

#Reviewer 1

This study reports three examples of lake outbursts on the Tibetan Plateau. Reported outbursts involved huge amounts of water, threatened infrastructure and are worth reporting considering the implications for future outburst hazards in the region. The text is in general well-written and the manuscript is accompanied by rich figures of high quality and information content. However, it is bit confusing for the readers that the authors describe two outbursts (from Lake Zonag in 2011 and from Lake Selin Co in 2023) in some parts of the study, while the study also contains the information about another one from Lake Donggei Cuona in 2024. To make the study clearer, I suggest the authors to introduce separate study area section (including brief description of three GLOF sites described further in the text) and to describe the studied GLOFs in separate sub-sections of the Results. I also recommend to revise discussion section, put reported outbursts in the context of other outburst in the region and present solid implications of this research for understanding outburst occurrence there. Detailed suggestions / comments / questions are provided below:

Response: Thank you for your careful review of our manuscript. After a thorough understanding of the reviewer's comments, we have carefully addressed each point raised. Of these, we have added the subsection in "2 Data and methods" section to describe three GLOF sites and have described the examined GLOFs in separate sub-sections of the Results. Meanwhile, we have enhanced the discussion of inland lake outburst with other GLOFs documented in the TP. Below, please find our detailed responses to the original feedback. For clarity, the original reviewers' comments are presented in black, and our responses are shown in blue.

L25: the 2011 GLOF has not accompanied the 2023 peak – please reword

Response: Thanks, we have improved this sentence as "Here, a long-term satellite lake mapping shows that the number and surface area of lakes on the Tibetan Plateau exhibit an increased trend over the past 50 years, peaking in 2023. Two notable outburst events occurred during this period: Zonag Lake (~150 km² in 2023) on 15 September 2011 and Selin Co (~2,465 km² in 2023, the largest lake in Tibet) on 21 September 2023.".

L29: Gt is not the unit of volume

Response: Thanks, you are right, and Gt is the unit of mass. Therefore, we have improved this sentence as "The Selin Co outburst resulted in a water mass loss of ~0.3 Gt, the downstream Bange Co experienced a water level rise of ~2.3 m and an area expansion of ~18%.".

L38: vertical motion of what?

Response: We mean vertical motion of moisture. We have improved this sentence as "For Zonag Lake, thermodynamic effects, i.e. changes in the atmospheric moisture, are the most important, while for Selin Co, dynamical effects, i.e. the vertical moisture motion induced by the changes in atmospheric circulation, dominate the precipitation patterns.".

L44: I suggest not to describe plateau lakes as alpine lakes (plateau environment and alpine environment differ in my understanding)

Response: We thank the reviewer for this suggestion and have revised "alpine lakes" to "plateau lakes".

Fig. 1: you might mention that 1970 – 2018 data come from Zhang et al., 2019

Response: We thank the reviewer for this suggestion and have added the sentence "Lake data from 1970 to 2018 are from Zhang et al. (2019a)." in the Fig.1 caption.

L78: please provide a reference

Response: We have added a related reference as follow.

Reference: Xu, F., G. Zhang, R. I. Woolway, K. Yang, Y. Wada, J. Wang, and J.-F. Crétau (2024), Widespread societal and ecological impacts from projected Tibetan Plateau lake expansion, *Nature Geoscience*, 17(6), 516–523.doi: 10.1038/s41561-024-01446-w.

L80: you actually describe three throughout the text

Response: We mainly analyzed Zonag Lake event on 15 September 2011 and Selin Co event on 21 September 2023 because of their widespread impacts, whereas the Donggei Cuona Lake event was only briefly discussed, as a dam at its outlet has subjected the lake to human intervention, and its outburst duration was relatively short. To avoid confuse, we have improved this sentence as "*In this study, we focus on two notable inland lake outburst events: Zonag Lake on 15 September 2011 and Selin Co on 21 September 2023. The Donggei Cuona Lake event on 18 February 2024 is briefly discussed due to the human management of the lake and the relatively short duration of the outburst.*".

L82: field surveying is mentioned here but not described in methods and data section – please provide more details or delete it from here

Response: Thanks for your suggestion, we have added the description about field surveying in the section "2.7 Field surveying" as follow:

"2.7 Field surveying

The field surveying was conducted in October 2023 and August 2024 for Selin Co outburst event. During the field surveying, we examined the breach, the flood channel, and damaged roads, and inlet of Bange Co. Uncrewed aerial vehicle (UAV) was used to capture the orthophotos of flood river channel from Selin Co to Bange Co, breach, as well as road and settlements at risk. Then, high accuracy DEM was generated from UAV orthophotos using Agisoft Metashape and Context Capture software to capture the depth and extent of Selin Co flood inundation.

L116: this is first time you mention this lake and outburst (see my general comment)

Response: Thanks for your suggestion, we have added the description about examined lakes in the section "2.1 Study area" as follow:

"2.1 Study area

Zonag Lake is situated in the north of Hoh Xil National Nature Reserve in Qinghai Province and the Sanjiangyuan National Park, where a large number of Tibetan antelopes are lambing, known as "Tibetan antelope delivery room" (Chen et al., 2021b). On 15 September 2011, Zonag Lake burst, forming a connected hydrological system with Kusai Lake, Hedin Noel Lake and Yanhu Lake. Zonag-Yanhu Lake basin covers a total area of ~8,564 km², with an extensive distribution of permafrost and periglacial landforms. The average elevation is 4600 m a.s.l. Based on nearby Wudaoliang meteorological station data from 1961 to 2019, the annual mean temperature is about -5.1 °C and the annual mean precipitation is 299.8 mm (Chen et al., 2021b). The region is characterized by three vegetation types: alpine meadows, grasslands and deserts (Liu et al., 2019).

Selin Co is the largest lake in Tibet and the second largest in the TP, with an area of ~2,465 km² in 2023. On 21 September 2023, an outburst occurred at Selin Co, resulting in flooding downstream into eastern Bange Co. The total area of Selin Co basin is ~44,437 km², covering 369.7 km² of glacier and 13,404 km² of permafrost (Wang et al., 2022b). Selin Co is fed by four major rivers: Zhajiazangbu, Boquzangbu, Alizangbu and Zhagenzangbu, and has several upstream exorheic lakes, including Qiagui Lake, Wuru Lake and Cuoe Lake. The basin is dominated by a cold, semi-arid monsoon climate, with an average temperature of around 0 °C and average annual precipitation of ~350 mm (Tong et al., 2016). Donggei Cuona Lake is located in the western part of TP (98.55° E, 35.28° N), with an area of ~260 km² in 2023. Donggei Cuona Lake is an exorheic lake with a dam at the outlet. On 18 February 2024, a breach occurred in the left sluice chamber of Donggei Cuona Lake, causing water to flow out of the lake."

L152: please provide more details how did you set this value? Based on field measurements?

Response: Thanks. Some of the previous parameters were based on assumptions and now we determined them based on field measurements and remote sensing observations. After updating the parameters, we rerun the model and the simulations were good. We have added more details about parameter as: "The width and breach formation time of the breach was determined by tracking its progression using high-resolution PlanetScope imagery. Specifically, the breach width was approximately 60 m on 23 September 2024, expanded to ~160 m by 27 September, reached ~180 m by 3 October, and finally developed to ~200 m on 8 October. Based on this progression, we estimated that the breach formation time took 18 days beginning from the initial breach on 21 September and width of breach was 200 m. The depth of the breach was set to 2 m, which is based on field measurements (Lei et al., 2024). The total calculation time was set from 21 September to 13 October 2023. The Manning roughness coefficient was set to 0.04 based on field surveys, which shows that the river channel area is covered by sparse herbaceous vegetation.".

L158-160: what is the justification of this assumption?

Response: Due to the lack of the continuous observations, there is uncertainty in the discharge fitted by the spline method. Therefore, we have removed this continuous spline-fitted discharge and kept only the mean discharge over a period calculated from the PlanetScope observation and hypsometric curve.

L163: I suggest to distinguish outburst drivers (e.g., climate change) and mechanisms (dam breaching)

Response: Thank you for your suggestion. While we acknowledge the importance of distinguishing between outburst drivers and mechanisms, the primary focus of our analysis is on the factors influencing lake outbursts, such as long-term precipitation increase and other related environmental drivers. The atmospheric mechanisms we analyzed mainly explain how increased precipitation contributes to lake expansion. Regarding the dam breaching mechanism, we interpret it as a natural result of the lake expanding to the maximum extent that the surrounding terrain can accommodate. Therefore, dam breaching occurs as a consequence of the lake's physical expansion, which is different from dam breaching for glacial lake, emphasizing dam stability or failure processes. Given the focus of our study, we have chosen to emphasize the atmospheric drivers.

L181: please consider moving this section before 2.4

Response: Thanks, we have moved this section forward.

L230: representativeness for what?

Response: The representativeness means representation of the natural expansion of lakes on the Tibetan

Plateau. We have improved this sentence as follow: *“Here, we focus on the outburst events in Zonag Lake and Selin Co due to their wide-ranging impacts (i.e., damage to infrastructure, ecosystems, and biodiversity) and representativeness of the natural expansion of lakes on the TP.”*

Fig. 3: since the study highlights the impact of precipitation increase on lake evolution, I suggest to plot lake areas shown in parts a and c against precipitation data from Fig. 7. For part b, please consider adding arrows and description directly in photos, so it is easier to understand what they illustrate

Response: We thank the reviewer for this suggestion. We have displayed the lake area in Fig.3a and 3c with precipitation change in Fig.7 in one subplot to facilitate comparison (Below). Also, for Fig.3b, the arrows and descriptions have been added to facilitate understanding.

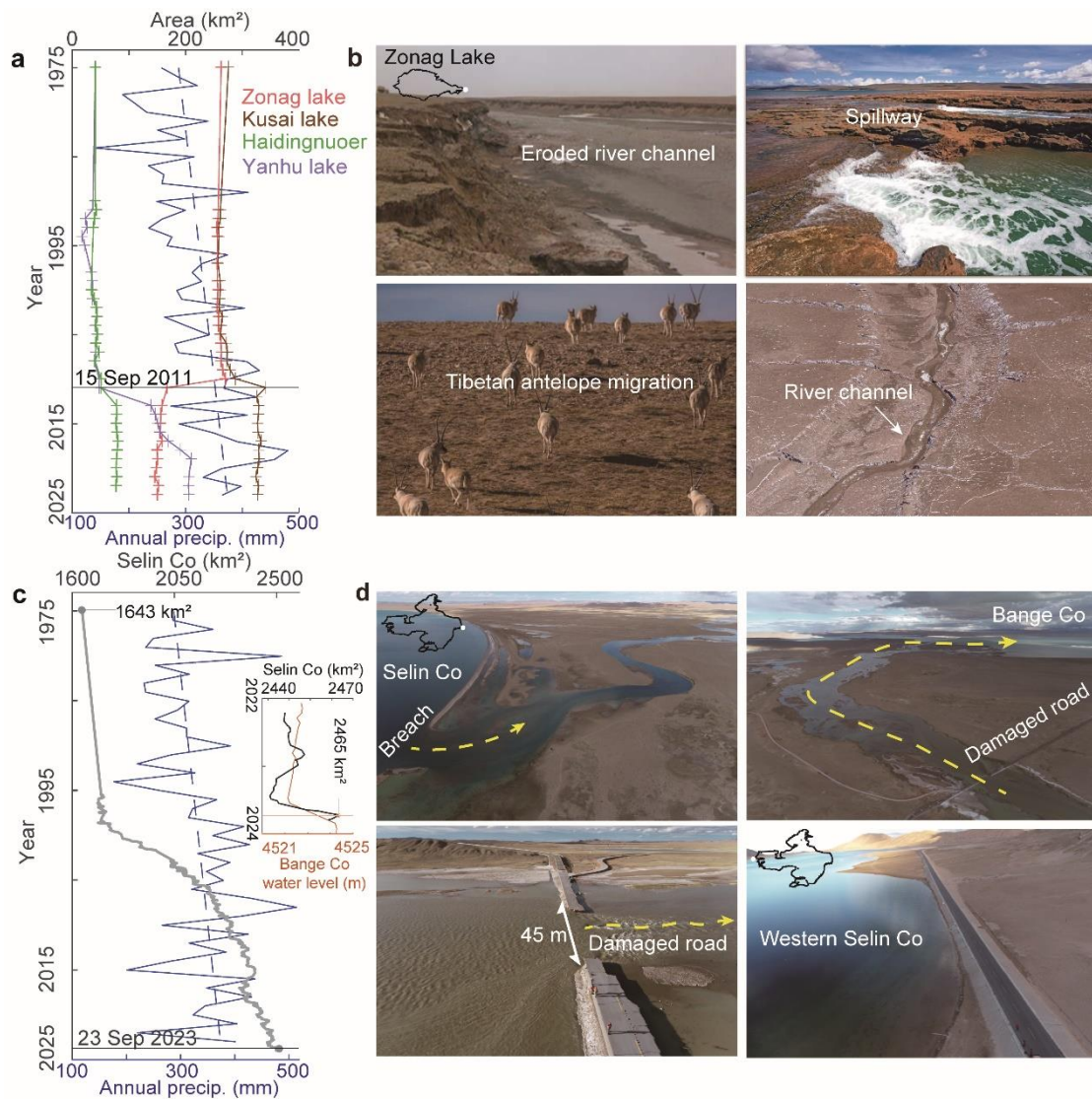


Figure 3. The changes and impacts of Zonag Lake and Selin Co. (a) The area change of Zonag Lake and downstream Kusai Lake, Haidingnuoer and Yanhu Lake, as well as the annual precipitation change from Wudaoliang weather stations (Blue). (b) The impact of Zonag Lake outburst, including the formation of new channel, soil erosion and the disruption of Tibetan antelope migration routes. (c) The area changes of Selin Co, as well as the annual precipitation change from Shenzha weather stations (Blue). The inset shows the rapid expansion of Selin Co and Bange Co in 2022-2024. (d) The impact of Selin Co outburst, including formed

breach, damaged road, new channel between Selin Co and adjacent Bange Co. Selin Co has also approached near the road on the south-west side (lower right panel).

L258: "water had reached he road" rather than "had accumulated near"?

Response: Thanks. We mean an accumulation of precipitation, not the outburst flood of Selin Co, which has not yet occurred. To avoid the confuse, we have improved this sentence as followed "*Selin Co was still in normal condition on 16 September, whereas by 20 September there was already a substantial amount of water near the S208 road indicating signs of heavy precipitation.*".

L259: what signs of heavy precipitation?

Response: Based on high-resolution Planet remote sensing imagery, it was found that Selin Co had not yet breached on 20 September 2024, but the road was heavily waterlogged, which implied that heavy precipitation was occurring.

L265; the precision of discharge to two decimal places is inappropriate considering uncertainties and assumptions of model inputs (including input hydrograph)

Response: Thanks, we have revised two decimal places to four decimal places for small discharge of Selin Co for this sentence.

Fig. 4: "The outburst" instead of "outbursting process"?; i and j – km instead of m on x axis?

Response: Corrected.

L286: how reliable is this number considering DEM resolution, accuracy and uncertainties of modelling?

Response: We thank the reviewer for this suggestion. To validate the reliability of the modelling, we conducted three verification actions. First, since all the floodwaters flowed into Bange Co, we compared the simulated water level change in Bange Co with satellite-based measurements. The model simulated a water level rise of 2.23 m, which matches well the observed increase of 2.30 m. Second, the simulated flood path and extent showed good spatial consistency with PlanetScope imagery. The extent of Bange Co observed on 13 October 2024 from PlanetScope imagery also aligned well with the simulated extent change. Third, we compared the simulated flood depth with UAV-derived DEM measurements of the post-breach flood channel. The model simulated flood depth at the right side the damaged road was 1.63 m, while UAV measurements indicated a depth of 1.96 m (the elevation difference between the riverbank and riverbed), showing good agreement. Therefore, the simulated flood process has good reliability. We have added more details as: "*To validate the reliability of the model, we implemented validation in three aspects. First, we compared the simulated water level changes in Bange Co with satellite-based measurements, as all floodwaters flowed into the lake. Second, the simulated flood path and extent were verified by comparing them with PlanetScope imagery to assess spatial consistency. Third, the simulated flood depth was validated with UAV-derived DEM measurements (the elevation differences between the riverbank and the riverbed can reflect the inundation depth of flood) of the post-breach flood channel.*" in method section, and "*A water level rise of 2.23 m was identified from the hydrodynamic simulation, which matches well the observed increase of 2.30 m. Additionally, the simulated flood path and extent as well as the boundary of Bange Co showed good spatial consistency with PlanetScope imagery. We also compared the simulated flood depth with UAV-derived DEM measurements of the post-breach flood channel. The model simulated flood depth at the right side the damaged road was 1.63 m, while UAV measurements indicated a depth of 1.96 m, showing overall good agreement (Figure 7).*" in "3.2.2 Selin Co outburst event"

subsection.

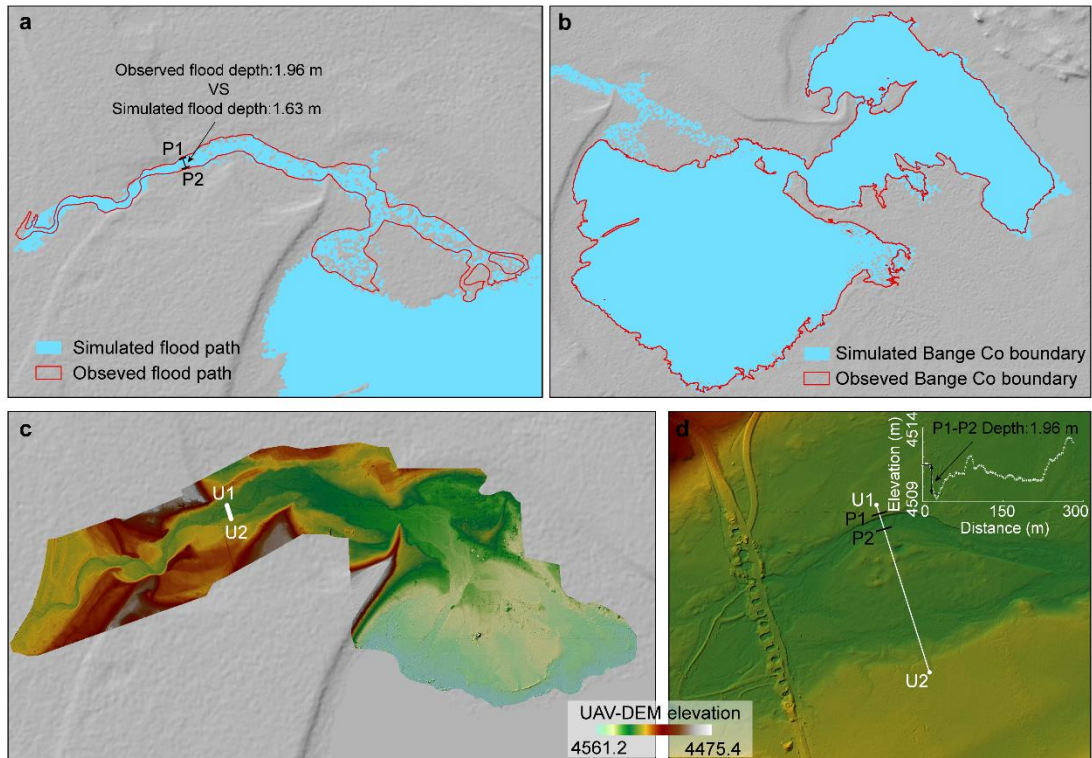


Figure 7. The validation of the Selin Co outburst flood simulation. (a) Comparison of the simulated flood path with PlanetScope observations of Selin Co on 13 October 2024. (b) Comparison of Bange Co boundary with PlanetScope observations of Selin Co on 13 October 2024. (c) The UAV-derived DEM of the Selin Co flood path. (d) The UAV-DEM near the damaged road, and the inset shows the elevation profile of the right side of the damaged road to indicate the flood inundation depth.

L288-293: the distance between the two lakes (according to Fig. 4) is about 12 km. This gives average flood velocity < 1 km per hour. This is very slow, definitely not rapid as described here.

Response: We thank the reviewer for this suggestion. We have improved this sentence as follow: *"This suggests that even in flat areas, the impact of flooding can be significant in a short period of time and requires the establishment of an early warning system"*.

L292: agree about what?

Response: We mean "agree with the flood inundation extent from remote sensing observations (Fig.5 and Fig. 7).

L299: is this the case in the TP?

Response: For endorheic lakes on the Tibetan Plateau, this is the case. The two recorded outburst events from endorheic lakes in the region (Zonag Lake and Selin Co), as mentioned in this study, both involved lakes that expanded until they overflowed, leading to erosion at the breach site. Of these, it can be noted from the Selin Co event that the width of the breach widened from about 60 m on 23 September 2024 to 200 m as a result of erosion. However, this mechanism does not apply to glacial lakes. Glacial lake outburst floods (GLOFs) are typically triggered by external forces such as ice avalanches or landslides, which cause rapid destabilization. In contrast, endorheic lake outbursts are more internally driven, as the lakes expand naturally due to increased

water input, eventually exceeding the terrain's capacity to contain them. When overflow occurs in endorheic lakes, it often initiates erosion of the dam, potentially turning overflow into a full breach. Therefore, while the risk of overflow and erosion is pertinent to endorheic lakes, it is less relevant for glacial lakes, where external triggers are the primary drivers of outburst events.

L300: how did you get this discharge? It is written in the >Methods that only the outburst of Selin Co was modelled. The 2,191 m³/s average discharge over 28 days gives outburst volume exceeding 5 km³ (!!). If so, this is among the largest (maybe even the largest) outburst floods in the Anthropocene and it should be highlighted

Response: Thank you for your comment. Upon reviewing the calculation, we have identified a minor discrepancy in the originally reported discharge. The discharge was calculated by dividing the total outburst water volume by duration. Based on changes in lake area (a decrease of 107.5 km²) and water level (a drop of approximately 25.59 m over 28 days), the total water volume loss was re-estimated using volume estimation formula (Eq 1), resulting in a total water loss of 5.42 Gt (km³). This corresponds to an average discharge of 2,238 m³/s over the 28-day period, slightly higher than the previously reported value of 2,191 m³/s. We will revise the manuscript to reflect the corrected value.

$$\Delta V = \frac{1}{3} \Delta h \times (A_1 + A_2 + \sqrt{A_1 \times A_2}) \quad (1)$$

where ΔV is the lake volume change (km³), which is usually converted to water storage change in Gt (gigaton) to compare water mass gain or loss; A_1 and A_2 are lake areas (km²) at stage 1 and stage 2, respectively; Δh is the water levels (m) at the corresponding stages.

Fig. 7: please add a trendline for part a and consider plotting this against lake area (see my suggestion above)

Response: We thank the reviewer for this suggestion. We have added a trendline for original Fig.7a (now Fig.3)

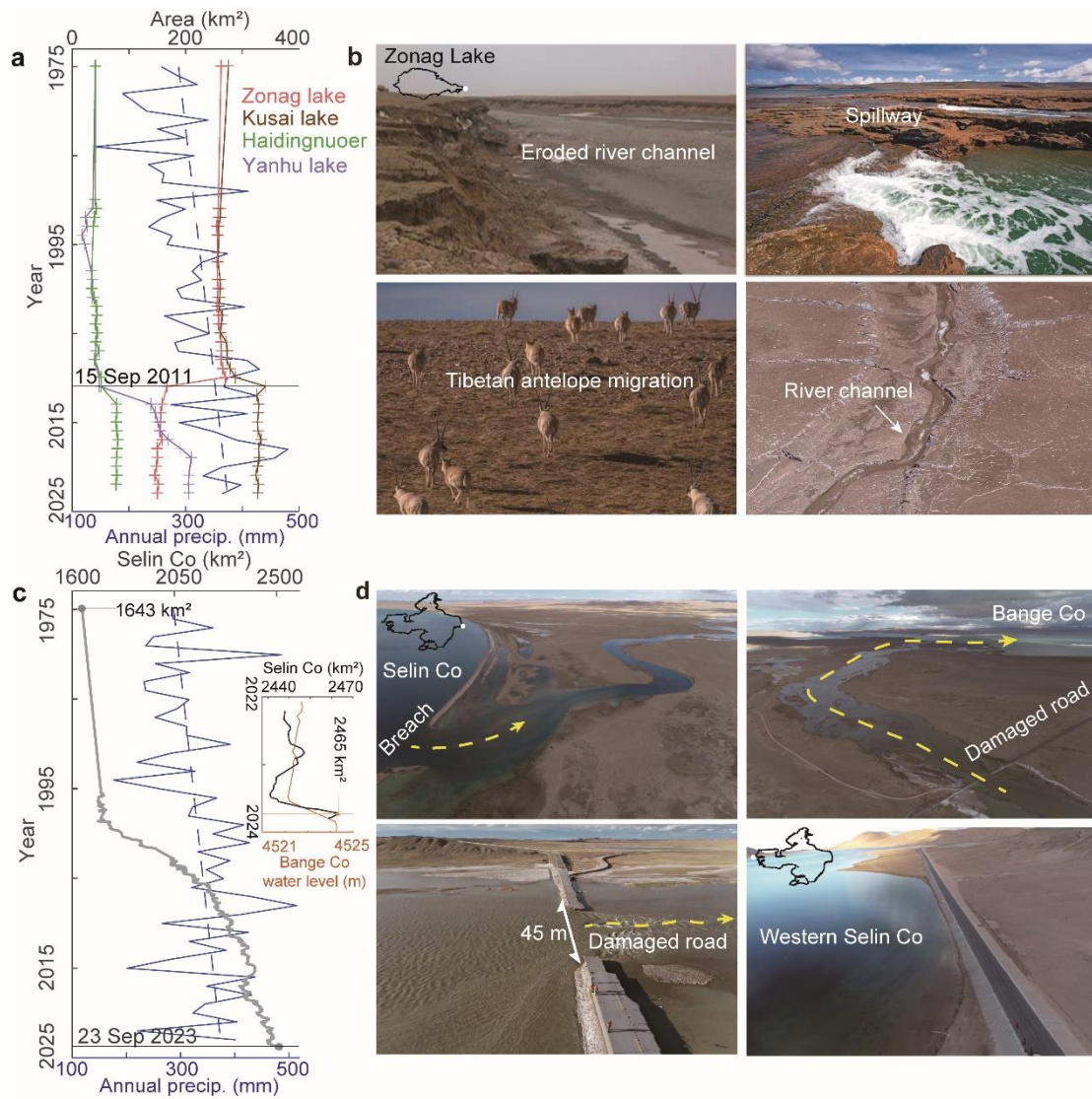


Figure 3. The changes and impacts of Zonag Lake and Selin Co. (a) The area change of Zonag Lake and downstream Kusai Lake, Haidingnuoer and Yanhu Lake, as well as the annual precipitation change from Wudaoliang weather stations (Blue). (b) The impact of Zonag Lake outburst, including the formation of new channel, soil erosion and the disruption of Tibetan antelope migration routes. (c) The area changes of Selin Co, as well as the annual precipitation change from Shenzha weather stations (Blue). The inset shows the rapid expansion of Selin Co and Bange Co in 2022-2024. (d) The impact of Selin Co outburst, including formed breach, damaged road, new channel between Selin Co and adjacent Bange Co. Selin Co has also approached near the road on the south-west side (lower right panel).

L312: I was also wondering whether is there possibly any substantial contribution from melting glaciers? Please discuss this

Response: The contribution of glacier melt to lake expansion is relatively small, with precipitation being the dominant factor. For Selin Co, DEMs derived from KH-9 and CoSSC-TanDEM-X data estimate glacier contributions to lake expansion at approximately 3.5% to 16.3% (Chen et al., 2021). Similarly, degree-day model simulations from 1976 to 2013 suggest a contribution of about 10% (Tong et al., 2016). For Zonag Lake,

model simulations indicate that glaciers and snow contribute around 21% to lake expansion (Wang et al., 2022). Therefore, glacier melt plays a relatively minor role in the overall lake expansion process.

References:

- Chen, W., Yao, T., Zhang, G., Li, S., and Zheng, G.: Accelerated glacier mass loss in the largest river and lake source regions of the Tibetan Plateau and its links with local water balance over 1976–2017, *Journal of Glaciology*, 67, 577-591, 10.1017/jog.2021.9, 2021.
- Tong, K., Su, F., and Xu, B.: Quantifying the contribution of glacier meltwater in the expansion of the largest lake in Tibet, *Journal of Geophysical Research: Atmospheres*, 121, 10.1002/2016jd025424, 2016.
- Wang, L., Liu, H., Zhong, X., Zhou, J., Zhu, L., Yao, T., Xie, C., Ju, J., Chen, D., and Yang, K.: Domino effect of a natural cascade alpine lake system on the Third Pole, *PNAS nexus*, 1, pgac053, 2022.

L330: this extreme precipitation prior the outbursts is not shown

Response: Thank you for this comment. We have added a subplot in original Figure 7 (now Figure 4) to show the daily precipitation changes prior to the outburst based on data from a nearby weather station, which indicate the continuous heavy precipitation prior to the outburst (Figure 4).

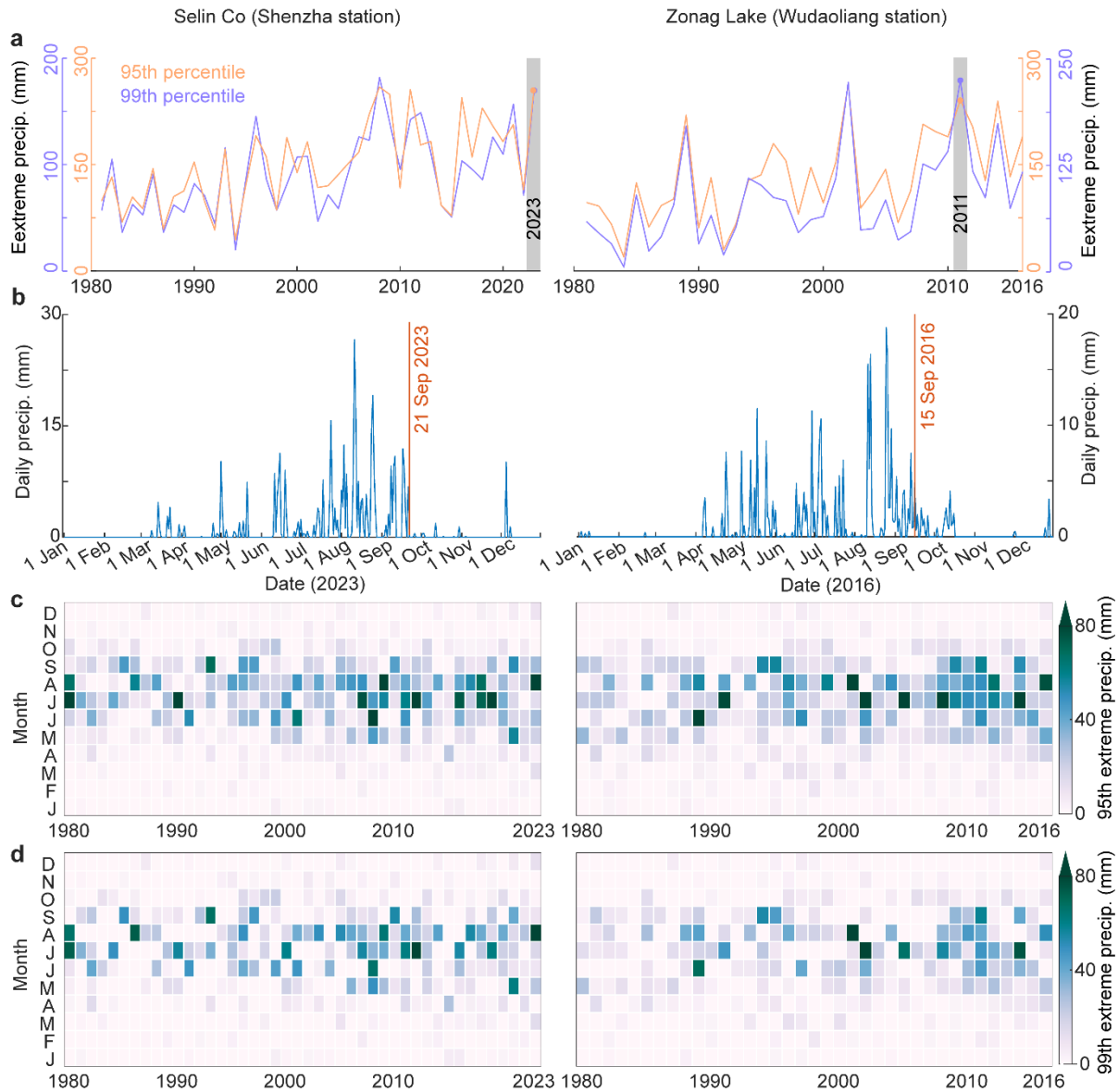


Figure 4 (original Figure 7). The change in extreme precipitation derived from Shenzhen (near Selin Co) and Wudaoliang (near Zonag lake) weather stations. (a) Extreme precipitation (total precipitation that exceeds a 95th and 99th percentile during the historical period from 1981 to 2010) change from 1980 to 2023. (b) The daily change of precipitation prior to the outburst. (c) Monthly extreme precipitation change based on the 95th percentile from 1980 to 2023. (d) Monthly extreme precipitation change based on the 99th percentile from 1980 to 2023. The location of the weather station was shown in Figure 1.

Figs. 8-11: these figures are difficult link to outbursts of the two lakes. Maybe one synthesizing figure can be presented in the main manuscript and the rest goes to the supplement?

Response: We appreciate the reviewer's suggestion. We would like to retain original Fig. 8 in the main manuscript as it serves as a summary figure. Original Figs. 9 and 10, which provide detailed analysis of different contributions, have been moved to the supplementary. However, due to the important role of atmospheric circulation on water vapor increase, we believe original Fig. 11 is important for understanding the overall process and would like to keep it in the main manuscript.

L411: how does it accelerated permafrost degradation?

Response: Using SBAS-InSAR analysis of Envisat and Sentinel-1 datasets, accelerated permafrost degradation around Yanhu Lake since 2014 was observed. This degradation is likely linked to alteration in the thawing-freezing cycles and melting of ground ice, which may have impacted hydrological connectivity and soil permeability (Lu et al., 2020). The changes in surface thermal conditions following the lake outburst may have further contributed to these processes.

Reference:

Lu, P., Han, J., Li, Z., Xu, R., Li, R., Hao, T., and Qiao, G.: Lake outburst accelerated permafrost degradation on Qinghai-Tibet Plateau, *Remote Sensing of Environment*, 249, 112011, 10.1016/j.rse.2020.112011, 2020.

L429: the recommendations mentioned in this section are general; to make stronger point, reported events should be put in the context of other GLOFs documented from the TP (in terms of outburst timing, drivers, etc.)

Response: We thank the reviewer for this suggestion. We have added the description about the discussion with other recorded GLOFs in the TP as follow:

"Lake outburst events on the TP can be divided into two categories based on their driving mechanisms: endorheic lake outbursts and GLOFs. The two documented endorheic lake outburst events in this region, Zonag Lake and Selin Co, both involved lakes expanding due to increased water input until they overflowed. This overflow led to erosion at the breach site, eventually resulting in full outbursts. For instance, in the Selin Co event, the breach widened from ~ 60 m on 23 September 2024 to ~200 m on 8 October 2024 due to ongoing erosion, which illustrates how overflow can rapidly escalate into a breach. In contrast, GLOFs are typically triggered by external factors such as ice avalanches and landslides. These events cause rapid destabilization of glacial lakes, leading to sudden, high-discharge floods that peak within hours or cause the end of flood releases. GLOFs tend to be more frequent due to the unstable nature of glaciers and other factors. For example, the Gongbatongsha Co outburst events in 2016 in China demonstrate the devastating potential of these sudden releases (Wang et al., 2024), which are often difficult to predict and have higher peak discharge compared to endorheic lake outbursts.

While both types of events pose significant risks, endorheic lake outbursts are more gradual in nature, driven by the internal dynamics of lake expansion. In contrast, GLOFs are driven by external forces, often resulting in more abrupt and catastrophic flooding. Understanding these differences is critical for risk assessment and management on the TP, as the two types of lakes require different monitoring and mitigation approaches. For instance, monitoring glacier dynamics and potential ice avalanches is crucial for GLOFs, whereas tracking lake water levels and identifying potential overflow points is key for managing endorheic lake outbursts."

Reference:

Wang, X., Zhang, G., Veh, G., Sattar, A., Wang, W., Allen, S. K., Bolch, T., Peng, M., and Xu, F.: Reconstructing glacial lake outburst floods in the Poiqu River basin, central Himalaya, *Geomorphology*, 449, 10.1016/j.geomorph.2024.109063, 2024.

To sum up, I'm convinced this study fits well in the journal and would be of interest for the readers. I recommend revisions of the structure, introduction of a separate study area section and revision of the discussion section (moderate to major revisions).

Response: We sincerely thank the reviewer for the careful and constructive comments. We agree that these

suggestions will enhance the overall quality of our manuscript. These changes have been made to ensure the manuscript is clearer and more accessible to the readers.