<u>Response to comments: Referee #1</u>

On behalf of all authors I would like to thank the referee the time implied in revising our work. As follows you will find a point-by-point response to your comments, with your comments in ***bold-italics*** and our responses in normal font.

In this article, Roman Quintero et al. project changes in landslide frequency due to climate change for a small region of mountainous Italy. They combine a previously developed physics-based landslide hazard model with ensemble forecasts of bias-corrected rainfall time series to produce their projections and analyze their results with multiple statistical methods. They found that the frequency of landsliding in their study area was generally projected to increase, although to varying degrees based on locality, future scenario, and season, with changes to the timing of rainfall having strong control on predicted frequencies. As part of their workflow, they also found high ensemble confidence that shallow soils in the region will be drier across seasons by 2070 than today.

The reviewer clearly understood the overall conceptual workflow and the core development of our contribution.

Overall, I find that the article fits the journal scope well, is written fairly well, and advances the science with a novel approach at a relatively small scale. My comments to improve the manuscript are minor and focused on clarifying aspects of the paper that I didn't fully understand. This includes some additional descriptions of the methods, explanation of the results, and further discussion of a few points. I look forward to seeing this interesting and important article in print.

On behalf of all coauthors, we appreciate the judgement with a positive balance of the referee on our work. We Thank you for the positive comments and we hope this work will inspire future contributions on this field.

Specific comments

Line 214: I'd like to see just a bit more methodological description here: what is the spatial structure and resolution of the FS predictions (i.e., raster grid cells? resolution?); is the failure plane also 2 m below the surface?

Thank you for raising this interesting question. The Factor of Safety (FS) estimations were conducted on a physical basis, reflecting conditions observed during major landslide events in the area (Greco et al., 2021). Although our study covers a subregional area, we did not perform a grid-based analysis that accounts for shifting geomorphological conditions. Instead, we intentionally used a standard slope class, treating geomorphological conditions as static variables. This approach minimizes 'noise' from geomorphological variability that might otherwise obscure signals from climate shifts and, more importantly, high climate variability, which operates on much shorter timescales than geological processes. However, we acknowledge the importance of these static geomorphological characteristics and will provide a more detailed explanation of our methodology in the revised manuscript.

Line 251: 10 ensemble members per scenario? 9 EURO-CORDEX members (lines 242-243) + 1 VHR-PRO_IT member?

Thank you for catching it. We actually used 8 EURO-CORDEX members +1 VHR-PRO_IT per scenario. We will make it clear in lines 242-243.

Lines 258-259: "limited by data availability in the VHR-PRO_IT dataset" do you mean that this data is only available through 2070? I didn't see this mentioned before, consider moving it to the previous paragraph (lines 244-250)

Thank you for raising this issue. The analysis was indeed done until 2070 because VHR-PRO_IT projections are available up to 2070. We will add an extra description to make it more clear in the revised version of the manuscript.

Line 304: don't hyphenate "bias-correction"

Thank you for catching it. We will correct it throughout the manuscript.

Line 338: "Rainfall hyetograph is known to be related to slope instabilities" I'm confused by this sentence, could you please expand on what is meant

Slope stability is sensitive to both internal and external factors, particularly the soil moisture state prior to a rainfall event (Marino et al., 2020). Recent studies indicate that regarding landslide-triggering events, the temporal distribution of rainfall can play an important role (Natalia and Yang, 2026). Specific rainfall patterns preceding a triggering event can create the conditions necessary to induce slope instabilities. In the case under study, the combination of a late-peak antecedent hyetograph followed by an early-peak triggering hyetograph appears particularly significant; this sequence results in wetter initial soil conditions, potentially triggering landslides with lower total rainfall volumes. We agree this warrants further analysis and will rephrase line 338 to encourage broader discussion within the community.

Lines 355-357: a bit more description here, please. For instance, am I correct in assuming that only 1 landslide can be predicted per storm event? Or is it 1 storm can be predicted in every 3-hour timestep such that a storm can produce more than one landslide at a given location? Or something else?

We appreciate this important suggestion regarding our event identification methodology. Your considerations are right. Landslide events were identified within the rainfall time series by monitoring the Factor of Safety (FS) of the slope. An event is recorded whenever the FS drops from a stable state (FS > 1.1) to a critical state (FS ≤ 1.1).

Our model simulates the physical processes governing slope stability, including rainfall infiltration, accumulation, and drainage, under unsaturated conditions. To ensure a robust statistical count, landslides triggered by the same continuous rainfall event are counted only once. Conversely, in the event when the FS drops below 1.1, recovers through drainage, and then drops below the threshold again, the occurrences may be recorded as two distinct events.

As depicted in Figure R1.1, we categorize these triggers based on the timing of the critical state:

- **Case 1:** If is reached during a dry interval following a storm (due to the lag in rainwater infiltration), the trigger is associated with the preceding rainfall event.
- **Case 2:** If the critical condition is reached during active precipitation, the landslide is associated with the ongoing event.
- **Case 3:** If subsequent rainfall occurs while the slope is already in an unstable state, these secondary pulses are not counted as new landslide events.

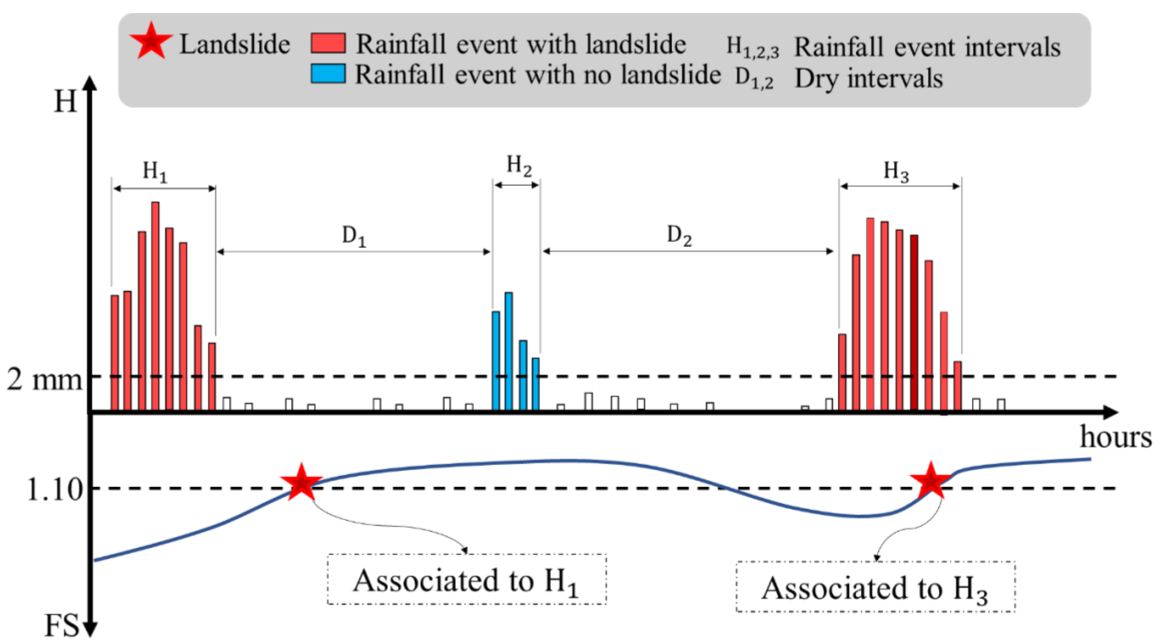

Figure R1.1. Landslide event definition scheme associated to various cases: Case H_1) FS≤1.1 after the end of a rainfall event (H_1) in a dry interval (D_1); Case H_3) FS≤1.1 within a rainfall event (H_3). From: Roman Quintero et al., 2025

We will add a more detailed description of this matter in the materials and methods section of new version of the manuscript.

Lines 358-359: Equation (1) is just an ensemble average, correct? i.e., the summation argument could be $\lambda_{LS,i}(t)$, the landslide frequency in year t for ensemble member i (equivalent to $N_{LS,i}(t)$ when measured over a time period of one year)

$\lambda_{LS,i}(t)$ can indeed be considered as an ensemble average, as it represents the average number of landslides per year for each ensemble.

Line 399: could you provide a sentence or two more on the patterns in CTRL displayed in Figure 6? Unless I'm missing something, some of them are surprising given that the current climate rainfall time series was drawn from a static distribution based on historical observations. For example, why does CTRL storm duration increase over time in panel (b)? Why does soil water content decline when PET is also kept the same?

These are indeed very interesting questions. Although the rainfall generator utilizes static statistical parameters to produce the CTRL rainfall, minor trends can emerge due to the stochastic variability inherent in random rainfall generation, which reflects the variability of observed rainfall over the relatively short analysis period. In fact, Figure 6, at the beginning of the Results section, already raises fundamental questions that this research aims to address. First, as mentioned above, trends may arise from stochastic processes. However, when analyzing rainfall-triggered landslide occurrence, statistical evidence shows that trends within climate change scenarios exhibit clear differences compared to the CTRL scenario, as demonstrated in Section 3.2.1.

Line 402: In Figure 6, what does the red and blue shading in each plot signify? I would guess the output range of the climate change ensemble, but it isn't stated clearly.

Thank you for catching it. Shaded areas represent the standard deviation for each climate change scenario: RCP4.5 (blue) and RCP8.5 (red). We would add a particular description further clarifying this point in the new version of the manuscript.

Line 413-414: Please move the sentence describing the use of Voronoi polygons to the Methods section, probably lines 149-154.

Thank you for this suggestion. We will move this part to the method section where it belongs, in the new version of the manuscript.

Line 417: Making sure I understand Figure 7 correctly, would –(53%) mean that the remaining 47% of the ensemble found a positive trend? Or would some fraction of that also include members that found no trend?

When in figure 7 one finds a –(53%) it means that the remaining 47% has a positive trend. In this case there is no statistical testing of trends so we're reporting the positive or negative sign of the trend. We will add couple lines to the new version of the manuscript to make it more clear.

Line 443: In Figure 8, I would appreciate if you added the ensemble shading of Figure 6 to these plots, too, in order to understand the spread in model predictions (and thus inform our confidence). Also applies to Figures 9 and 11 (10 would probably be too busy with shading).

Thank you for this suggestion; however, we respectfully disagree in this instance. On the one hand, adding shaded areas would significantly increase the visual complexity, making the figures more difficult to interpret. On the other hand, our primary focus is on the trends themselves; their variability is being rigorously tested via ANOVA to provide a more accurate assessment of how scenario variability influences landslide occurrences. Nevertheless, for informative purposes, we will add the standard deviation for the beginning of the period at the top of each figure, alongside the average values currently presented.

Line 466: Can you please introduce the use of Φ in the methods that describe the rainfall type (i.e., near Figure 5).

Yes, thank you for this suggestion.

Lines 474-475: the colors described in these sentences differ from the shades of red (negative) to green (positive) presented in Table 1. This error is also present in the table caption.

Thank you for catching it, we will correct it in the new version of the manuscript.

Line 479: In Table 1, there are some very strong correlations between $\Delta\lambda_{LS}$ and the rainfall types, which I take to mean that the model results are largely determined by the trend in rainfall timing. I was hoping to see more in the Discussion on this point with ties to the literature, e.g., has a trend in rainfall timing been detected in observations, so far?

This is a very insightful comment, closely related to another previously addressed. Indeed, existing literature suggests such a relationship may exist. There is empirical evidence supporting this process; for example, some studies link specific rainstorm hyetographs to landslide initiation during heavy rainstorms in Hong Kong, other studies show specifical laboratory experiments indicating the same direction (Jayakodi et al., 2023; Ng et al, 2001). Recent studies directly highlight the relationship between antecedent and triggering rainfall events (Natalia and Yang, 2026), and our findings indicate that antecedent rainfall determines the soil conditions rendering slopes prone to failure. As shown in Figures 10 and

11, the rise in landslide frequency is strongly correlated with an increase in Type 3 antecedent rainfall, which elevates antecedent soil moisture before the onset of triggering events. We described these aspects of our results in lines 484–490 and discussed them in lines 561–568; however, we will further strengthen the discussion by incorporating additional considerations from the literature.

Line 556: One question that comes to mind is the role of sediment supply in this region/environment. Soil lost due to more frequent landsliding would not be replenished on the decadal timescales of this study (are there any studies of soil production rate for the area?). How do you think this might affect your results?

This is a very interesting point, though unfortunately beyond the scope of the present study. You are correct that under current geomorphological conditions, major landslides may deplete available material that is not replenished within the analyzed timescales. However, large landslides in this area typically occur approximately once every 20 years (Greco et al., 2021). The affected area of such an event is between 20,000 and 30,000 m^2, representing only 0.012% to 0.018% of the total soil-mantled slopes prone to failure. Given this frequency and our evaluation period (up to 2070), the reduction in material availability due to landsliding is minimal. Therefore, we believe that treating geomorphological conditions as static remains a valid simplification for this study.

References

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