Author's response to reviewers

Thank you for the reviewer's various lines of constructive criticism which were very helpful in improving analysis and the manuscript. Our revisions will be made on the revised manuscript submitted last time, and point-by-point reply for each reviewer can be found in the following:

Reviewer #1

This is my second review of this paper. I visited the changes to the manuscript found that the authors have addressed most of the comments posed by the reviewers well. However, I am still skeptical of how their data can be interpreted in terms of the effects of earthquakes and climate. The reason is not that I don't believe that climate and earthquakes affect debris flows. Rather, there are three main points, I am not sure I cannot quite get on board with:

Thank you for your appreciation! And we are very grateful for various lines of constructive criticism which were very helpful in improving analysis and the manuscript. Point-by-point replies can be found in the following:

(i) The authors suggest (I think) that the 1950 Earthquake led to elevated sediment transport for around 40 years based, I think, on the rate of decline of NVA values between 1950 and 1990. I would need a bit more detail on how the NVA forms to follow the point. Debris flows will directly increase NVA. There are three debris flows in the 40 years after the 1950 event, but their effects on the NVA seem small (or at least they do not show up clearly on Fig 12d). Rather, in the 40 years post 1950, the NVA slowly declines. Isn't the 40 year of declining NVA just representative of the timescale that it takes to re-vegetate the surface? In other words, couldn't it be that the decline of NVA has to do with the timing of vegetation growth rather than the impact of the 1950 earthquake on increased sediment transport? What is happening to the fan surface in-between the major debris flows that you report?

- Author's response:

We appreciate the reviewer's insightful comments and questions regarding the interpretation of NVA and its relationship with sediment transport following the 1950 earthquake. Here, we provide a detailed response to address the concerns raised:

We conducted a new orthophoto acquisition of the ZLL watershed on November 17, 2024, using the DJI Mavic 3E aerial drone. Based on the control points selected from the drone orthophotos taken on September 10, 2020, we generated an unbiased orthophoto for 2024 in Pix4D. We selected two bare land areas at the watershed outlets caused by the 2020 event, both located at higher terraces and unaffected by subsequent debris flows, with a total area of 2375.708 m^2. Since the orthophotos were taken in mid-November, some vegetation stems and leaves had withered, but thanks to the high resolution of the images (~0.04m*0.04m), we visually interpreted the newly grown vegetation area (VA) within these two regions in 2024 on the Qgis platform, totaling 506.112 m^2 (Fig S1 a) (the visual interpretation error is described in section 3.2.2 of the manuscript). During the four growing periods from September 2020 to November 2021, the proportion of VA per unit area in these two regions increased by 0.053 annually. However, with the NVA (Non-Vegetated Area) of 780,000 m^2 in 1950 as a reference, the proportion of NVA per unit area decreased at a rate of 0.023 per year from 1950 to 1990 (Fig S1 b). This indicates that the 40-year decline in NVA does not represent the timescale required for surface vegetation to re-grow, as the rate of vegetation re-growth is much higher than the rate of NVA decline caused by debris flows.

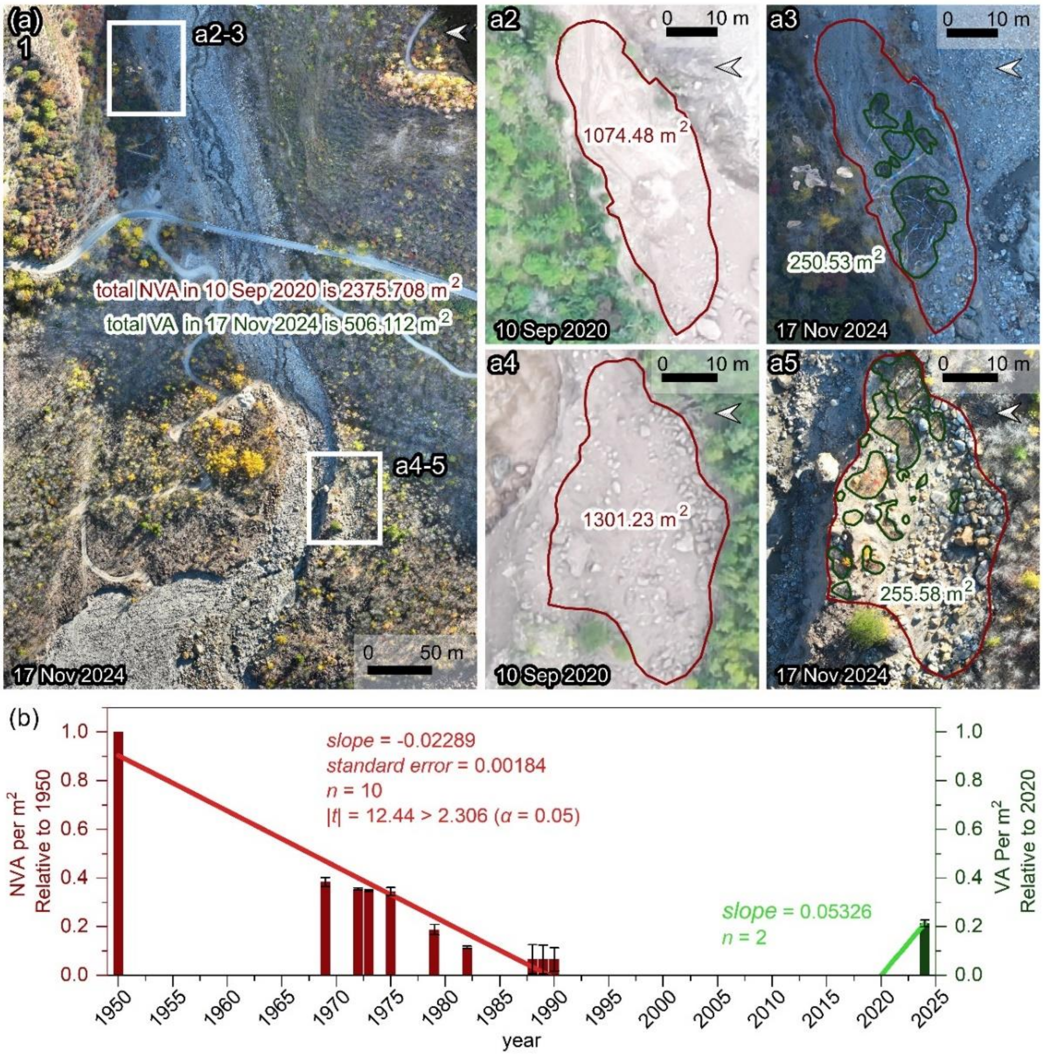

Figure S1: (a) Interpretation of newly grown vegetation on two bare land areas caused by the 2020 event; (b) Changes in the proportion of NVA per unit area and changes in the proportion of newly grown vegetation area (VA) per unit area.

The three debris flow events following the 1950 earthquake are well-documented in the literature (Zhang and Shen, 2011; Zhang, 1985, 1992). Figure S2-a2 shows significant deposition in the middle of the fan in 1969, characterized by a rough fan surface and indistinct channels, indicating a large-scale event prior to December 1969 (likely in 1968). By February 1972, these deposits were noticeably flattened (Fig. S2-b2). Images from March 1973 show a marked collapse of the terminal glacier compared to February 1972 (Fig. S2-b3 and 2-c3), suggesting that the event referred to as the 1973 event by Peng et al (2022) likely occurred in the summer of 1972. The depositional fan in December 1975 exhibits significant brightness variations (Fig. S2-d2), with pronounced channelization above the glacier (Fig S2-d1), indicating possible debris flow activity prior to this time. Compared with 1975, the depositional fan in 1979 displays a flatter terrain and more distinct channelization (Fig. S2-e2), indicating the modification of the rough fan surface by debris flow activity. This also implies that, due to limited information at the time, additional events during this period may have gone unrecorded. By 1982, noticeable vegetation had recovered in the middle part of the depositional fan. Additionally, glacier ablation intensified, exposing lateral moraines (Fig. S2-e3 and S2-f3), and the lowest section of the glacier developed numerous crevasses (Fig. S2-f4 and S2-f5). These fractured ice bodies and moraine materials, under the impact of the 1984 ice avalanche at 3700 m described by Zhang (1992), contributed to the formation of the large-scale debris flow.

However, from 1950s to 1980s, available remote sensing data are scarce, especially in remote areas such as the ZLL watershed. High-resolution remote sensing images immediately before or after the major events were not accessible. As a result, the NVA caused by these three events cannot be specifically delineated. Nevertheless, as previously mentioned, due to highly active glaciers and moraine materials, more than three debris flows occurred between 1950 and 1990, beyond those documented in the literature, as evidenced by the NVA interpreted from high-quality images of other years (Fig. 12d in manuscript). Due to the depletion of available material sources and the gradual decline in glacial activity over time caused by the earthquake, the scale of these debris flows progressively decreased, and the NVA of the 1968, 1972, and 1984 events lies within the overall declining trend of NVA (Fig. 12d in manuscript).

We hope this clarification addresses the reviewer's concerns and enhances the understanding of our findings regarding the long-term impact of the 1950 earthquake on sediment transport processes.

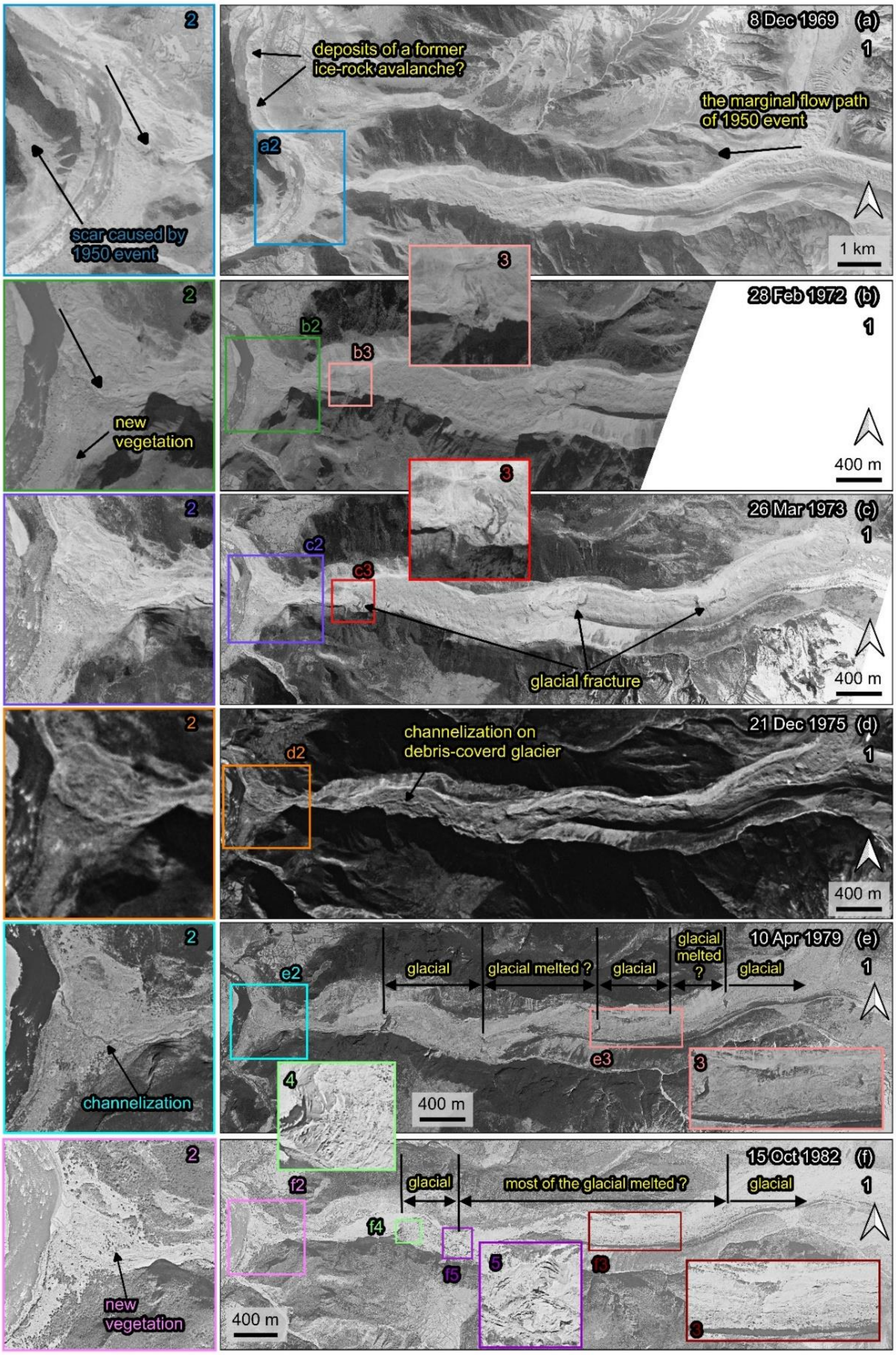

Figure S2: Variations of the Zelunglung alluvial fan and channel during 1969 – 1982. The images were taken from Keyhole reconnaissance satellites (https://earthexplorer.usgs.gov/).

- Author's changes in manuscript:

We have replaced Figure 3 with Figure S2 and added more descriptions regarding the changes in the fan surface and glacier in Section 4.1 as follows:

The fan in December 1975 exhibits significant brightness variations (Fig. 3-d2), with pronounced channelization above the glacier (Fig. 3-d1), suggesting possible debris flow activity prior to this time. Compared with 1975, the fan in 1979 displays a flatter terrain and more distinct channelization (Fig. 3-e2), indicating the modification of the rough fan surface by debris flow activity. This also implies that, due to limited information at the time, additional events during this period may have gone unrecorded. By 1982, noticeable vegetation had recovered in the middle part of the fan (Fig. 3-f2). Concurrently, accelerated glacier ablation exposed lateral moraines (Fig. 3-e3 and 3-f3), while the glacier terminus developed an extensive crevasse network (Fig. 3-f4 and 3-f5). These fractured ice bodies and moraine materials, under the impact of ice avalanche at 3700 m described by Zhang (1992), contributed to the formation of the 1984 large-scale debris flow.

(ii) I am still not sure about the proposed link between the 2020 event and the role of climate. You write that "The correspondence between the recent increases in the local air temperature and the NVA implies that the debris flow occurrences transfer from the tectonic-driven to the climatic-driven", and "based on the fact that the trend of the 1990-2020 NVAs shows a good agreement with that of the air temperature in the same period, it is likely that the 2020 event was driven by the recent local warming rather than by geological events". I have some questions/challenges with that rational

- First, I do not see the correspondence between NVA and temperature. Sure, there is an increase in the unvegetated area after the 2020 debris flow – which is just a product of a debris flow happening. The NVA does not seem to increase just with warming (which starts in 2018).
- Author's response:

Thank you very much! Yes, we can not conclude that there is correspondence between NVA and temperature. An increase in the unvegetated area after the 2020 debris flow is a direct result of a debris flow happening. From Fig.S3, it is observed that the local air temperature and the NVA exhibit similar trend between 1990 and 2020 despite the sudden increase in NVA is 2-4 years later than that in the local temperature.

Studies have shown a correlation between climate warming (particularly summer warming) and slope failures. For instance, in the Saint Elias Mountains of Alaska, non-seismic rock avalanches occurring between 1964 and 2019 were associated with above-average temperatures. The frequency of such events is expected to continue increasing with ongoing climate warming (Bessette-Kirton and Coe, 2020). In the Mont Blanc region of the Swiss Alps, the warmest periods since 1860 strongly correlate with 58 recorded rockfall events (Deline et al., 2015). However, the correlation is not a strict one-to-one relationship (i.e., a higher air temperature in a specific year does not necessarily correspond to a higher rate of slope instability in the same year). Some findings explicitly indicating a delay or lag in the response, rather than being an immediate reaction. Long-term rockfall records from Täschgufer in the Swiss Alps (1920–2020) demonstrate that sustained warming facilitates rockfall release, with activity changes significantly correlated with temperature variations on interannual and decadal timescales (Stoffel et al., 2024). Notably, rockfall activity during 1949–1953 increased following the sustained warm summers of 1943–1947, and the 1994–1995 peak in activity similarly followed the warm summers of 1990–1993 (Stoffel et al., 2024). Comparable correlations between increased rockfall and warming have been documented in other locations within the region (Stoffel et al., 2024). Evidence from a case study in Tianmo Valley, approximately 60 km from the ZLL catchment, also indicates that prolonged and sustained warming has a significant impact on the triggering of peri-glacial debris flows (Deng et al., 2017). Furthermore, glacial lake outburst flood events in the Himalayan region exhibit delayed responses to warming (Zou et al., 2024), indirectly reflecting the lagged responses of ice/rock avalanches (as triggers for such events, including debris flows) to climatic changes. It is also worth mentioning that prolonged increases in air temperature drive changes in moraines, supplying abundant active debris that is highly susceptible to triggering by high-altitude rockfalls, ice-rock avalanches, and other processes—mechanisms critical to large-scale debris flow formation (Deng et al., 2017).

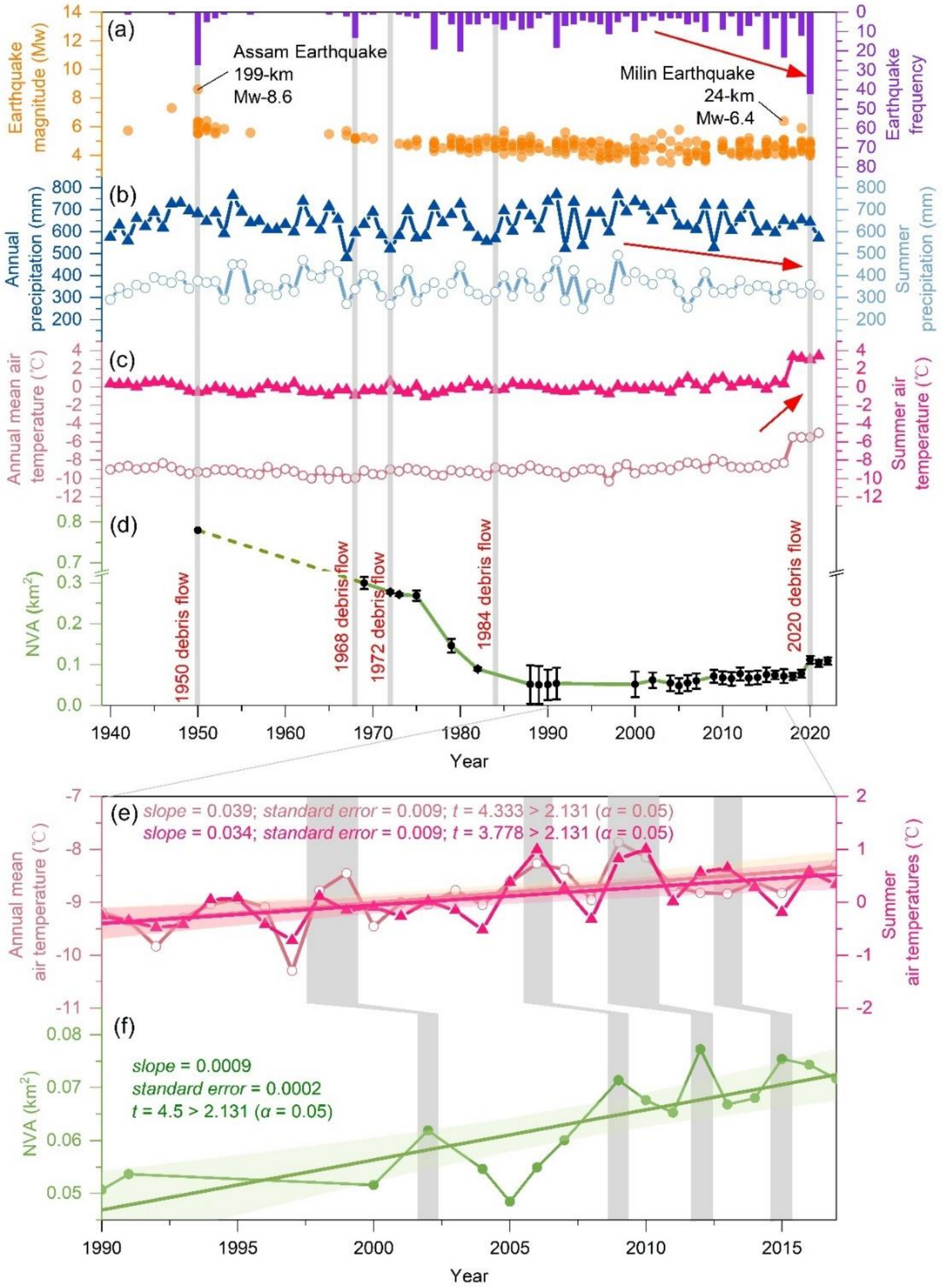

Figure S3 (a) Seismic events within a 200 km distance to the Zelunglung from 1940 to the present. (b) Changes in the annual and summer precipitation in the Zelunglung from 1940 to the present. (c) Changes in the annual mean and summer air temperatures in the Zelunglung from 1940 to the present. (d) Changes in the non-vegetated area of the Zelunglung alluvial fan from 1969 to the present (although the deposition of the 1950 event did not happen at the Zelunglung's outlet like the later events, we plot the NVA of the 1950 event as the starting point). (e) Changes in the annual and summer precipitation in the Zelunglung from 1990 to 2017. (f) Changes in the non-vegetated area of the Zelunglung alluvial fan from 1990 to 2017.

- Author's changes in manuscript:

We have replaced Figure 12 with Figure S3, and added explanations in L455 and L464:

L455: Figure 12f highlights four distinct NVA peaks, which likely correspond to small mountain torrents or debris-flows, as suggested by Zhang and Shen (2011). These NVA peaks exhibit a lag of 2–4 years relative to annual mean or summer air temperature peaks (Figure 12e and 12f). Similarly, the sharp increase in NVA caused by the 2020 debris flow event occurred two years after the 2018 warming anomaly (Fig. 12b and 12d). This lag phenomenon has also been observed in other comparable regions (Stoffel et al, 2024)

L464: However, based on the fact that the lag relationship between the fluctuation peaks of NVAs and temperature fluctuations from 1990 to 2020, it is likely that the 2020 event was triggered by the recent local warming.

- Second, given that NVA is driven by debris flows, isn't the argument (a link between climate and NVA changes are indicative of the role of climate on debris flows) a bit circular or redundant? It feels the same as saying: The fact that the 2020 debris flow occurred within a warming trend means that it was triggered by warming. In particular, the occurrence of one debris flow event within a warming period does not seem to me enough evidence to say that warming triggered that debris flow.

- Author's response：

Thank you very much! You pointed out there is a bit circular in our expression. Our expression is not exact, which leads to misunderstanding. As explained above, it is not a corresponding relationship but ta similar trend between the local air temperature and the NVA between 1990 and 2020. Historical records and high-resolution remote sensing imagery only capture five documented debris flow events in this catchment. Therefore, it is necessary to identify an alternative indicator, such as NVA, to infer debris flow occurrences and their magnitude. For this reason, we argue that the relationship between climate and NVA changes serves as a proxy for understanding the relationship between climate and debris flows, representing a unidirectional rather than cyclical process, i.e., climate → debris flows → NVA changes.

As shown in Figure S3 (e) and (f), both temperature and NVA exhibited a similar trend from 1990 until the warming anomaly in 2018. Notably, Figure S3(f) highlights four distinct NVA peaks, which likely represent small-scale flash flood or debris flow events (Zhang and Shen, 2011). These NVA peaks show a lag of 2–4 years relative to annual mean or summer air temperature peaks. Similarly, the sharp increase in NVA caused by the 2020 debris flow event occurred two years after the warming anomaly in 2018 (Fig. S3-e and d). This lag phenomenon has also been observed in other comparable regions (Stoffel et al., 2024). Therefore, we conclude that the 2020 event, along with the small mountain torrents or debris-flows between 1990 and 2017, was driven by climate warming.

Regarding why earthquake triggers are excluded as a factor, this will be addressed in detail in our response to the third comment.

- Author's changes in manuscript:

Consistent with the previous response, we have replaced Figure 12 with Figure S3, and added explanations in L455 and L464:

L455: Figure 12f highlights four distinct NVA peaks, which likely represent small mountain torrents or debris-flows, as Zhang and Shen (2011) mentioned. These NVA peaks show a lag of 3–5 years relative to annual mean or summer air temperatures (Figure 12e and 12f). Similarly, the sharp increase in NVA caused by the 2020 debris flow event occurred two years after the warming anomaly in 2018 (Figure 12b and 12d). This lag phenomenon has also been observed in other comparable regions (Stoffel et al, 2024)

L464: However, based on the fact that the lag relationship between the fluctuation peaks of NVAs and temperature fluctuations from 1990 to 2020, it is likely that the 2020 event was triggered by the recent local warming.

- Third, you seem to discount Earthquakes as a trigger for the 2020 event even though you have the highest earthquake frequency on your record right around the 2020 event. As far as I understand, the reason you discount the earthquake trigger is (also?) because the earthquakes do not fall below the Keefer curve (similar to the 1968 and the 1984 events). How robust is this characteristic? What triggered the 1968 and 1984 events then if it wasn't earthquakes or warming? Isn't it possible that the 2020 event is just similar to these two events and was not directly triggered by the warming?

- Author's response：

Large earthquakes (≥ Mw 6.0) can significantly influence mass-wasting processes (Jones et al., 2021). Our previous studies on the 2017 Milin earthquake (Mw 6.4) revealed that the maximum intensity (VIII degree) region covered approximately 310 km², with an average impact radius of about 10 km. Co-seismic landslides were almost entirely confined to this region, and no slope failures were observed in the ZLL catchment (Hu et al., 2019). As highlighted in the manuscript (L470), if the 2017 Milin earthquake had strongly impacted the glaciers in the ZLL, ice-rock failures would likely have occurred within a few months, similar to what was observed in the Sedongpu catchment. However, no such events were documented in the ZLL. While the highest frequency of earthquakes occurred near the time of the 2020 event, the maximum magnitude during this period was only Mw 5.2, with an average magnitude of Mw 4.6 (Fig. S3 a and Fig. S4). Furthermore, the epicenters were all located more than 30 km from the ZLL catchment (Fig. S4), well beyond the impact radius of the 2017 Mw 6.4 Milin earthquake. We applied the criteria established by Keefer (1984) to identify earthquakes within the magnitude and distance thresholds, a methodology also employed in studies of rock avalanches in Alaska (Coe et al., 2018). None of these seismic events during this period fell within the range of influence as defined by the Keefer curve (Fig. S4). These analyses collectively lead us to conclude that earthquakes were not the trigger for the 2020 event.

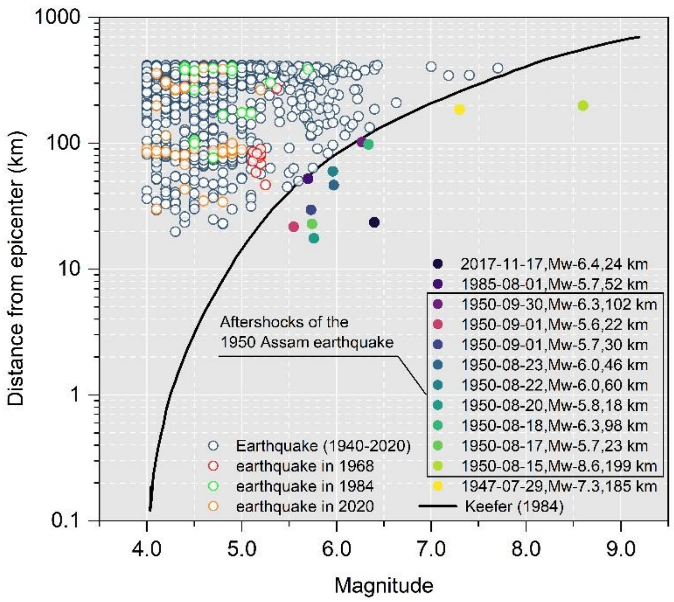

Figure S4: Distance from epicenters of the collected seismic events to the Zelunglung vs. the seismic magnitude (the black solid curve refers to Keefer (1984)).

As stated in the previous answer, the events of 1950, 1968, and 1984 are well-documented in the literature (Zhang and Shen, 2011; Zhang, 1985, 1992). The 1950 event coincided with the Assam earthquake and is considered directly related to this seismic event. This disaster occurred immediately after the earthquake, destabilizing the terminus of the ZLL Glacier at an elevation of 3,650 m and forming a glacier dam in the Yarlung Tsangpo River. During the 1968 event, the ZLL Glacier again formed a dam over 50 m high in the Yarlung Tsangpo River. By 1982, the fractured glacier had been divided into six segments due to differential melting. The First Qinghai-Tibet Scientific Expedition observed in 1984 that a localized rupture occurred at 3,700 m on the ZLL Glacier. The broken ice, carrying loose moraine debris, traveled horizontally up to 150 m. By 1989, three of the glacier segments had melted, detached from the main glacier, and were buried under thick moraine deposits. In fact, the 1972 event was also caused by the collapse of the terminal glacier (Fig. S2-b3 and 2-c3). These events clearly indicate that the frequent ruptures, collapses, and differential melting of the ZLL Glacier were associated with disturbances caused by the 1950 earthquake. While rising temperatures likely contributed to the melting and instability of the glacier, temperature alone could not have caused the direct collapse of the main trunk glacier and the subsequent debris flows. The root cause was the structural damage and exposure of the glacier to lower-altitude warming following the earthquake. Since 1990, the only large-scale event in this region has been the 2020 event, which was triggered by an ice-rock avalanche on the southern ridge of the catchment, unrelated to the trunk glacier. The frequency of large-scale disaster events in the 40 years after the 1950 earthquake was significantly higher than that after 1990, suggesting that glacier instability during this period can be regarded as a preconditioning effect of the earthquake. Therefore, we consider the 1968 and 1984 events to be related to the 1950 earthquake.

- Author's changes in manuscript:

We have replaced Figure 13 with Figure S4. The narrative logic of the first paragraph in Section 6.1 has been reorganized, and additional explanations have been incorporated as follows:

L423: While the highest frequency of earthquakes occurred near the time of the 2020 event, they could be ignored due to their small magnitude (Mw≤5.2) and long distance (>30km) (Fig 13). This is because even the 2017 Mw 6.4 Milin earthquake, with an epicenter 24 km from the

ZLL, had a very limited impact area (310 km^2, ~10 km impact radius) (Hu et al., 2019), and there were no report or sign of such glacier-related hazards in the ZLL.

L418: The 1950 debris flow event was directly triggered by the 1950 Assam earthquake (Zhang, 1992), and the root causes of the 1968, 1972 and 1984 events were the structural damage to the glacier and its exposure to lower altitudes with higher temperatures, both resulting from the 1950 earthquake.

(iii) There are also suggestions in the manuscript in places that the climate change increases the frequency of debris flow events. (e.g. L439: “Undoubtedly, the on-going warming increases the frequency of such glacier-related slope failures”.). I am not convinced the data in this work speak to the presence or absence of such a link, and the link between climate change and glacier-related natural hazards can be complex. For example, the frequency of GLOFs does not necessarily just simply increase with climate warming (Veh et al., 2019; Veh et al., 2023)

- Author's response：

Thank you very much for your insightful comments. It is important to clarify that the statement in L439 is not derived directly from the data in this study. We agree that the wording in its current form is overly absolute. A more appropriate revision would be: "Recent studies have shown that the on-going climate warming increases the frequency of such glacier-related slope failures" Following this statement, we have cited case studies from similar regions globally to support the argument that the 2020 event in the ZLL catchment was very likely driven by warming.

- Author's changes in manuscript:

To clarify, we revised the sentence as follows:

Recent studies have shown that the on-going climate warming increases the frequency of such glacier-related slope failures. For instance, the number of rockfalls per decade shows a similar growing trend with mean annual air temperature in Chamonix, Mont Blanc massif, France since 1934 (Deline et al., 2015). The frequency of non-seismic rock avalanches in the glaciated Saint Elias Mountains of Alaska was associated with above-average temperatures and is expected to continue increasing with ongoing climate warming (Bessette-Kirton and Coe, 2020). Shugar et al (2021) suggested that the 2021 Chamoli catastrophic ice-rock avalanche and subsequence mass flow resulted from a complex response of the geologic and topographic settings to regional climate change.

Line comments

Several of the new sections would benefit from review of the language (e.g.: “Little attentions are paid on” or “imagery for interpretating glacier changes”)

- Author's response:

Thank you very much for your valuable comments and suggestions. We have carefully reviewed the language in the new sections and made the necessary corrections.

- Author's changes in manuscript:

We have revised "Little attentions are paid on" to "Little attention has been given to…", and “imagery for interpretating glacier changes” to "imagery for interpreting glacier changes". We also have made the necessary corrections in other sections.

L47: Maybe “triggered by” rather than “driven by”?

- Author's response:

Thank you for your suggestion. We agree that "triggered by" is more appropriate in this context. We have revised "driven by" to "triggered by" accordingly.

- Author's changes in manuscript:

We revised "driven by" to "triggered by".

L71: “It is believed that historical earthquakes and ongoing climate warming drove these events” needs a citation or justification. Who believes that?

- Author's response:

Thank you for your suggestion. The driving factors behind the historical debris flow events in the ZLL catchment require further discussion in this manuscript. Therefore, we have revised "these events" to "such events" for greater precision. Additionally, we have included references to studies of similar hazards in other regions worldwide at the end of this sentence to provide proper justification.

- Author's changes in manuscript:

  we revised the sentence as follows:

  It is believed that historical earthquakes and ongoing climate warming drove such events (Bessette-Kirton and Coe, 2020; Deline et al., 2015; Stoffel et al., 2024; Zhang et al., 2022).

L129: As I said before, I do not see an increase in precipitation rates here. The increase is so small it must surely be within the uncertainty of the scatter of the data. If you plotted the confidence bands of the regression or added the standard error of the slope of the line, I would bet it is way within uncertainty of 0 or a decreasing trend. Also, in the discussion, you say there is no significant trend in precipitation.

- Author's response：

  We sincerely thank the Reviewer for their careful review. We agree with the Reviewer's point that the observed increase in precipitation rates may fall within the uncertainty range of the data. As suggested, we have re-analyzed the data by calculating the standard error of the slope (Fig. S5). The results show that the slope value is 0.065, the standard error is 4.215. The *t*-statistic value is approximately 0.0153, which is much smaller than the critical t-value of 2.086 at the significance level of α=0.05. This indicates that the trend is not statistically significant. In the revised manuscript, we have clarified that there is no significant trend in precipitation over the study period, aligning the discussion with the updated statistical analysis.

- Author's changes in manuscript:

  We have replaced Figure 2 with Figure S5, and changed the L109 as: The annual precipitation ranges from 514 mm to 972 mm, exhibiting notable inter-annual variation, with no distinct trend over the past 20 years.

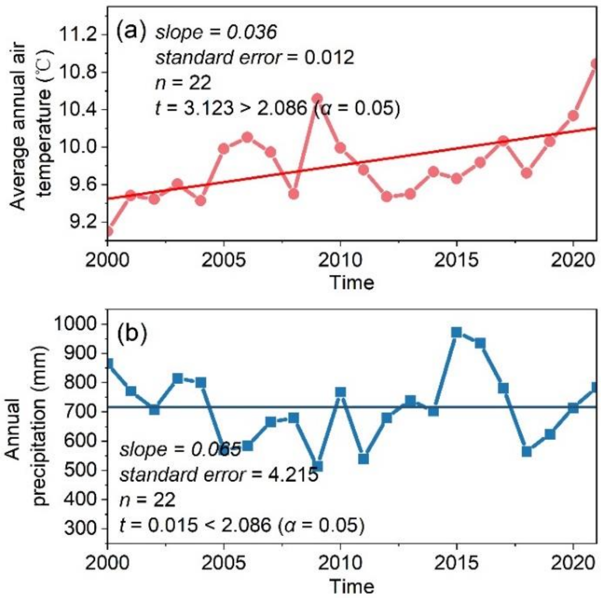

Figure S5: Annual temperature and precipitation data from 2000 to 2021 at Linzhi Meteorological Station (Data source: https://www.ncei.noaa.gov/maps/annual/).

L414: What do you mean by “the Keefer curve did not detect any of these seismic events”? A curve cannot detect anything.

- Author's response:

Thank you for pointing out this unclear statement. The phrase "the Keefer curve did not detect any of these seismic events" is indeed poorly worded and could be misleading. The statement "the Keefer curve did not detect any of these seismic events" is a metaphorical way of saying that the seismic events did not meet the criteria defined by the Keefer curve for having a significant impact on landslide or debris flow activity. The Keefer curve relates the magnitude of an earthquake to the maximum distance from the epicenter where landslides or other seismic-induced geological phenomena are likely to occur.

In the context of the research, the authors are suggesting that while there were seismic events recorded, none of them were of a magnitude and distance combination that would be expected to trigger significant landslides or debris flows according to the Keefer curve. Therefore, the curve serves as a threshold or benchmark to assess whether the seismic activity is likely to have caused geological disturbances such as debris flows. The phrase "did not detect" is used to imply that the seismic events fell below the threshold of impact as defined by the curve.

- Author's changes in manuscript:

To clarify, we revised the sentence as follows:

Although 13 earthquakes of Mw > 5.1 occurred in 1968 and 6 earthquakes of Mw ⩾ 4.5 occurred in 1984, none of these seismic events fell within the range of influence as defined by the Keefer curve (Fig. 13). This suggests that these earthquakes did not have a significant influence on the debris flow events of 1968 and 1984.

L440: "show a similar growing trend". Similar to what?

- Author's response:

There is an important increase in the frequency of rock falls and a strong correlation between the warmest periods and the occurrence of 58 rock falls in the Mont Blanc massif. As shown in Figure S6, the number of rockfalls per decade show a similar growing trend with mean annual air temperature in Chamonix, Mont Blanc massif, France since 1934 (Deline et al., 2015).

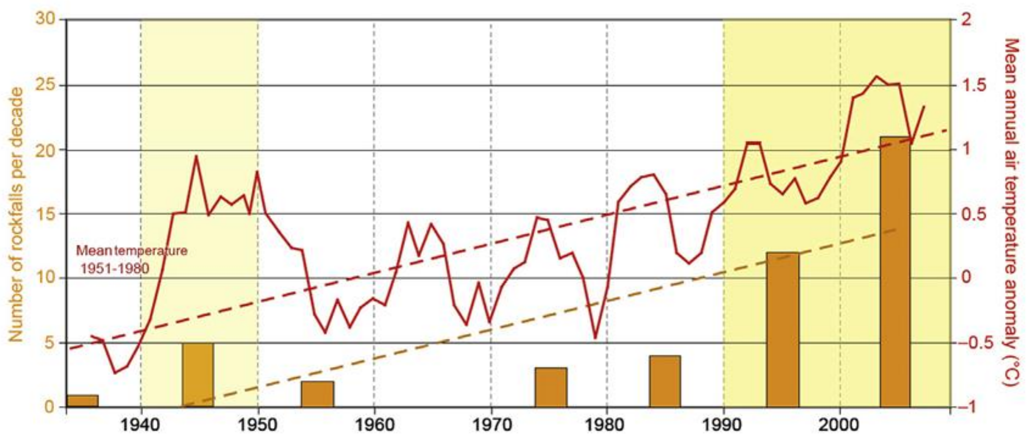

Figure S6: Meanannualair temperature in Chamonix (1,040 masl) since 1934 and number of rock falls per decade **in the West face of the Drus and on the North side of the Aiguilles de Chamonix, Mont Blanc massif, France. Dashed lines: linear regressions.**

- Author's changes in manuscript:

We made no changes to this part of the manuscript.

L448: "the trend of the 1990-2020 NVAs shows a good agreement with that of the air temperature in the same period".

- Author's response：

As mentioned in our previous response, the correlation between slope failures and air temperature is not a strict one-to-one relationship (i.e., a higher air temperature in a specific year does not necessarily correspond to a higher rate of slope instability in the same year). This relationship is more likely to manifest on interannual and decadal time scales. Over the longer time scale of 1990–2020, there is a positive correlation between the debris-flow induced NVA and air temperature (Fig. S1). Of course, to avoid ambiguity, we changed this sentence to: However, based on the fact that the lag relationship between the fluctuation peaks of NVAs and temperature fluctuations from 1990 to 2020, it is likely that the 2020 event was triggered by the recent local warming.

- Author's changes in manuscript:

To clarify, we revised the sentence as follows:

However, based on the fact that the lag relationship between the fluctuation peaks of NVAs and temperature fluctuations from 1990 to 2020, it is likely that the 2020 event was triggered by the recent local warming.

L459: Unclear which of the debris flows “the debris flow” corresponds to (presumably the 2020 one, but it’s unclear from this paragraph).

- Author's response：

Thank you for your suggestion. Yes, the term "the debris flow" in this paragraph refers to the debris flow that occurred in 2020. We have revised the text to replace "the debris flow" with "the 2020 debris flow" for clarity.

- Author's changes in manuscript:

We have revised the text to replace "the debris flow" with "the 2020 debris flow".

Reviewer #2

One of the problems is that the authors do not present any higher resolution imagery between the 1950 event and 1969 (first image). The conclusions about the influence of the 1950 Assam earthquake on debris flow activity from the glacial area over 40 years are based on weak data (first manuscript version). The increasing influence with time of climatic triggers is not enough taken into consideration. Also the stats-graphs are not clear about that influence.

As such, defenders of the pure climatic influence on high-mountain hazards (see some recent papers about this analysis in the Andes) will continue to believe that those types of hazards are influenced by earthquakes only immediately after the event.

Additionally, I think that without modelling this long-term effect of earthquakes on natural hazards (and see .. site located more than 100! km away from the Assam epicentral region!), especially on such high-mountain hazards, will not be proved especially if no high-quality image material is available for the time before and after the earthquake (as in this case, with the main seismic event in 1950 !). Even for the Wenchuan earthquake, the longterm influence on increased geohazard activity is considered to have finished after 10years (as indicated by the authors as well), even for sites very close to the activated fault.

Concluding: as the authors present a very detailed study, I would still recommend a major revision (and not rejection) - but the discussion should more highlight the extreme uncertainty affecting this 'exteme long-term' effect of a major earthquake in high-mountain areas (which are obviously the most strongly affected by climatic variations), especially as the zone is located so far from the epicentral area, and also of the fault (if I see well).

- Author's response：

Thank you very much for your insightful comments. Unfortunately, we were unable to obtain high-resolution remote sensing imagery for the period between the 1950 event and 1969, which indeed would provide the most direct evidence. However, the 1950, 1968, and 1984 events are well-documented in the literature (Zhang and Shen, 2011; Zhang, 1985, 1992). The 1950 event occurred immediately following the Assam earthquake and is considered to be directly associated with the seismic activity. Notably, the earthquake triggered simultaneous debris flows in as many as 13 gullies in the Yarlung Tsangpo Grand Canyon area (Liu, 1984). During the 1950 event, the terminus of the ZLL trunk glacier advanced from 3650 m a.s.l to the Yarlung Tsangpo at 2810 m a.s.l, forming a glacial dam in the Yarlung Tsangpo River.

During the 1968 event, the ZLL Glacier again formed a dam over 50 m high in the Yarlung Tsangpo River, while the 1972 event was similarly caused by the local collapse of the glacier terminus (Fig. S7-b3 and c3). The images from 1979 also show significant glacier fragmentation and differential ablation (Fig. S7-e3). Compared to 1979, glacier ablation intensified in 1982, exposing lateral moraines (Fig. S7-e2 and S7-f3), and the lowest section of the glacier developed numerous crevasses (Fig. S7-f4 and S7-f5). These fractured ice bodies and moraine materials, under the impact of the 1984 ice avalanche at 3700 m observed by the First Qinghai-Tibet Scientific Expedition (Zhang, 1992), contributed to the formation of the 1984 large-scale debris flow. By 1989, three of the glacier segments had melted, detached from the main glacier, and were buried under thick moraine deposits. These events clearly indicate that the frequent ruptures, collapses, and differential melting of the ZLL Glacier were associated with disturbances caused by the 1950 earthquake. While rising temperatures likely contributed to the melting and instability of the glacier, temperature alone could not have caused the direct collapse of the stable trunk glacier and the subsequent debris flows. The root causes were the structural damage to the glacier and its exposure to lower altitudes with higher temperatures, both of which were consequences of the 1950 earthquake. Since 1990, the only large-scale event in this region has been the 2020 event, which was triggered by an ice-rock avalanche on the southern ridge of the catchment, unrelated to the trunk glacier. The frequency of large-scale disaster events in the 40 years after the 1950 earthquake was significantly higher than that after 1990, suggesting that glacier instability during this period can be regarded as a preconditioning effect of the earthquake.

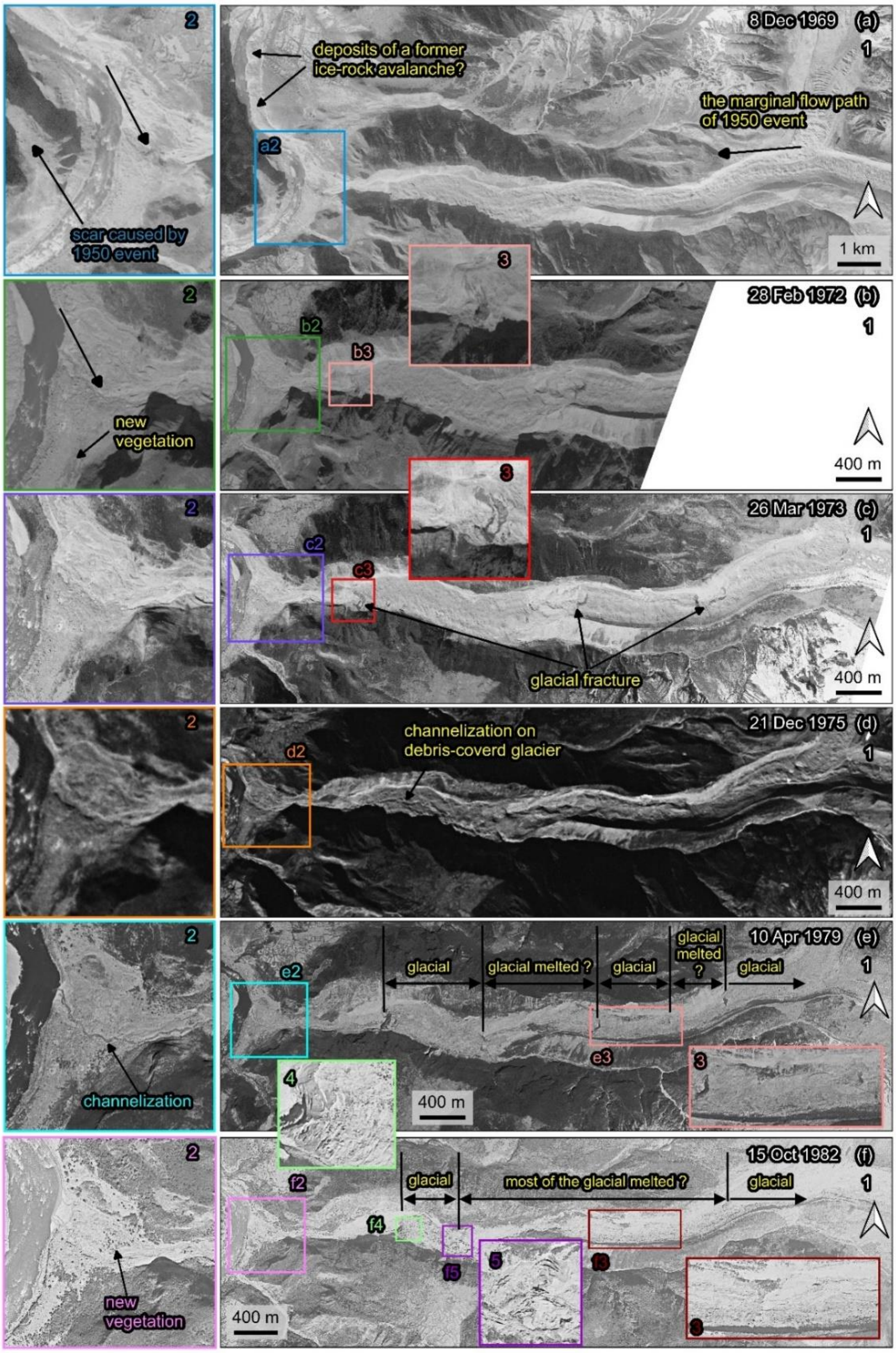

Figure S7: Variations of the Zelunglung alluvial fan and channel during 1969 – 1982. The images are taken from Keyhole reconnaissance satellites (https://earthexplorer.usgs.gov/).

The duration of earthquake preconditioning effects shows considerable regional heterogeneity. Even for the same earthquake, estimates of the preconditioning duration can vary across studies. For example, the ChiChi earthquake preconditioning lasted for 2-5 years (Marc et al., 2015). Cui et al (2011) predicted that the Wenchuan earthquake's influence on post-seismic debris flows would persist for 10–20 years, while Huang (2011) estimated 20–25 years. Thus, the impact of large earthquakes on glacial or peri-glacial regions, especially in small glaciated catchments, may differ significantly from those in non-glacial regions.

Furthermore, the 2015 Gorkha Mw 7.8 earthquake in Nepal triggered co-seismic landslides extending up to 130 km from the epicenter. Beyond this range, a slight increase in landslide frequency was attributed to the contribution of the Mw 7.3 Dolakha aftershock (~140 km from the mainshock) (Martha et al., 2017). The 1950 Assam earthquake, with its epicenter approximately 199 km from the ZLL catchment, had a very high magnitude (Mw 8.6) and occurred in the tectonically active eastern Himalayan syntaxis. Coudurier-Curveur et al. (2020) recalibrated the aftershock distribution within the first four months post-earthquake, revealing a proximal aftershock up to Mw 5.5 adjacent (~1km) to the ZLL catchment (Fig. S8). Therefore, coupled with subsequent high-magnitude aftershocks near the ZLL catchment (Fig S9), the seismic impact on the ZLL catchment was significantly amplified despite the distance. This seismic event also triggered a prolonged period of debris flow activity, persisting for decades, in Guxianggou, approximately 50 kilometers northeast of the ZLL Valley (Du and Zhang, 1981).

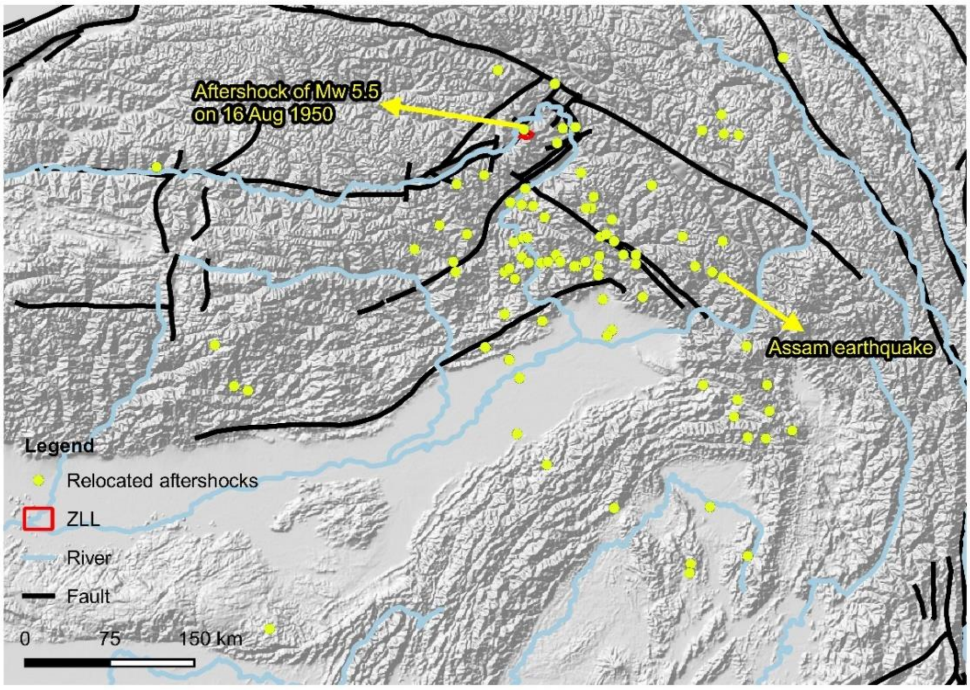

Figure S8: Relocated aftershocks of the 1950 Assam earthquake (using fixed depth relocation) (Coudurier-Curveur et al., 2020).

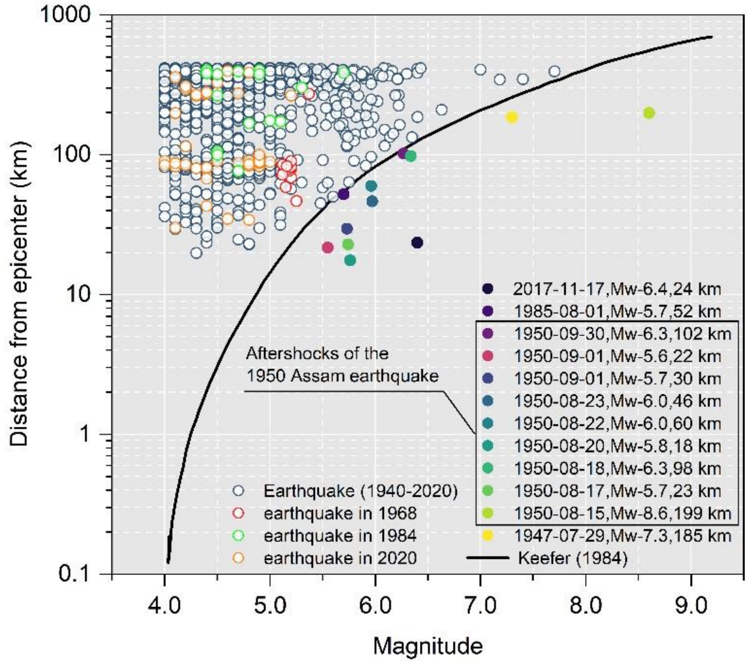

Figure S9: Distance from epicenters of the collected seismic events to the Zelunglung vs. the seismic magnitude (the black solid curve refers to Keefer (1984)).

- Author's changes in manuscript:

We have replaced Figure 3 with Figure S7 and Figure 13 with Figure S8. Additionally, the following explanation has been added to the manuscript::

L221: The fan in December 1975 exhibits significant brightness variations (Fig. 3-d2), with pronounced channelization above the glacier (Fig. 3-d1), indicatingpossible debris flow activity prior to this time. Compared with 1975, the fan in 1979 displays a flatter terrain and more distinct channelization (Fig. 3-e2), indicating the modification of the rough fan surface by debris flow activity. This also implies that, due to limited information at the time, additional events during this period may have gone unrecorded. By 1982, noticeable vegetation had recovered in the middle part of the fan (Fig. 3-f2). Concurrently, accelerated glacier ablation exposed lateral moraines (Fig. 3-e2 and 3-f3), while the glacier terminus developed an extensive crevasse network (Fig. 3-f4 and 3-f5). These fractured ice bodies and moraine materials, under the impact of ice avalanche at 3700 m described by Zhang (1992), contributed to the formation of the 1984 large-scale debris flow.

L409: Notably, the impact distance of a large earthquake can reach hundreds of kilometers. For example, the co-seismic landslides triggered by the 2015 Gorkha Mw 7.8 earthquake extended to a distance of over 130 km from the epicenter (Martha et al., 2017). The 1950 Assam earthquake, with its epicenter approximately 199 km from the ZLL, had a very high magnitude (Mw 8.6) and occurred in the tectonically active eastern Himalayan syntaxis. Coupled with subsequent high-magnitude aftershocks near the ZLL (Fig. 13), the seismic impact on the ZLL was significantly amplified despite the distance.

L418: The 1950 debris flow event was directly triggered by the 1950 Assam earthquake (Zhang, 1992), and the root causes of the 1968, 1972 and 1984 events were the structural damage to the glacier and its exposure to lower altitudes with higher temperatures, both resulting from the 1950 earthquake.

Other changes by the author

1. We have corrected and replaced Figures 8 and 14 because of errors in the image sequence number and font.
2. In addition to the language expression problems pointed out by the reviewers, we further checked and proofread the possible language errors.
3. We have modified all the reference formats according to the requirements of Copernicus Publications.

Reference:

Bessette-Kirton, E. K. and Coe, J. A.: A 36-Year Record of Rock Avalanches in the Saint Elias Mountains of Alaska, With Implications for Future Hazards, FRONT EARTH SC-SWITZ, 8, https://doi.org/10.3389/feart.2020.00293, 2020.

Coe, J. A., Bessette-Kirton, E. K., and Geertsema, M.: Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery, LANDSLIDES, 15, 393–407, https://doi.org/10.1007/s10346-017-0879-7, 2018.

Coudurier-Curveur, A., Tapponnier, P., Okal, E., Van der Woerd, J., Kali, E., Choudhury, S., Baruah, S., Etchebes, M., and Karakaş, Ç.: A composite rupture model for the great 1950 Assam earthquake across the cusp of the East Himalayan Syntaxis, Earth and Planetary Science Letters, 531, 115928, https://doi.org/10.1016/j.epsl.2019.115928, 2020.

Cui, P., Chen, X.-Q., Zhu, Y.-Y., Su, F.-H., Wei, F.-Q., Han, Y.-S., Liu, H.-J., and Zhuang, J.-Q.: The Wenchuan Earthquake (May 12, 2008), Sichuan Province, China, and resulting geohazards, NAT HAZARDS, 56, 19–36, https://doi.org/10.1007/s11069-009-9392-1, 2011.

Deline, P., Gruber, S., Delaloye, R., Fischer, L., Geertsema, M., Giardino, M., Hasler, A., Kirkbride, M., Krautblatter, M., Magnin, F., McColl, S., Ravanel, L., and Schoeneich, P.: Ice Loss and Slope Stability in High-Mountain Regions, in: Snow and Ice-Related Hazards, Risks, and Disasters, edited by: Shroder, J. F., Haeberli, W., and Whiteman, C., Academic Press, Boston, USA, 521–561, https://doi.org/10.1016/B978-0-12-394849-6.01001–5, 2015.

Deng, M., Chen, N., and Liu, M.: Meteorological factors driving glacial till variation and the associated periglacial debris flows in Tianmo Valley, south-eastern Tibetan Plateau, Nat. Hazards Earth Syst. Sci., 17, 345–356, https://doi.org/10.5194/nhess-17-345-2017, 2017.

Du R. and Zhang S.: CHARACTERISTICS OF GLACIAL MUD-FLOWS IN SOUTH-EASTERN QINGHAI-XIZANG PLATEAU, Journal of Glaciology and Geocryology, 10–16, 81–82, 1981.

Hu, K., Zhang, X., You, Y., Hu, X., Liu, W., and Li, Y.: Landslides and dammed lakes triggered by the 2017 Ms6.9 Milin earthquake in the Tsangpo gorge, Landslides, 16, 993–1001, https://doi.org/10.1007/s10346-019-01168-w, 2019.

Huang, R.: AFTER EFFECT OF GEOHAZARDS INDUCED BY THE WENCHUAN EARTHQUAKE, gcdzxb, 19, 145–151, 2011.

Jones, J. N., Boulton, S. J., Stokes, M., Bennett, G. L., and Whitworth, M. R. Z.: 30-year record of Himalaya mass-wasting reveals landscape perturbations by extreme events, NAT COMMUN, 12, 6701, https://doi.org/10.1038/s41467-021-26964-8, 2021.

Keefer, D. K.: Landslides caused by earthquakes, Geol Soc America Bull, 95, 406, https://doi.org/10.1130/0016-7606(1984)95<406:LCBE>2.0.CO;2, 1984.

Liu S.: DEBRIS FLOWS IN THE MT.NAMJAGBARWA REGION, Mountain Research, 212–215, 1984.

Marc, O., Hovius, N., Meunier, P., Uchida, T., and Hayashi, S.: Transient changes of landslide rates after earthquakes, GEOLOGY, 43, 883–886, https://doi.org/10.1130/G36961.1, 2015.

Martha, T. R., Roy, P., Mazumdar, R., Govindharaj, K. B., and Kumar, K. V.: Spatial characteristics of landslides triggered by the 2015 Mw 7.8 (Gorkha) and Mw 7.3 (Dolakha) earthquakes in Nepal, LANDSLIDES, 14, 697–704, https://doi.org/10.1007/s10346-016-0763-x, 2017.

Peng, D., Zhang, L., Jiang, R., Zhang, S., Shen, P., Lu, W., and He, X.: Initiation mechanisms and dynamics of a debris flow originated from debris-ice mixture slope failure in southeast Tibet, China, Engineering Geology, 307, 106783, https://doi.org/10.1016/j.enggeo.2022.106783, 2022.

Shugar, D. H., Jacquemart, M., Shean, D., Bhushan, S., Upadhyay, K., Sattar, A., Schwanghart, W., McBride, S., de Vries, M. V. W., Mergili, M., Emmer, A., Deschamps-Berger, C., McDonnell, M., Bhambri, R., Allen, S., Berthier, E., Carrivick, J. L., Clague, J. J., Dokukin, M., Dunning, S. A., Frey, H., Gascoin, S., Haritashya, U. K., Huggel, C., Kääb, A., Kargel, J. S., Kavanaugh, J. L., Lacroix, P., Petley, D., Rupper, S., Azam, M. F., Cook, S. J., Dimri, A. P., Eriksson, M., Farinotti, D., Fiddes, J., Gnyawali, K. R., Harrison, S., Jha, M., Koppes, M., Kumar, A., Leinss, S., Majeed, U., Mal, S., Muhuri, A., Noetzli, J., Paul, F., Rashid, I., Sain, K., Steiner, J., Ugalde, F., Watson, C. S., and Westoby, M. J.: A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya, Science, 373, 300–306, https://doi.org/10.1126/science.abh4455, 2021.

Stoffel, M., Trappmann, D. G., Coullie, M. I., Ballesteros Cánovas, J. A., and Corona, C.: Rockfall from an increasingly unstable mountain slope driven by climate warming, NAT GEOSCI, 17, 249–254, https://doi.org/10.1038/s41561-024-01390-9, 2024.

Zhang, J. and Shen, X.: Debris-flow of Zelongnong Ravine in Tibet, J. Mt. Sci., 8, 535–543, https://doi.org/10.1007/s11629-011-2137-0, 2011.

Zhang W.: Some features of the surge glagier in the MT. Namjagbarwa, Mountain Research, 234–238, 1985.

Zhang, W.: Identification of glaciers with surge characteristics on the Tibetan Plateau, Ann. Glaciol., 16, 168–172, https://doi.org/10.3189/1992AoG16-1-168-172, 1992.

Zhang, X., Hu, K., Liu, S., Nie, Y., and Han, Y.: Comprehensive interpretation of the Sedongpu glacier-related mass flows in the eastern Himalayan syntaxis, J. Mt. Sci., 19, 2469–2486, https://doi.org/10.1007/s11629-022-7376-8, 2022.

Zou Q., Zhou B., Yang T., Chen S., Yao H., Jiang H., and Zhou W.: Spatio-Temporal Differentiation Characteristics of Glacial Lake Outburst in the Himalayas, Earth Science, 49, 4047–4062, https://doi.org/10.3799/dqkx.2024.083, 2024.