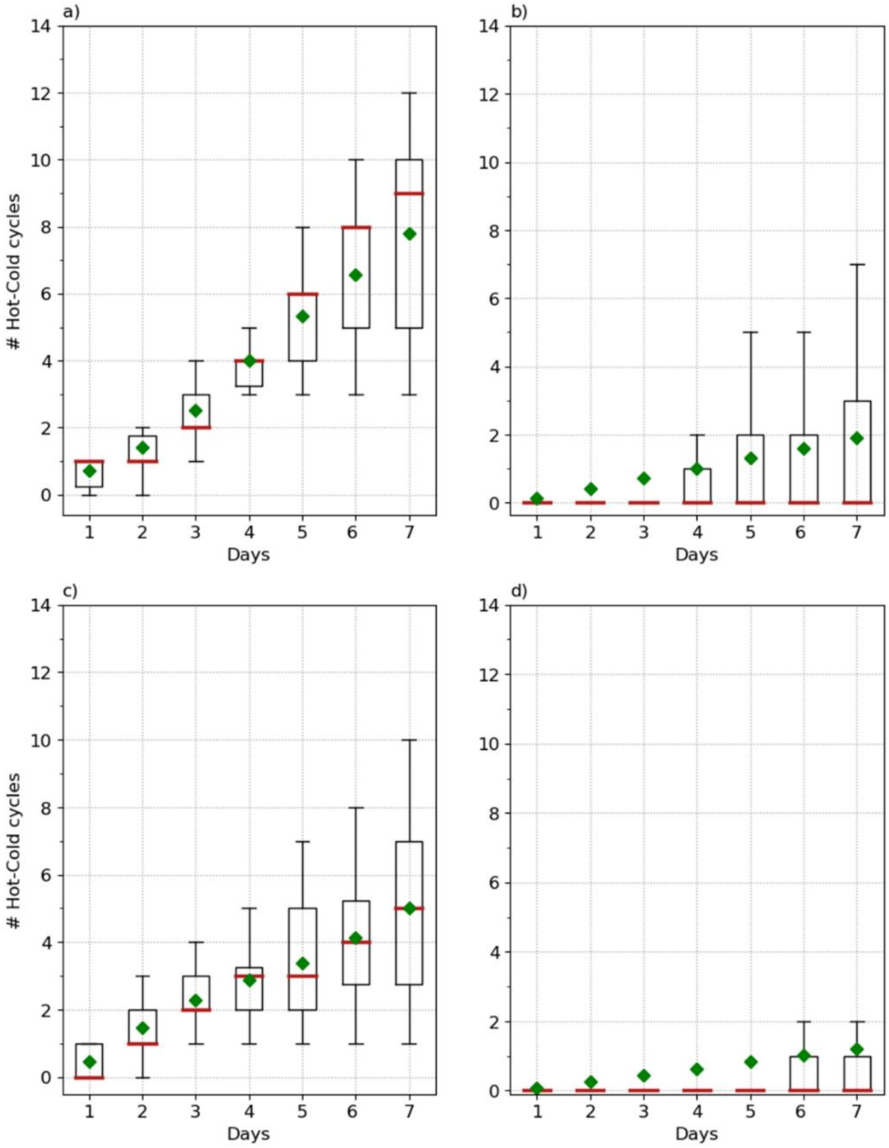


Figure 7 Box plots showing the cumulative number of hot-cold cycles observed for different durations before rockfall event days (a) and before no-event days (b) in Gudbrandsdalen, and before rockfall event days (c) and before no-event days (c) in Romsdalen. The red lines represent the median. Green triangles represent the mean number of cycles.

Regarding the accumulated effective water inputs, our results show that as expected, the effective water input amounts increase with duration of the time window used to compute the accumulations. As expected, lower effective water accumulations are registered in Gudbrandsdalen (Figure 8 a b) than in Romsdalen (Figure 8 c d). This fact can be due to the different climate that the two areas have.

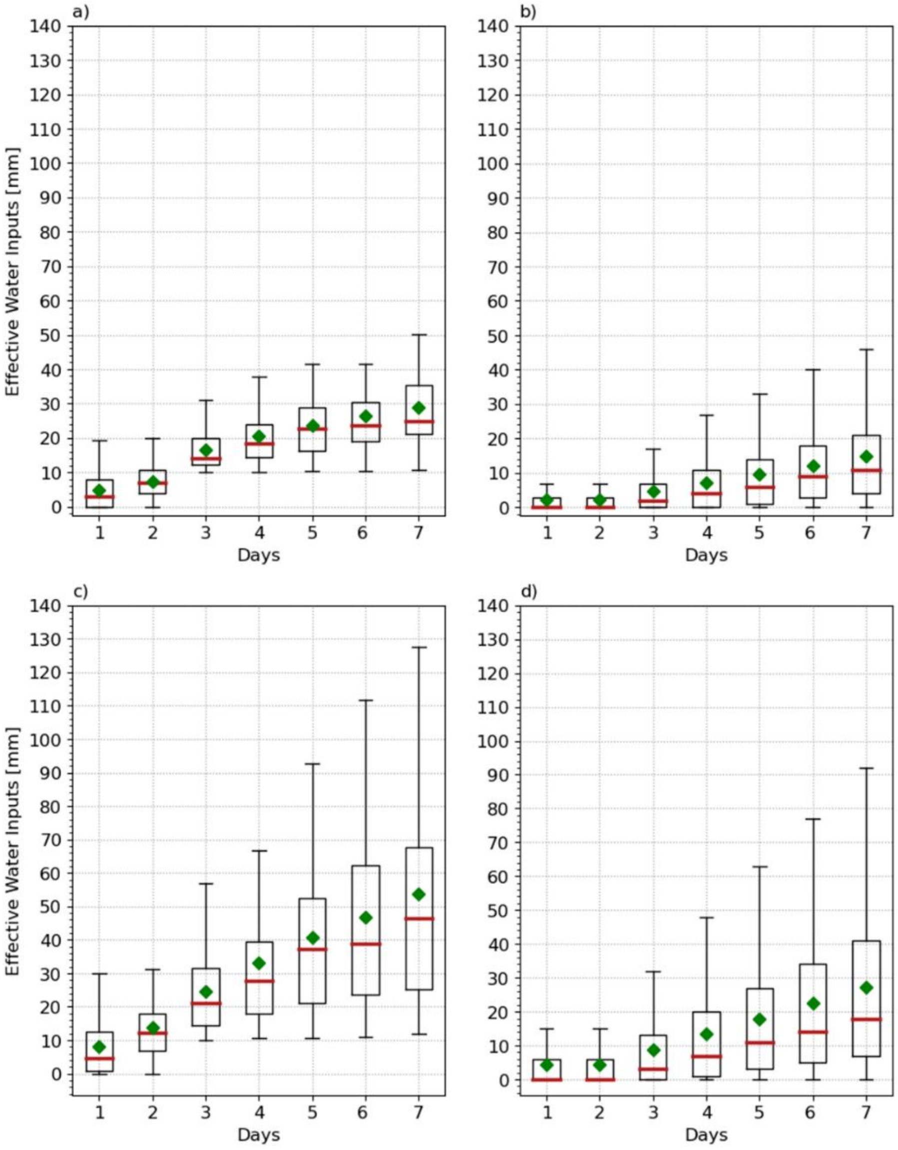


Figure 8 Box plots showing the effective water input accumulations over different durations of rockfall events before rockfall event days (a) and before no-event days (b) in Gudbrandsdalen, and before rockfall event days (c) and before no-event days (c) in Romsdalen. The red lines represent the median effective water input. Green triangles represent the average effective water inputs.

In both areas, the effective water inputs recorded prior to days with rockfall events (Figure 8 a and c) are generally slightly larger than those recorded before non-event days. However, the distribution of the effective water inputs accumulations of event days, and non-event days exhibit a substantial overlap, especially in the Romsdalen area. Therefore, from our results it seems that using the effective water input accumulation as the only parameter to determine rockfall initiation might not be appropriate.

In summary, our results show that in the two areas a larger number of freeze-thaw cycles and hot-cold cycles can generally be observed before rockfall event days than before no-event days. However, we have not observed significant differences when comparing the effective water inputs of rockfall event days and no-event days.

5.2 Analysis of the correlation between multiple-meteorological factors

From the visual analysis in section 0 it has been possible to identify that a large number of the rockfalls in the inventory could be related to a combination of freeze-thaw cycles and effective water inputs, or to a combination of hot-cold cycles and effective water inputs. Herein we have analysed the correlation between the number of freeze-thaw cycles and effective water inputs, and the number of hot-cold cycles and effective water inputs before rockfall events and before no-events in the two areas.

For this analysis, the inventory has been filtered to select only the rockfall events which have been triggered by either freeze-thaw cycles or hot-cold cycles. That is to say, first only the location of rockfalls for which at least two freeze-thaw cycles have been registered within the three days before the rockfall event have been selected. Then, the inventory has been filtered to select only the location of rockfalls for where two or more hot-cold cycles were observed during the three days before the rockfall event day. Since at all the locations we have only one event day, we have analysed a significantly larger number of non-events than events.

Figure (Figure 9 a and b) shows the difference between the distributions of number of freeze-thaw cycles and effective water inputs observed the 6 days prior to rockfall events (Figure 9 a) and no-events (Figure 9 b) in the Romsdalen area. Most of the rockfalls have been observed when the accumulated effective water inputs ranged from 10 mm to 140 mm, and at least two freeze-thaw cycles have been observed. The highest percentage of freeze-thaw triggered rockfalls in Romsdalen have been observed after recording more than four freeze-thaw cycles and for effective water inputs ranging from 10 mm to 50 mm. Generally, no freeze-thaw cycles have been observed before most non-event days. The effective water input accumulation before most of non-event days are quite variable and range between 0 mm and 100 mm.

Generally hot-cold induced rockfalls were registered coinciding with effective water input accumulations that ranged from 0 mm to 90 mm during the previous week (Figure 9 c). However, the majority of the rockfalls that were observed coinciding with the occurrence of hot-cold cycles in Romsdalen where registered for rather low effective water input accumulation (0-10 mm) and two to ten hot-cold cycles during the previous week. No-events days generally coincide with periods where no hot-cold cycle has been observed during the previous week, disregardful of the effective water input accumulations.

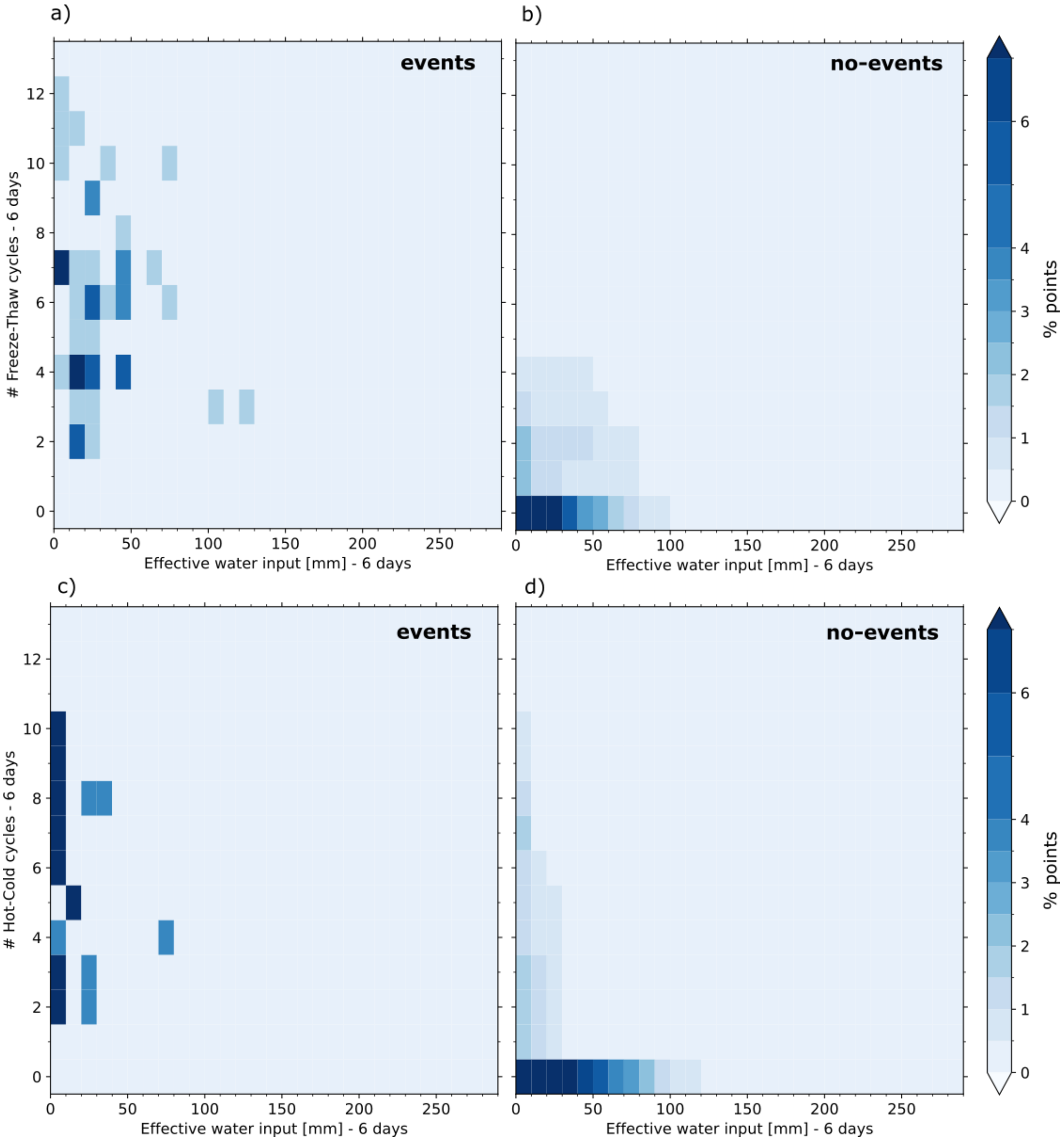
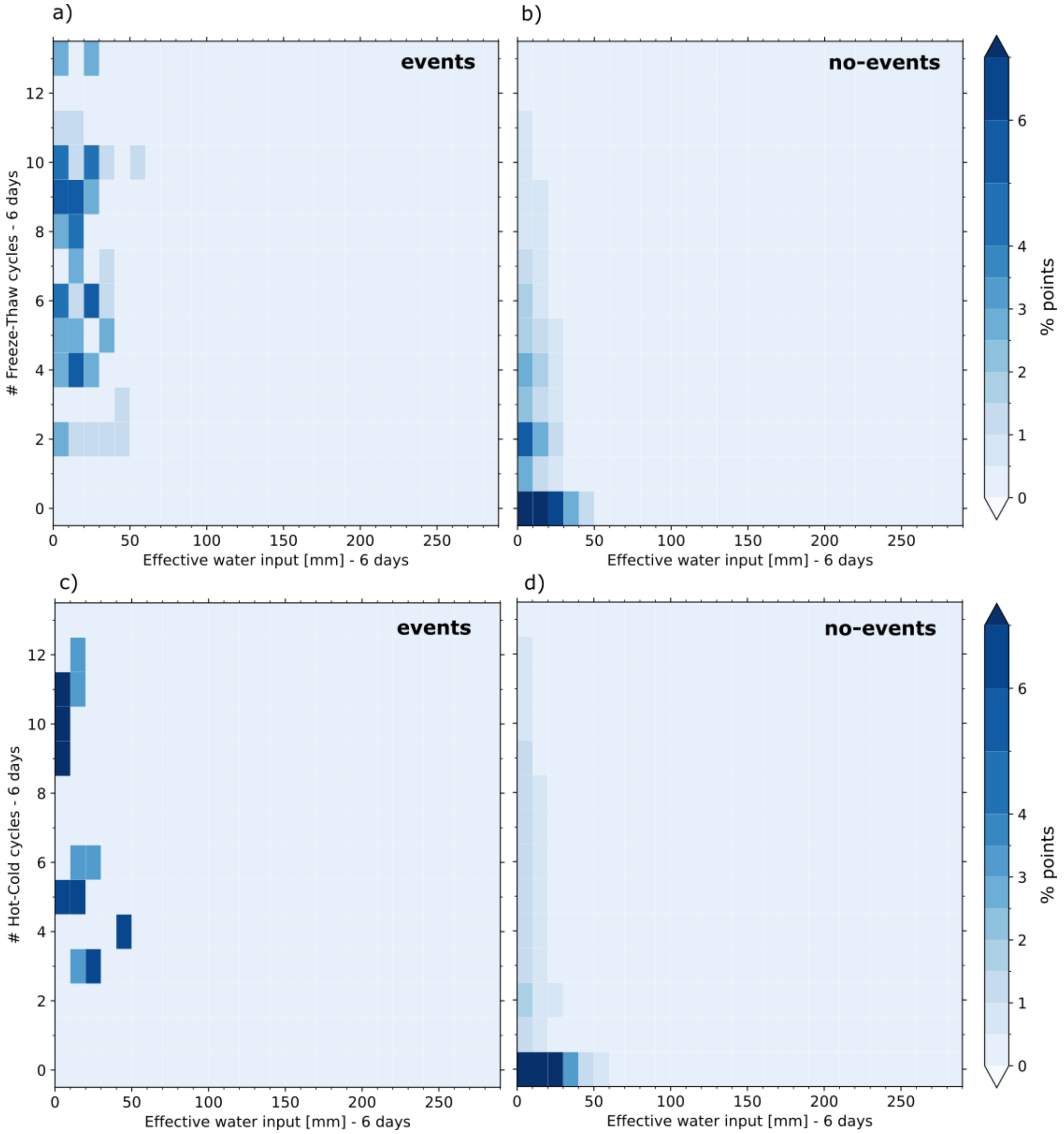


Figure 9 Top panel: density plots of number of freeze-thaw cycles and effective water input accumulations in the Romsdalen area for (a) rockfall events, and (b) rockfall non-events. Bottom panel: density plots of the 6 days number of hot-cold cycles and effective water input accumulation in the Romsdalen area (c) before rockfall event days, and (b) non-event days.

As expected in the Gudbrandsdalen area (Figure 10), the accumulated effective water input before rockfall events and non-event days is generally smaller than in Romsdalen, ranging from 0 to 50 mm. Rockfall events typically occur after at least four freeze-thaw or three hot-cold cycles. (Figure 10 a and c). No freeze-thaw or hot-cold cycle has been observed before the majority of non-events (Figure 10 b and d).

From our results it can be argued that freeze-thaw cycles and hot-cold cycles are more significant factors in rockfall initiation in the two study areas than the accumulation of effective water inputs. In general, it can be expected that rockfalls may occur if there have been at least four freeze-thaw cycles or three hot-cold cycles in the previous week. However, due to limitations in available datasets, it is difficult to determine a classifier that enables us to perfectly depict between rockfall triggering conditions and non-triggering conditions.



305 **Figure 10 Top panel: density plots of number of freeze-thaw cycles and effective water input accumulations in the Gudbrandsdalen area for both (a) rockfall events, and (b) rockfall non-events. Bottom panel: density plots of the 6 days number of hot-cold cycles and effective water input accumulation in the Gudbrandsdalen area (c) before rockfall event days, and (b) non-event days.**

6 Implications for future climate scenarios

Climate projections indicate that until 2100 the average temperature in Norway will increase by more than 1.6°C (Hanssen-Bauer et al. 2017). The increase in temperature is expected to be more significant during the winter months (December, January, and February) than during the summer months (June, July, and August). Regarding precipitation, it is not only expected that the annual accumulations increase between 8 % and 18% by the end of the century but also that the frequency and intensity of extreme rainfall events increase. The Gudbrandsdalen area is among the areas with the most significant increase in short term precipitation, with recommended climate factors of 1.6 for 1 hour precipitation (both with 5 and 200 year return intervals), and 1.4 for 24-hour precipitation (Dyrrdal and Førland 2019). Freeze-thaw cycles and hot-cold cycles, also in combination with precipitation, have been identified as one of the most relevant climatic triggers for rockfalls. Thus, the expected increase in air temperatures might lead to change in the seasonality and the frequency of future rockfall events.

In this section, we examine how climate change will impact the frequency of the meteorological conditions that are relevant for rockfall initiation. More specifically, the changes in the number of days with the following four criteria have been analysed:

- hot-cold cycles: Tmax > 18 °C and Tmax – Tmin > 10 °C
- freeze-thaw cycles: Tmax > 2 °C and Tmin < -2°C
- high precipitation accumulations: RR > 20 mm in Romsdalen, RR > 10 mm in Gudbrandsdalen.
- freeze-thaw cycles combined with precipitation: Tmax > 2 °C and Tmin < -2°C, and RR > 10 mm in Romsdalen and RR > 3 mm in Gudbrandsdalen.

Where Tmax and Tmin refer to the maximum and minimum daily temperature respectively, and RR is the 24-h accumulated precipitation.

Data series of daily rainfall, minimum and maximum daily temperature data for the period 2005 – 2100 have been analysed at one location in Otta, Gudbrandsdalen (780 m a.s.l., ETRS 89 UTM 33N, 213391E, 6860302N) and one location in Trollstigen, Romsdalen (855 m a.s.l., ETRS 89 UTM 33N, 122220E, 6945635N). These locations are chosen at grid cells with elevations relevant to rock fall release areas are. Figure 12 and Figure 11 show the average change in terms of number of days during which the analysed hydrometeorological conditions are expected to occur in future at these two locations. The period 1971-2000 has been used as a reference to assess the expected increase or decrease in the number of days when these conditions will occur towards the end of the century. For our analysis, we have employed 10 climate projections from the RCP8.5 scenario downscaled to 1x1 km spatial resolution provided by the Norwegian Centre for Climate Services (Hanssen-Bauer et al., 2015). The RCP8.5 scenario assumes that greenhouse gas emissions will continue to increase throughout the 21st century, and thus provides a picture of the worst-case scenario.

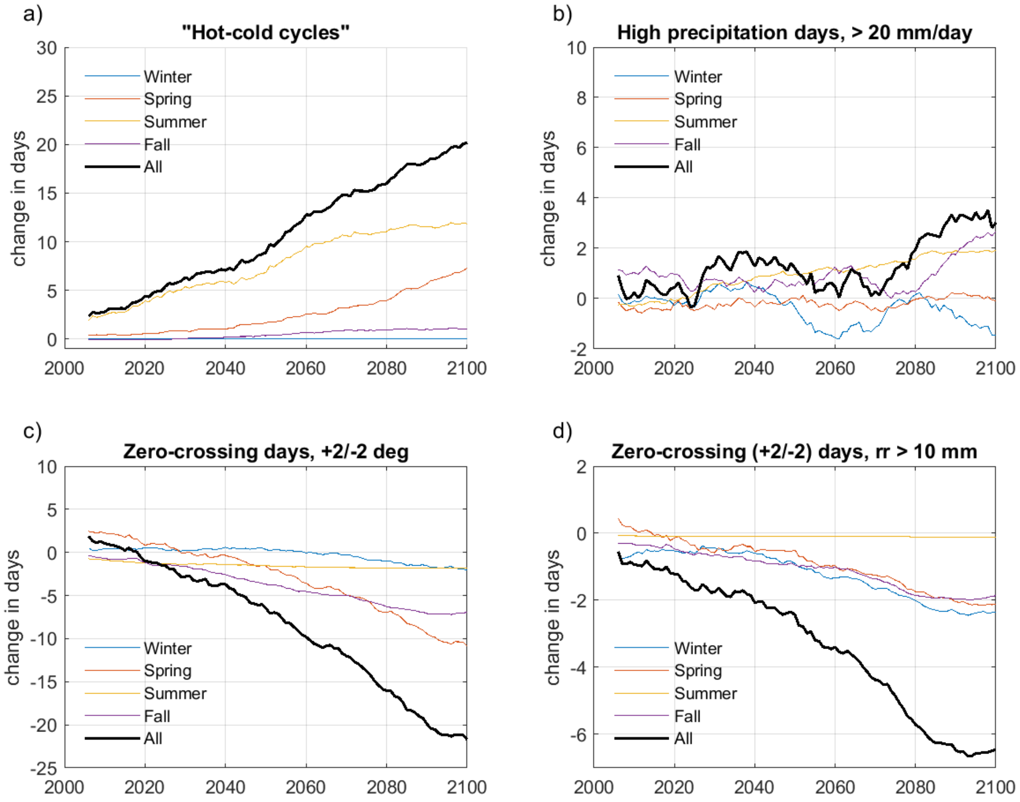
Our results show that the number of days with hot-cold cycles will monotonically increase on average in both areas (Figure 11 a and Figure 12a). Towards the end of the century the number of days with hot-cold cycles is expected to increase by more than 20 days, with the largest increase expected during summer. In Trollstigen this phenomenon will also increase during spring but will remain rather constant during autumn and winter (Figure 11 a). In Otta the number of days with hot-cold cycles are expected to increase during spring and autumn but will remain constant during winter (Figure 12a).

The number of days with significant precipitation in Trollstigen (Figure 11 b) will experience a slightly monotonically increasing trend during summer, will remain rather constant during spring months and will have more variable patterns during winter and fall. In contrast, climate change projections show an increase in the number of days with significant precipitation accumulations recorded during all seasons in the Gudbransdalen area (Figure 12 b).

The number of days with freeze-thaw cycles is expected to experience a decrease on average in the two study areas (Figure 12c and Figure 11c). In Trollstigen, the number of days with freeze-thaw cycles is expected to decrease by more than 20 days. The decrease will be more significant during spring and fall. The number of days with freeze-thaw cycles during winter will remain relatively constant in Otta but will slightly decrease towards the end of the century. In Trollstigen, the number of days with freeze-thaw cycles is also expected to decrease monotonically in spring and autumn (Figure 12c). However, the average decrease in the number of days with freeze-thaw cycles is expected to be less significant than in Otta (around 7 days less).

Similarly, number of days during which freeze-thaw cycles and precipitation will be recorded is also expected to decrease during spring, summer and autumn in Trollstigen (Figure 11d) will but will remain rather constant in winter. Towards the end of the century, the number of days per year with these phenomena is expected to decrease by an average of 6.5 days. However, in Otta the number of days with freeze-thaw cycles and precipitation is expected to decrease to a much lesser extent (Figure 12d). On the one hand, fewer days with such conditions will be experienced during spring and autumn. On the other hand, the number of days with freeze-thaw cycles and precipitation will remain rather constant during summer months and will have more variable trends during winter. On average, the yearly decrease will be of only 1.5 days.

The significant increase in the frequency of hot-cold cycles during spring and summer, and the general decrease in the frequency of freeze-thaw cycles might indicate a shift in the seasonality for rockfalls in the future. Our results show a clear correlation to hot-cold cycles in historic rock fall releases, and in the future a larger number of rockfalls might be expected due to hot-cold cycles during summer. In contrast, fewer rockfalls might be released because of freeze-thaw cycles during spring and autumn, while the number of rockfalls triggered by freeze-thaw cycles might experience a slight increase or remain the same during winter.



365

Figure 11 Trollstigen, 855 m.a.s.l: change in annual days classified as a) Hot-cold cycles, b) high precipitation days, c) Zero-crossing days, and d) zero crossing days with precipitation days. Change is days are relative to the average of the reference period 1971-2000. The numbers are averages derived from of the 10 climate scenarios for RCP8.5 presented in Klima 2100 (Hanssen-Bauer et al. 2017).

370

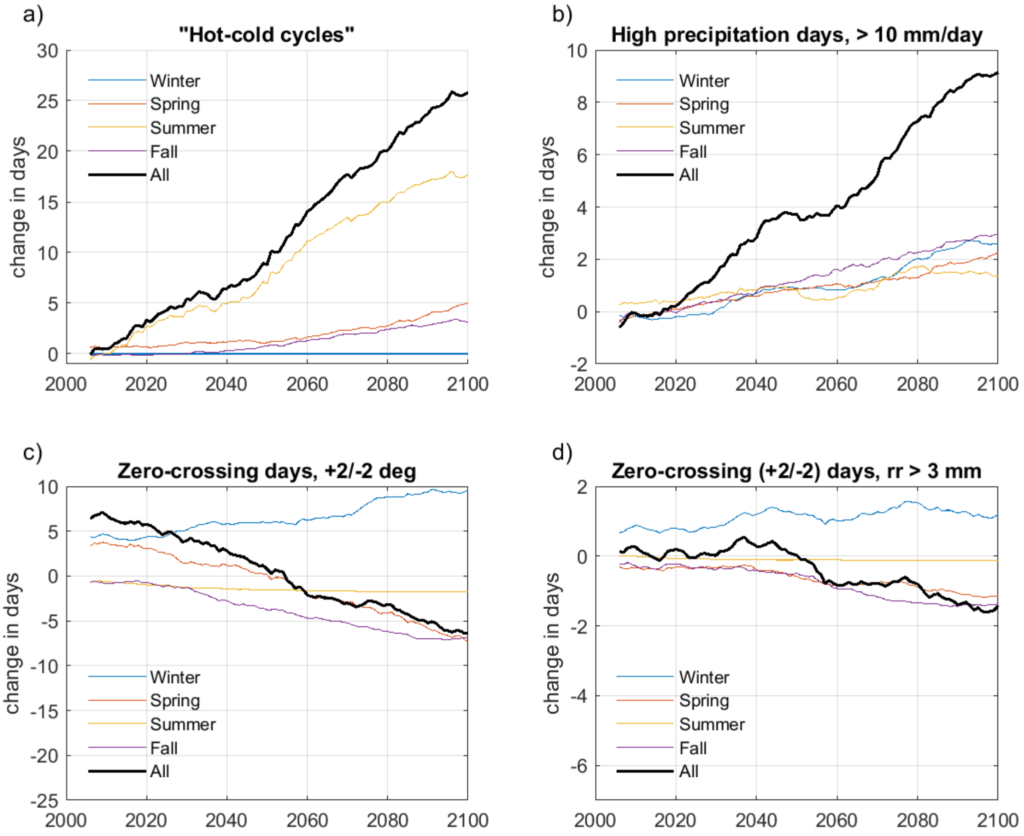


Figure 12: Otta 780 m.a.s.l.: Change in annual days classified as a) Hot-cold cycles, b) high precipitation days, c) Zero-crossing days, and d) zero crossing days with precipitation days. Change is given as change in days relative to the average of the reference periode 1971-2000. The numbers are averages derived from of the 10 climate cenarios for rcp 8.5 presented in Klima 2100 (Hanssen-Bauer et al. 2017).

7 Discussion and conclusions

The aim of this study has been to explore the relation between rockfall occurrence and climate in two areas in Norway that exhibit different climate and improve the understanding on how climate change might influence the rockfall hazard in these two areas. To do so rainfall, snowmelt and temperature data have been employed to identify freeze-thaw cycles, hot-cold cycles and accumulated effective water inputs. In addition, climate models have been run to explore how the rockfall hazard might change in future climate conditions.

One of the limitations of the presented study is the unavailability of continuous monitoring of rockfall events in the two study areas. Therefore, we have focused on identifying the climate related triggers of the rockfalls contained in the Norwegian National Mass Movement Database. This inventory only includes single occurrence of rockfalls. Therefore, it is possible that some unreported rockfalls have been triggered during some of the no-event days. An additional limitation of the inventory is that it is generally biased towards rockfalls that affected linear infrastructure, in particular roads, and that rockfalls are mostly represented at their deposition areas. Identifying the location of rockfall release areas has been a tedious and challenging manual process. This has added uncertainty to our analysis since air temperature considerably varies with altitude.

To analyse the possible climate triggers for rockfalls daily gridded rainfall and snowmelt information, as well as 3-hourly temperature data, available at a national level with a 1 km resolution (Lussana et al. 2019; Lussana et al. 2019) have been employed. However, this approach represents a significant limitation of our method as the weather data might not accurately reflect the conditions within the rock mass.

Our analysis has shown that the frequency in which the different weather-related parameters can be identified prior to rockfall events changes depending on the season. During winter and spring, freeze-thaw cycles are most frequent. In contrast, hot-cold cycles are a crucial factor to consider in the summer months. It has not been possible to identify any of the analysed weather-related factors prior to around 50 % of the rockfalls in Romsdalen and 32 % of the events registered in Gudbrandsdalen. This suggests that non-weather-related parameters such as intrinsic factors of the rock mass, or biological and human activity play an important role in rockfall initiation in the two study areas.

Generally larger effective water input accumulations, and more freeze-thaw and hot-cold cycles have been observed before rockfall event days than before no-event days. Due to the regional differences in the climate, we have identified a spatial variation in the effective water inputs registered before rockfall events in the two study areas. Rainfall and snowmelt are more significant at Romsdalen than in Gudbrandsdalen. However, the distributions of effective water input before rockfall event days and no-events have a considerable overlap, especially in the Romsdalen area. Thus, as already pointed out by Sandersen et al. (1996), predicting the occurrence of rockfalls in Norway based solely on effective water inputs information is not straightforward.

Our results show that the overlap between the distributions of the number of freeze-thaw cycles observed before rockfall event days and no-event days, and the overlap between the distributions of the number of hot cold-cycles observed before rockfall event days and no-event days are less significant. In both study areas rockfalls are more common when at least four freeze-thaw cycles or three hot-cold cycles have been observed during the week before, regardless of the accumulated effective water inputs. This contrasts with the findings by Mateos et al. (2012) who identified freeze-thaw cycles in combination with rainfall infiltration as the most relevant factors for rockfall initiation in Mallorca (Spain), and Bajni et al. (2021) who obtained similar results for rockfalls in Valle d'Aosta (Italy).

From our analysis we can conclude that temperature oscillations might be better suited to predict the occurrence of rockfalls in both Romsdalen and Gudbrandsdalen. This observation agrees well with the findings of Collins and Stock (2016), Villarraga Diaz et al. (2021), and Gasc-Barbier et al. (2021) who stress the importance of temperature oscillations in the fracturing of the rock mass, and the subsequent occurrence of rockfalls. However, defining thresholds for regional-scale early warning of rockfalls with the available data is still challenging. This fact could be partly due to the limitations in the inventory data, and the available temperature data. It may also indicate that non-climate related triggering mechanisms are important for rockfall initiation.

The analysis of future climate projections in the two areas allows us to anticipate that towards the end of the century, there will be a general decrease in the average number of freeze-thaw cycles. Conversely, a significant increase in the number of days with hot-cold cycles experienced during summer is expected. In addition, the number of days with severe precipitation events in Gudbrandsdalen is expected to increase significantly. This fact might imply a change in the seasonality and triggers of future rockfall events in the two study areas.

In summary, the presented results provide valuable insights into the complex relationship between climate and rockfall occurrence, which can inform future research and risk reduction strategies. Further research is needed to explore the potential of using cumulative temperature oscillations as a threshold for rockfall early warning at the regional scale. In this regard, having a more exhaustive time-series of rockfalls events at some locations could help improve our analysis. Additionally, rock temperature measurements could be used to establish the relationship with air temperature in a similar way as done by Hipp et al. (2014).

Competing interests

The contact author has declared that none of the authors has any competing interests.

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Author contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Rosa M Palau and Kjersti Gisnås. The first draft of the manuscript was written by Rosa M Palau and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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