Response to Reviewer 3

General comments:

The authors present and impressive EWS setup in the Namche Barwa massif, an area that has been subject to multiple hazard cascades in recent years and decades. They present a combination of sensors at different locations and based on a limited number of months of observations are able to track movements and show the potential of these setups for early warning. Especially useful, as has been shown in other sites, is a geophone that is able to pick up mass movements of different magnitude well before they become the actual risk when damming the main river channel.

The study is well presented and the setup and the insights present a valuable contribution to NHESS. Before recommending it for publication the authors however need to embed their findings into the state of knowledge on EWS in the region, especially in light of their geophone/wavelet analysis angle. Other studies exist and those need to be brought into context to make this not just a description of a successful first test of the setup but a contribution that will be helpful for the scientific community. NHESS requires this to be a novel contribution, and at the moment I miss a discussion of the added value (apart from of course the value the specific EWS has for local stakeholders). While this requires some more work on the Discussion, I believe that seeing the quality of the manuscript up to this stage this should be well possible to do.

Reply: We are grateful to Dr. Jakob Steiner for the detailed and insightful comments and suggestions. We have substantially restructured the Discussion section to discuss the relationship between the occurrence of ice-rock collapses and meteorological factors, and to address the multi-parameter observations for early warning. The relevant previous published studies will be discussed and the possible challenges of the EWS will be discussed following your suggestions. Please see the detailed responses to the main and specific comments below.

Main comments

L153: What are the 'various variables'? There is also no discussion on how the meteo data is useful or used. Are they required at all? What role do they play in the EWS chain of communication/analysis?

Reply: The meteorological variables in the 10m integrated observation tower of the destroyed EWS2 includes wind speed/direction, air temperature, relative humidity, four components of radiation, rainfall, atmospheric pressure. We will add this information in the revised manuscript.

In fact, there are no previous meteorological records in this unpopulated Sedongpu valley. Therefore, these in-situ AWS measurements were designed to investigate the possible meteorological triggers (e.g. extreme high air temperature/heavy rainfall) for the ice-rock collapses and debris mass flows, and also to provide the local meteorological background for further study of the mechanism and process of ice-rock collapses based on the glacier thermo-dynamic models. In the revised manuscript, we will add a new section 5.1 to discuss the relationship between the occurrence of repeated ice-rock collapses and the time series of meteorological factors. The following new figure will be included in the revised manuscript to help the reader understand that there are no immediate meteorological triggers for the ice-rock collapses.

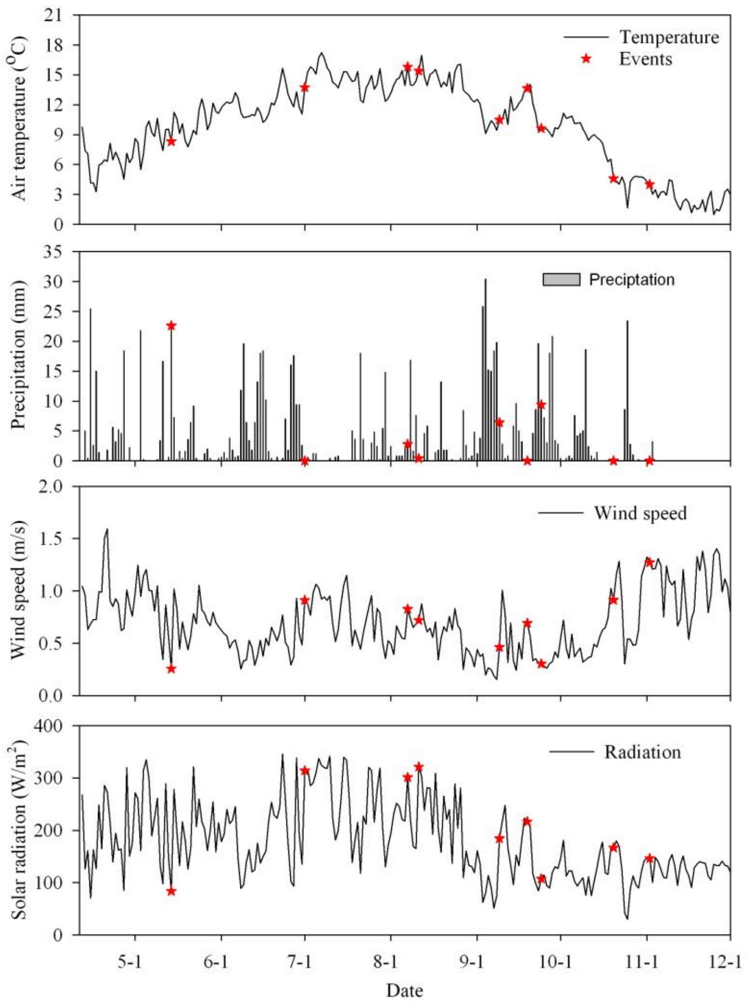


Figure 8: The occurrence of repeated ice-rock collapses (red stars) and the time-series of meteorological factors including air temperature(a), rainfall(b), wind speed(c) from EWS1 and incoming shortwave radiation from EWS3(d).

Figure 4: It is very hard for me to make out changes on these images. In a/b can you indicate flow direction, what the deposit and what water is? In c to f I can not really see change between the two images. Can you indicate what change the reader should perceive? It would also be important in the text to clarify how these images are used in early warning – to validate? Is there an algorithm that traks changes on the images as was the case at Kyagar? Stick to one writing of Yarlung Tsangpo/Yarlungzangbo

Reply: Following your suggestion, the flow direction of the Yalung Tsangpo River (white colour in the thermal image) has been added to the revised figure. Due to the contrasting surface temperature, the colour of the cold debris flow was dark in the thermal image. We have highlighted the fresh debris in the image.

And we have enlarged the source region to show its changes by comparing two thermal images. Please see the following new Figure 4. The collapse source on the ridge of Mt. Gyala Peri was also manually delimited by comparing Figure 4 e,f.

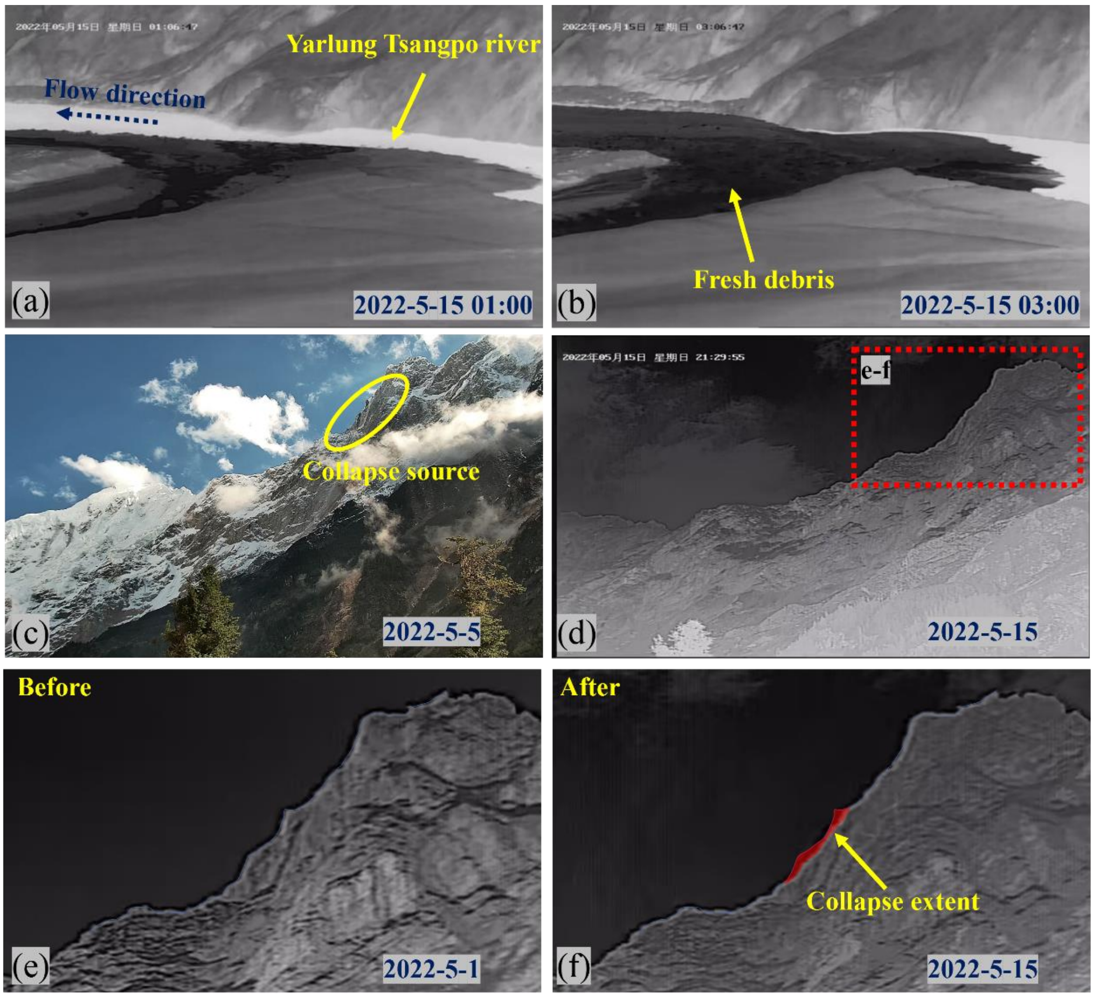


Figure 4: The debris-induced blockage of the Yarlung Tsangpo River (a, b) and the optical and thermal images showing the topographic conditions at the targeted monitoring of the collapsed area (c, d) with the zoomed region (red dashed rectangle) shown in e-f, and the change of ridgeline before and after the repeated ice-rock collapses on 14 May 2022 and

the extent of the collapse source are manually outlined in transparent red.

Due to the influence of cloudy and rainy weather in the Sedongpu Valley, both optical and infrared photographs at EWS1 hardly capture the cloud-free photographs during the monsoon season and are therefore not applicable for use as real-time warning indicators. The selected pre- and post-collapse photographs are generally used to determine the location and extent of collapse. In the revised manuscript, we will add the relevant text to clarify the purpose of the photographs in section 3.1.

In contrast, EWS2 near the outlet of the Sedongpu valley tends to have the highest quality imagery due to less cloud cover and the shorter distance to the blockage. Therefore, the repeated comparison of optical/infrared images is helpful in determining the time and magnitude of the river blockage. In fact, we are now trying to use the deep learning method to aromatically outline the extent of debris fans and the river area. Such information would be an important automatic way to complement the current real-time early warning system.

We have unified the term as Yarlung Tsangpo river.

Figure 6: As in Figure 4 I find it hard to see anything in c to f. Would it be possible to zoom in for the purpose of the manuscript? You need to tell the reader how these images are useful for interpretation.

Reply: We have acknowledged that it is very difficult to see the change for Figure 4c,f without a dynamic comparison (such as GIF). These figures have therefore been moved to the supplementary material. Both Figure 5 and Figure 6 have been combined to show the river blockage and the ice-rock avalanche process (please see the following new figure). In addition, the relevant videos of two recorded ice-rock collapses are also provided in the supplementary video for the reader.

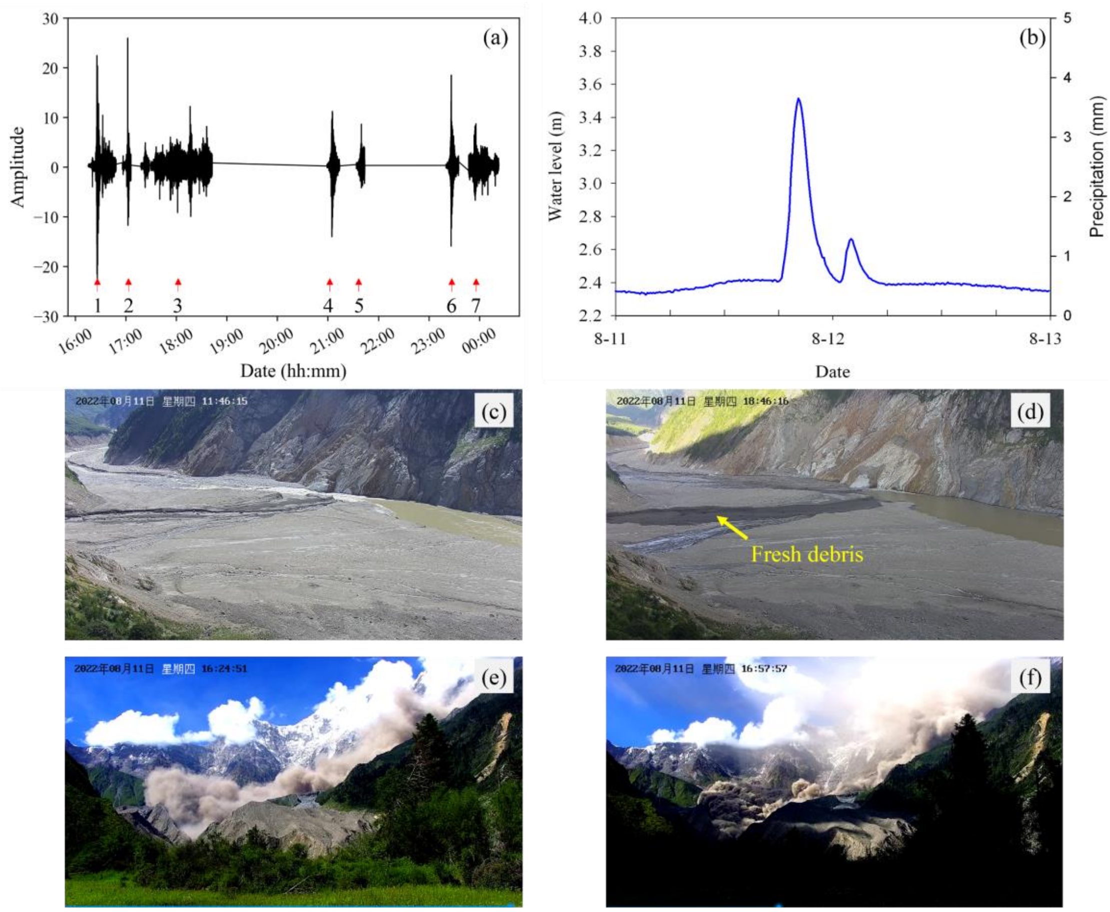


Figure 5: Recorded waveform of seven collapses on 11 August 2022 (a) and the water level rise due to small-scale debris flow (b), and the photos before and after the occurrence of fresh debris flow into the Yarlung Tsangpo River (c,d), and video screenshots of two rock collapses at 16:24 and 16:57 on 11 August 2022

L253: Here and then again the Discussion/Conclusion I would expect some critical reflection on potential pitfalls. Why for example did EWS2 not send a warning when the debris flow mass must have reached the location before midnight? Or did it only reach the location that late? You defined a threshold for amplitude based on a few observations, how is this robust? What about false positives or false negatives? The amplitude of the first August 2022 event was larger than the second but you say the second event was larger in volume. What about the smaller events well below 20, would your system then not record them at all and send no potential warning? How does expert judgment of these data and images work, who interprets it and who takes final responsibility for the judgement made? You also introduce a 'three level warning system' based on different amplitudes (L264) but then never explain where this comes from or how it is used. This needs to be clarified.

Reply: Thank you very much for these insightful comments. In the revised manuscript, a new discussion will be added in Section 5.3 to address the above issues. We will discuss the possible challenges and pitfalls in EWS, including your concerns about why EWS2 does not send a warning, the robustness of the warning threshold, and the possible exclusion of false warnings. The challenges and priority of seismic warning will also be discussed.

Firstly, seismic energy generated in surficial catastrophic activities is easily saturated or attenuated with distance. The geophone at EWS1 inside the Sedongpu Valley performed well due to its proximity to the source of the collapse. In contrast, the geophone at EWS2 near the Yarlung Tsangpo River was influenced by river-generated noise and was less sensitive to the small-scale collapse events in 2022 due to its distance from the source regime. However, the geophone at EWS2 would also play the warning role in the event of catastrophic mass flow, as occurred on 22 March 2021 (Zhao et al., 2021). In the revised manuscript, we will address that the installation of seismic stations for event detection is a function of the desired minimum detectable event size and the deployment of the optimized seismic stations is critical important to obtain the signal with high-quality signal-to- noise ratio in the rugged mountainous regions.

Regarding the robustness of the amplitude threshold at EWS1, a total of 9 repeated ice-rock collapses and the associated debris flows in 2022 provided an opportunity to ensure the threshold reliability of the seismic warning (amplitude greater than 20) in the Sedongpu Valley. Each warning event was confirmed by using multi-parameter observations including the photographs, videos, water level. The geophone recorded all signals with amplitude greater than 3. Based on the photographs and videos at EWS1, there were few debris flows occurring when the waveform amplitude at EWS1 was less than 20. In contrast, when the waveform amplitude was greater than 20, the occurrence of debris flows was confirmed at the Sedongpu Valley outlet. There were still two false warnings occurred in June and September. However, the detailed analysis of the waveform can easily exclude such false warnings. The duration and characteristics of the waveform are different, as shown in the following figure (Figure S1). The typical collapse-induced waveform usually lasts several minutes and displays a gradually decreasing amplitude (Figure S1 c). However, the two abnormal waveforms are very short, indicating the possible waveform noise and can be easily excluded by the warning system (Figure S1 ab). However, it should be noted that this local threshold (amplitude above 20) is only suitable for EWS1. Each phase of the disaster chain has a different seismic signature and a different limit of detection at far-field stations. It is recommended that the local thresholds of seismic warning in other hazard regions should be determined by corresponding historical records and the field multi-parameter observations. The above discussion will be added in section 5.3.

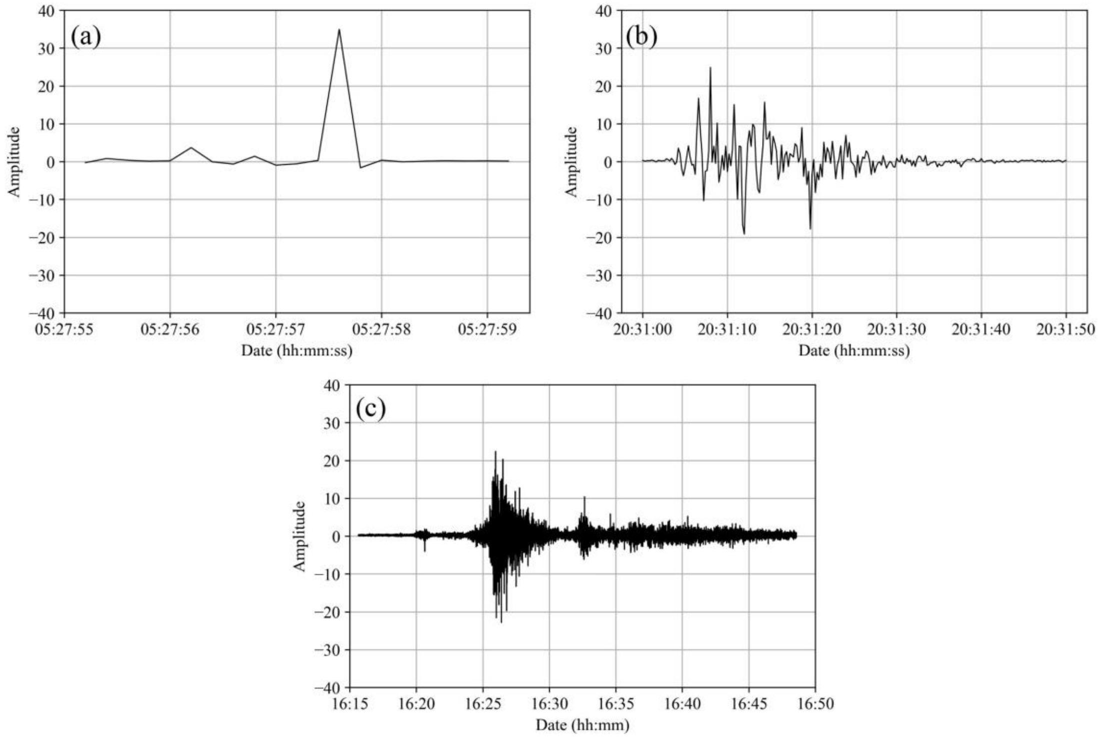


Figure S1: The two abnormal waveforms occurred on 2 June 2022 (a) and 1 October 2022 (b) and the collapse-induced waveforms occurred on 11 August 2022 (c), showing the different waveform and duration.

The amplitude of the first August 2022 event was larger than that of the second. There is in incorrect expression in the manuscript. We will correct the expression in the revised manuscript.

Whenever any geophone waveform or water level exceeded the specified thresholds, the warning signals were automatically sent to the mobile phones (message and Wetchat) of two responsible experts at the office of the Second Tibetan Plateau Scientific Expedition and Research Program. Subsequently, the observers checked the multi-parameters including the real-time photos, videos, water level and the waveform characters to determine the glacier (EWS1) and river status (EWS2) and informed the local government. The official Disaster Emergency Management Department is responsible to lunch the alarm initiating evacuation. We have added this information in the beginning of Section 4.

In terms of the three-level warning, in fact, the geophone amplitude of 20 was indeed confirmed as the first-level warning threshold. As no catastrophic events occurred in 2022, the EWS in this study temporally defined twice (40) and three times (60) of the first-level threshold as the second and third warning thresholds, which will be optimized by future observations. We will add such an explanation in the revised manuscript.

In Figure 8 and the text above you very briefly touch upon this topic but I think this needs to be further expanded. What about the noise before the rock collapse, not visible before a rupture, could this be exploited as a prewarning signal?

Reply: Following your suggestion, we will compare in detail the waveforms between nine ice-rock collapses and seismic activity in new figure (Please see the following figure). We clarified that the waveform of a typical ice-rock collapse is completely different from that of an earthquake in terms of duration and waveform morphology. Detailed retrospective analysis of the waveform also showed that some possible precursors were present before the collapses. However, regarding the possible noise is concerned, there is no solid evidence that such signals could be used as the pre-warning way. In fact, the amplitude of the waveform is still the most practical and simple way to warn the occurrence of collapses.

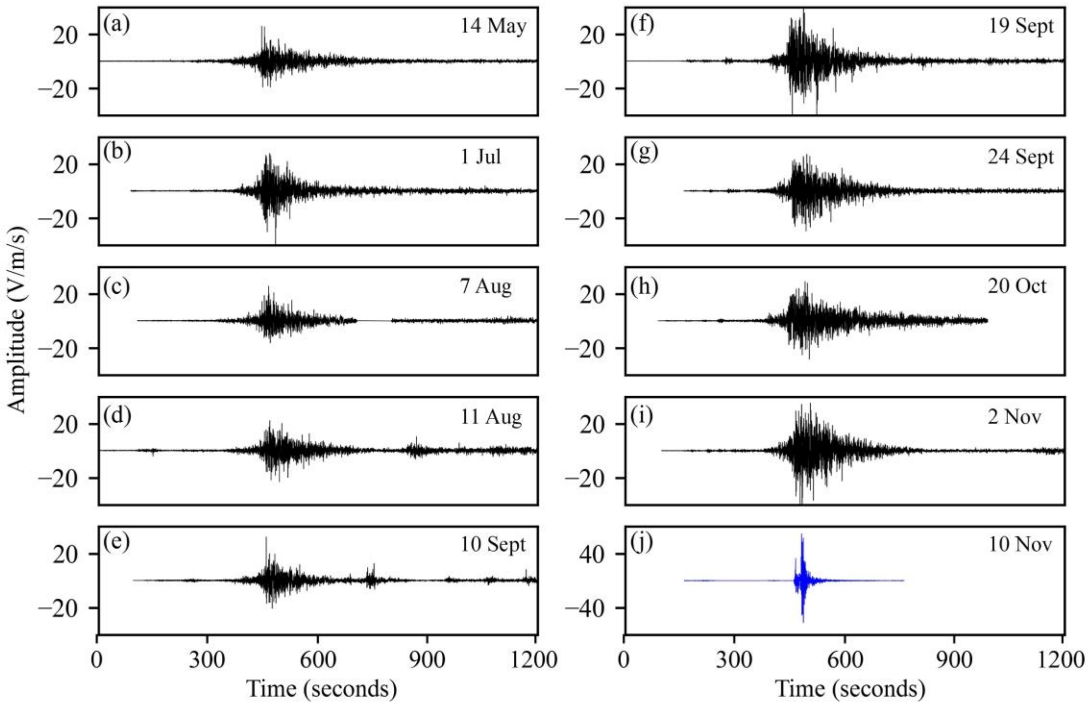


Figure 7: Comparison of the waveforms generated by a series of rock collapses occurred on 14 May (a), 1 July (b), 7 August (c), 11 August (d), 10 September (e), 19 September (f), 24 September (g), 20 October (h), 2 November (i) and the seismic waveforms generated by the earthquake on 10 November 2022 (j). Note the different y-axis limits.

L282: The Discussion misses two crucial points:

1. a discussion of the presented approach keeping in mind similar approaches, one of which you mentioned but did not discuss (Maurer et al. 2020) and one that didn't occur at all (Cook et al. 2021). Both these studies have discussed the potential especially of wavelets in the region for similar events and it is crucial that for a scientific publication the previous literature is looked into and put into context for a solid conclusion on a way forward.

Reply: Thank you for pointing this out. Previous studies have shown that seismic waveform is an important way to understand the dynamic process of various catastrophic disasters such as ice-rock collapse, glacier lake outburst flood, rock landslide, and has important potential for detecting the precursor signals before the event as an early warning by the distant seismic stations up to 100 km from the disaster. The EWSs in the world are generally equipped with geophones, which are one of the main instruments. In the revised manuscript, the relevant studies including Cook 2021; Tiwari et al. 2022; Stähli et al. 2015; Massey et al. 2010 Haemming et al. 2014 are cited in section 5.3.

Massey, C. I., Manville, V., Hancox, G. H., Keys, H. J., Lawrence, C., and McSaveney, M.: Out-burst flood (lahar) triggered by retrogressive landsliding, 18 March 2007 at Mt Ruapehu, New Zealand—a successful early warning, Landslides, 7, 303-315, 2010.

Haemmig, C., Huss, M., Keusen, H., Hess, J., Wegmüller, U., Ao, Z., and Kulubayi, W.: Hazard assessment of glacial lake outburst floods from Kyagar glacier, Karakoram mountains, China, Annals of Glaciology, 55, 34-44, 2014.

Tiwari, A., Sain, K., Kumar, A., Tiwari, J., Paul, A., Kumar, N., Haldar, C., Kumar, S., and Pandey, C. P.: Potential seismic precursors and surficial dynamics of a deadly Himalayan disaster: an early warning approach, Scientific reports, 12, 3733, 2022.

Stähli, M., Sättele, M., Huggel, C., McArdell, B. W., Lehmann, P., Van Herwijnen, A., Berne, A., Schleiss, M., Ferrari, A., Kos, A., Or, D., and Springman, S. M.: Monitoring and prediction in early warning systems for rapid mass movements, Nat. Hazards Earth Syst. Sci., 15, 905–917, https://doi.org/10.5194/nhess-15-905-2015, 2015.

Cook, K. L., Rekapalli, R., Dietze, M., Pilz, M., Cesca, S., Rao, N. P., Srinagesh, D., Paul, H., Metz, M., and Mandal, P.: Detection and potential early warning of catastrophic flow events with regional seismic networks, Science, 374, 87-92, 2021.

2. A discussion of the institutional challenges. The authors are aware of the challenges within China (e.g. Kyagar) but also with other countries of the region (e.g. downstream Nepal) to make such systems work. How is this setup managed locally for success? Are recommendations understood and transported on? What stakeholders need to be included. I realize that this is not the main part of the manuscript and also doesn't need to take up a part in the Results but should surface in the Discussion. Otherwise many of the technical observations often become unsustainable. Wanting a radar is nice, but so expensive that it is hardly ever feasible and you need to chain of command at the end of a signal too to turn such data into actual actionable information.

Reply: Thank you for this insightful comment. We fully agree with your comments. The installation and maintenance of many EWSs generally face institutional challenges and are necessary to gain government support and recognition from local people, especially those with strong religious beliefs. The repeated destruction caused by river blockages improved the knowledge of the local population and the government about the ice-rock collapse and the importance of an early warning system in the Sedongpu valley. As a result, we received strong support from the local government. The official Disaster Emergency Management Department is responsible for triggering the evacuation alarm when the massive ice collapses and associated river blockages are warned and further confirmed by experts and officials. The implementation of similar EWS in other high-risk regions should not only focus on monitoring techniques, but also pay much attention to the cognitive and response capabilities of the government and the population. We will add this discussion in section 5.1.

Radar is expensive and is unlikely to be feasible for all EWS in the Himalayas and Tibetan Plateau. For some key regions related to large infrastructure (e.g. hydropower dams), we think such methods are worthwhile to detect deformation and instability of rock and ice in high altitude glaciated regions. We are now trying to develop the relatively inexpensive radar with Chinese companies. We hope that such radar could be used to monitor cryospheric disasters such as snow avalanches and ice-rock collapses.

Minor comments

L32: remove ‘giant’, not a relevant descriptor

Reply: We have changed it.

L45: ‘before a glacier collapse’

Reply: We have changed it.

L45f: ‘…data is subject to favourable weather conditions and revisit cycles.’

Reply: We have changed it.

L46: ‘a glacier collapse’ – also state here what you mean by short, what is the time frame to be expected from known cases.

Reply: The duration was about 5 minutes for 2021 collapse in Sedongpu Valley (Zhao et al., 2022) and was about 2–3 minutes for the 2016 Aru collapse (Kääb et al, 2018). We will add this time duration in the revised manuscript.

L47: ‘glacier catastrophes’ is a new term you now use while earlier you used ‘glacier-related disasters’ or just specifically ‘glacier collapse’. I would stick to one and only use another if strictly necessary to describe something else.

Reply: Thank for pointing out this issue. We will unify the term as ‘glacier collapse’.

L49: remove ‘regimes’

Reply: We did it.

L67: ‘are’ not ‘were’

Reply: We changed it.

L128/L151: As you are here describing a setup, details for all sensors are crucial. What kind of thermal and why a thermal camera - refer to the Table where appropriate.

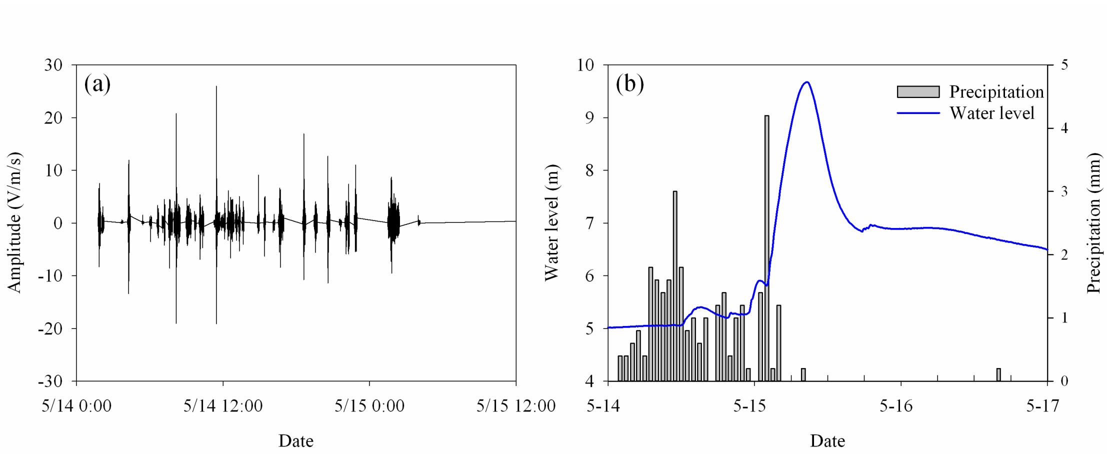
Reply: Thanks for this comment. In the Table 1, we will add the details of sensor e.g. pixels for thermal/optical and resolution of water level sensor in the revised manuscript.

L180: ‘is briefly described’

Reply: Done

Figure 3b: Legend missing making clear what is level and what is precipitation

Reply: We have added the legend in the revised manuscript.



L262: Spelling is generally ‘Medog’ in local Tibetan or if you use Chinese placenames ‘Motuo’

Reply: We have changed it as Medog.