Response to reviewer2's comments (essd-2021-354)

Spatio-temporal evolution of glacial lakes in the Tibetan Plateau over the past 30 years

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Dear reviewer,

Thank you for your careful review of our manuscript and for your many high-quality comments and observations. We carefully re-evaluated the novelty and originality of our study, especially by comparing with other published studies, i.e. Wang et al. (2020) and Chen et al. (2021). Actually, novelty of a study is always the first and the most important thing to evaluate before conducting any research. The overall objective of our research project is to reveal the spatio-temporal evolution of glaciers and glacial lakes in Tibetan Plateau and their response to climate change. We intended to use currently available glacial lake inventories, but after a thorough literature review, we found that the temporal and spatial resolutions of published glacial lake inventories did not yet meet our research needs. There are some inventories has high temporal resolution but only cover small regions, while some other inventories cover larger area of Tibetan Plateau but derived from one or two periods (i.e. Wang et al., 2020). Besides, some inventories cover more recent period (with later start time of mapping, i.e. Chen et al., 2021). Please refer to the Introduction and Discussion (5.1 Comparison with other glacial lake datasets) in the revised version for details. This gap motivates us to spend more than one year to collect data and develop methods to create a new inventory, achieving a more complete, accurate product with higher temporal resolution (covering three periods for the whole Tibetan Plateau).

We provide more evidence and responses to your concerns as follows. We hope you could make a reconsideration to our study.

Thank you again for reviewing the manuscript.

Best regards,

Xuanmei Fan on behalf of all coauthors

Deputy director of State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology

Broad Comments:

Reviewer comment 1:
Indeed, the authors have done a tremendous job in mapping glacial lakes in this region, which I greatly acknowledge. The largest number and size of glacial lakes is also a newsworthy result, and the figures can largely be used to illustrate the regional pattern of glacial lakes. However, to make an original and novel contribution, this study needs more justification and discussion of why it is different from all previous studies. From the current structure, it remains unclear why this study represents a major advance in either the technical processing of satellite imagery or the physical understanding of glacial lakes on the Tibetan Plateau. The authors do cite some previous studies dealing with lake mapping. However, given the differences in temporal and spatial extent, minimum mapping units, distance to different glacier inventories, mapping uncertainties, time periods studied, aggregated time intervals, etc., it remains difficult for the reader to say why this inventory is a "must read" or a "must have" for future studies.

Response 1:

We are thankful for your appreciation of the work we did. To your concern about our *technical processing*, *original and novel contribution,* and *why this inventory is a "must read" or a "must have" for future studies*, we provide the following discussions:

(1) After a thorough literature review, we found deficiencies in the spatial and temporal resolution of published glacial lake inventories of Tibetan Plateau. Some have only covered small regions or have significant missing data, others have only one to two periods of data mapping, or cover only recent periods. However, limited by the quality and quantity of early satellite images, it is difficult to conduct year-by-year

mapping of the whole Tibetan Plateau glacial lakes. In this regard, **we adopted an image aggregation technique that has not been applied in the field of glacial lake mapping on the whole Tibetan Plateau.** Multi-year images with no or few clouds and no terrain shading were selected and fused into a single image under relevant parameters within the Google Earth Engine platform, and glacial lake boundaries were mapped. Based on this, we obtained three images by fusing the highest quality Landsat images without cloud cover and mountain shadows from July to November each year, in which 42,833 Landsat images were used in total.

(2) As the reviewer mentioned, we cited some previous studies on lake mapping and compared our work with the inventories of Wang et al. (2020) and Chen et al. (2021), which have relatively better spatial and temporal resolution coverage. Although the temporal resolution of Chen et al. (2021) is finer, but it covers more recent periods without mapping of earlier glacial lakes. Moreover, Chen et al. (2021) extracted the least number of glacial lakes among the three glacial lake inventories. Although Wang et al. (2020) mapped more glacial lakes compared to Chen et al. (2021), there are some omissions and Wang et al. (2020) only mapped two separate periods of data for 1990 and 2018, leaving considerable data gaps.

To further prove this point, we randomly selected several regions of the Tibetan Plateau to prove the accuracy and completeness of our inventory. Please note that in the figures - blue polygons show the glacial lakes from our inventory, red polygons are from Wang et al. (2020), and yellow polygons are from Chen et al. (2021).

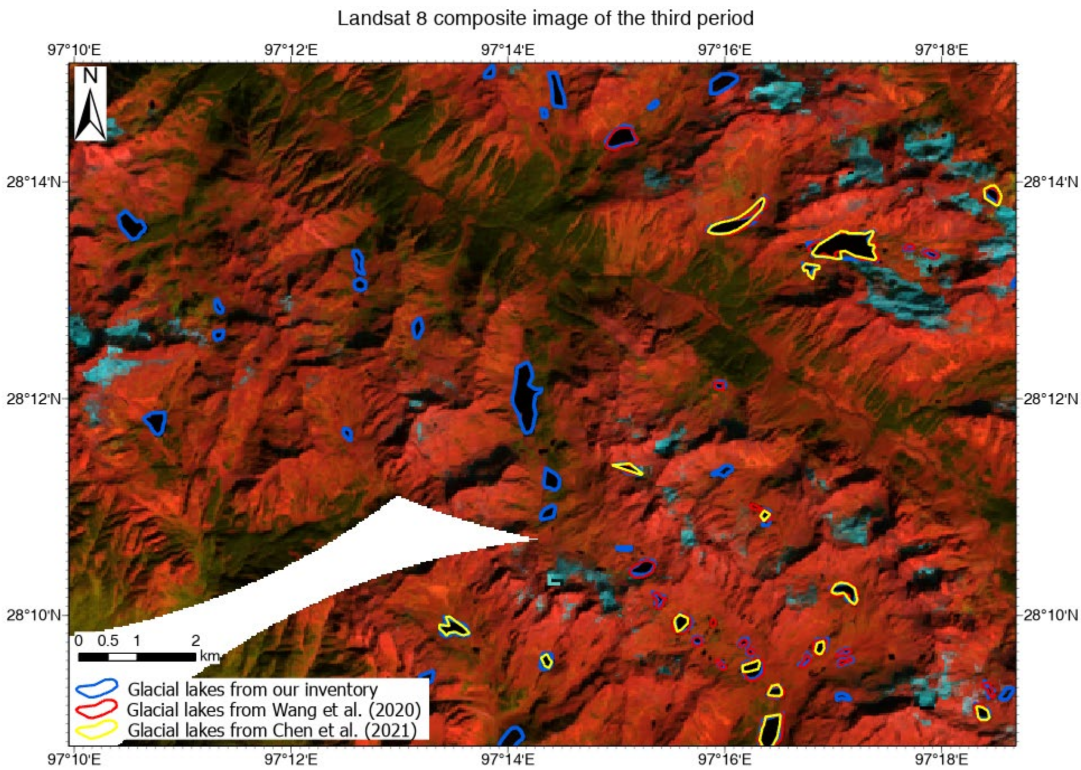


Figure 1. Automatic extraction of glacial lakes using Landsat 8 composite imagery for randomly selected region #1 (blue polygons from our inventory; red polygons from Wang et al. (2020); yellow polygons from Chen et al. (2021))

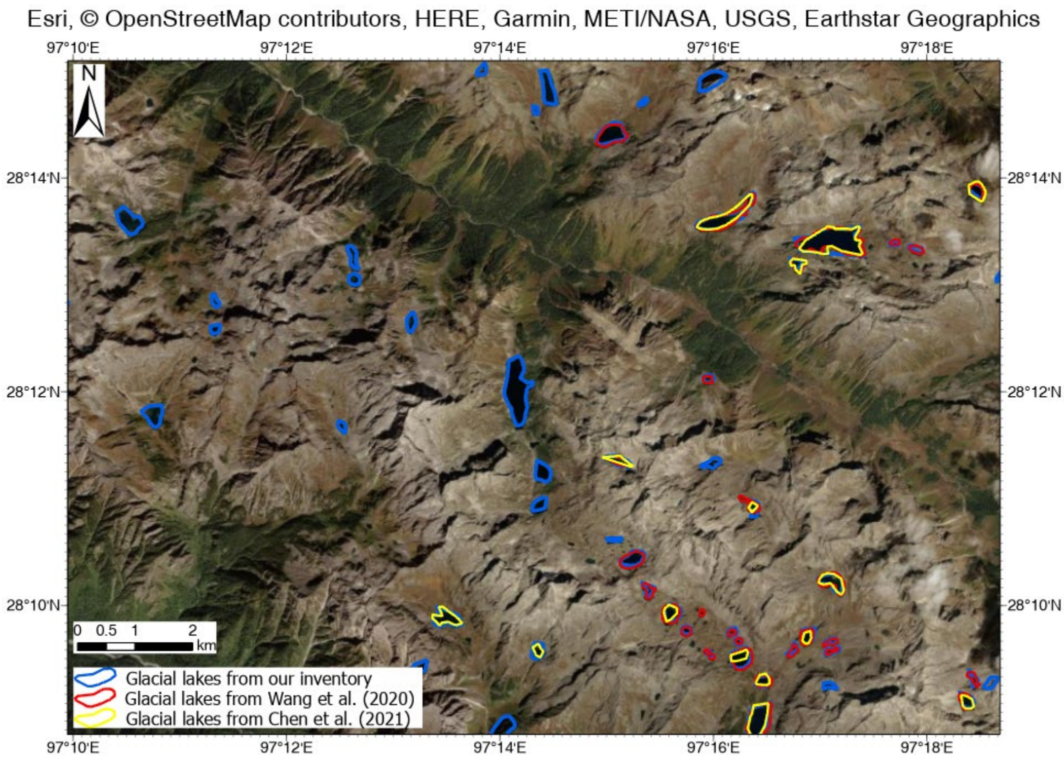


Figure 2. Extracted lakes from Figure 1 overlaid on ESRI online maps

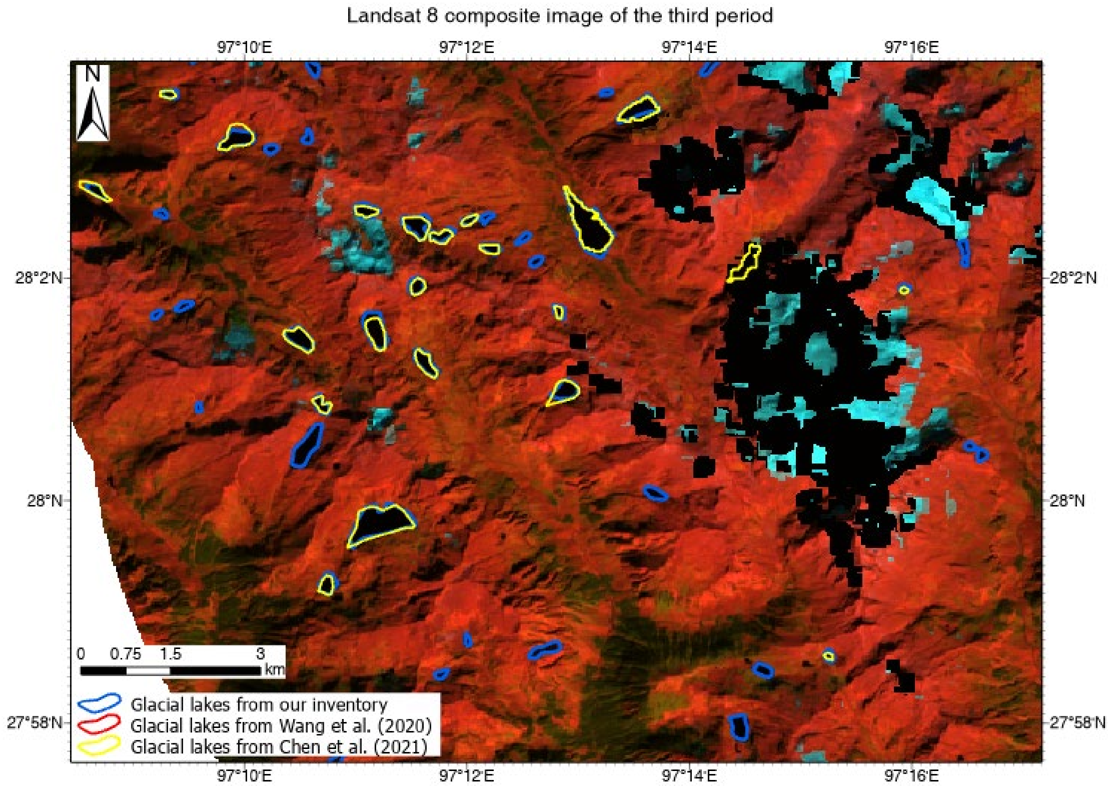


Figure 3. Automatic extraction of glacial lakes using Landsat 5 composite imagery for randomly selected region #2. Note Wang et al. (2020) 's inventory did not map any lakes in this region.

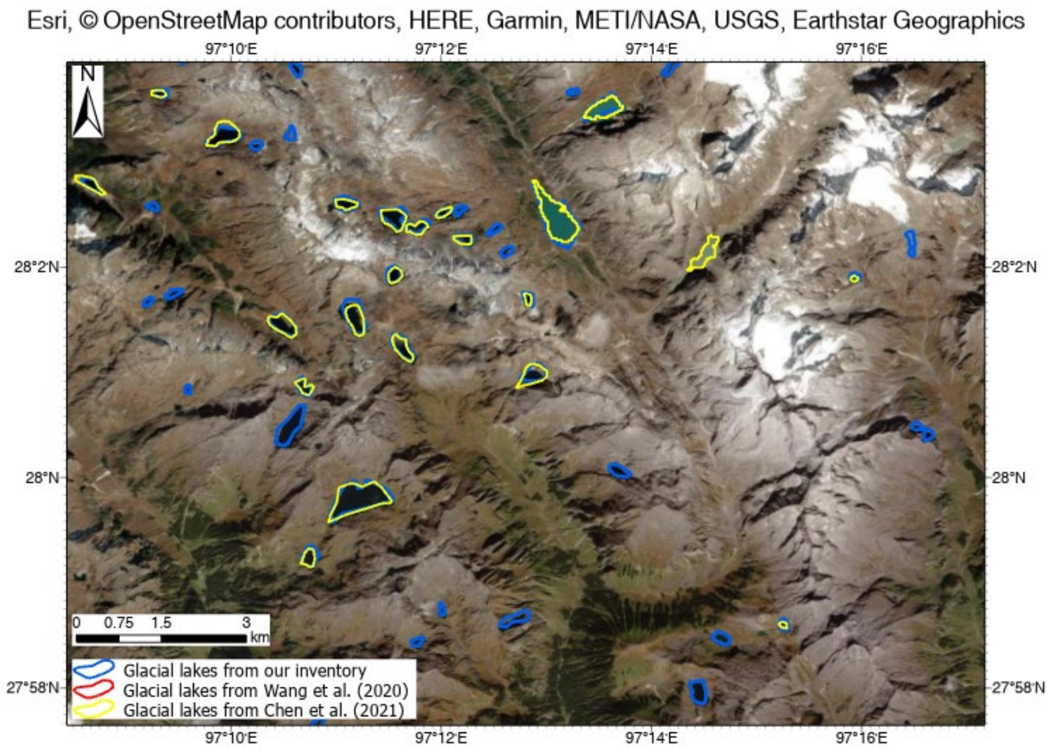


Figure 4. Extracted lakes from Figure 3 overlaid on ESRI online maps. Note Wang et al. (2020) 's inventory did not map any lakes in this region.

From the above comparisons in randomly selected regions, **we can see that several glacial lakes are missing in Wang et al. (2020) and Chen et al. (2021).** Thus we mapped larger number and area of glacial lakes, see Table 2 in page 20 of our manuscript as follows.

Table 2 Number and area of glacial lakes from this study and Wang et al. (2020) and Chen et al. (2021)

Dataset sources	Time	Number	Area (km^2)
This study	1990-1999	19183	1509.17
	2000-2012	20655	1637.01
	2013-2019	22468	1767.99
Wang et al. (2020)	1990	18025	1349.214
	2018	20250	1579.009
Chen et al. (2021)	2008	11149	1199.478
	2009	11572	1149.932
	2010	11590	1218.32
	2011	11712	1212.695
	2012	11758	1194.173
	2013	12473	1222.587
	2014	12385	1238.371
	2015	13356	1267.209
	2016	13073	1260.805
	2017	13601	1273.41

It is worthy mentioning that constrained by lack of yearly available high quality images, a year-by-year inventory of glacial lakes is currently not possible. Our approach, therefore, provides the latest inventory with a possible inclusion of almost all glacial lakes in the whole Tibetan Plateau. We believe it also provides the greatest possible demonstration of the dynamic evolution of glacial lakes with higher temporal resolution.

(3) We are pleased that you have raised the issue of *"the differences in temporal and spatial extent, minimum mapping units, distance to different glacier inventories, mapping uncertainties, time periods studied, aggregated time intervals, etc."* of your query. Prior to this work, we considered the determination of some thresholds in the glacial lake mapping process. We believe that it is crucial to choose the same determination criteria as the mainstream inventories, including spatial extent, methods for assessing the uncertainty of results, minimum mapping units (this is explained in detail below), and the time period of the study, when performing original and novelty work on a work that has already been similarly studied. Of course, in our study, we focus on the spatial extent of the entire Tibetan Plateau region, not on a small area. In terms of time scale, we have mapped three periods

from 1990 to 2019, and we have not only the beginning and end time data coverage, but also the intermediate time coverage compared to other databases of long time scale. We chose to be consistent with most of the data datasets in terms of minimum map units and distances to glacier terminus, but we used the more accurate GAMDAM glacier database for the selection of glacier data. And for the time of data aggregation, we even used this aggregation time-periods images technology for the first time in the study. While ensuring that our study is of the same standard in terms of cross-sectional comparisons with other studies, we also used more and higher quality data (e.g., up to 42,833 Landsat images, and higher quality AW3D30 DEMs (Chen et al., 2022)) to complete our work.

Reviewer comment 2:
The minimum mapping unit: This is a known issue particularly for lakes at the lower size-distribution. Mixed spectral signatures can cause a lake that persists throughout the study period to fall either within or outside the threshold chosen in this study (81,000 m²). Nie et al. (2017, p.10) used the same threshold, and report that "other research selected 0.0001 km2 (Salerno et al.,2012), 0.0027 km2 (Zhang et al., 2015), 0.0036 km2 (Gardelle et al., 2011) or 0.0045 km2 (Li and Sheng, 2012) as the minimum mapping unit. Our result indicates that 8.1% of glacial lakes belonged to the size class 0.0081–0.01 km2, which only took up 0.79% of the total area. It is obvious that the minimum mapping unit has a significant effect on the total number of glacial lakes, however it affects the total area only slightly." I thus wonder how large this effect is, even when comparing this study with that of Chen et al (2021) and Wang et al. (2020) who used similar mapping units. Figure 12 is interesting in this regard, as it suggests that this study on average reports more lake area of a given size than Wang et al. and Chen et al. However, dots above the diagonal line suggest those studies also report a number of cases that have more lake area than this study, and I wonder why? A more detailed assessment of the reasons behind these differences could add a convincing point to readers why to choose the presented dataset from now on.

Response 2:

Thanks for your careful review and comment.

About the report that *"It is obvious that the minimum mapping unit has a significant effect on the total number of glacial lakes, however it affects the total area only slightly"* you mentioned of Nie et al. (2017), we performed statistics for our data here. According to the inventory, we can get the percentage of the total number of glacial lakes with the area between 0.0081 km^2 - 0.01 km^2 to the total number of glacial lakes are 8.53%, 8.12% and 7.61%, with the total area percentages are 9.81%, 9.29% and 8.77%, respectively. These two sets of data show that the number and area percentage of glacial lakes in the range of 0.0081 km^2 - 0.01 km^2 are decreasing, while the overall total number and total area of glacial lakes are increasing. This indicates that the addition and expansion of glacial lakes have been accelerating in recent years, and there may be some nascent lakes with starting areas exceeding 0.01 km^2. However, we believe this requires more rigorous in-depth study and analysis, and therefore it is not presented in this manuscript.

"Figure 12" is a comparison of the results of our inventory and Wang et al. (2020) and Chen et al. (2021). We aggregated the total glacial lake areas in TP on the 0.1°×0.1° grids, then conducted the spatial correlation of the distributions of glacial lakes in the three inventories with linear fit. Here we have modified *"Figure 12"* by adding a 1:1 diagonal line (as shown in Figure 12, all figures will be updated in subsequent revisions of this manuscript). In Figure 12, two clear and strong fitting curves can be observed for all the statistics, and most of dots are distributed around the 1:1 diagonal line, which shows good consistency between our inventory and Wang et al. (2020) and Chen et al. (2021). In the comparative check of the datasets, we also found that there were some regions that were not covered by our inventory but they were. After checking, we found that the reason might be that we chose different glacier boundaries to divide the coverage area of the glacial lake, as we described in the second paragraph of *Section 5.1:*

"To obtain a more accurate distribution range of glacial lakes, the GAMDAM glacier inventory with higher quality was selected in our study to create the buffer of 10 km of distance from the glacier terminus to lakes (Nuimura et al., 2015), while the other two datasets applied RGI and other glacier inventories. Different glacier inventories are bound to create a difference in buffers, which leads to different numbers in the glacial lake datasets."

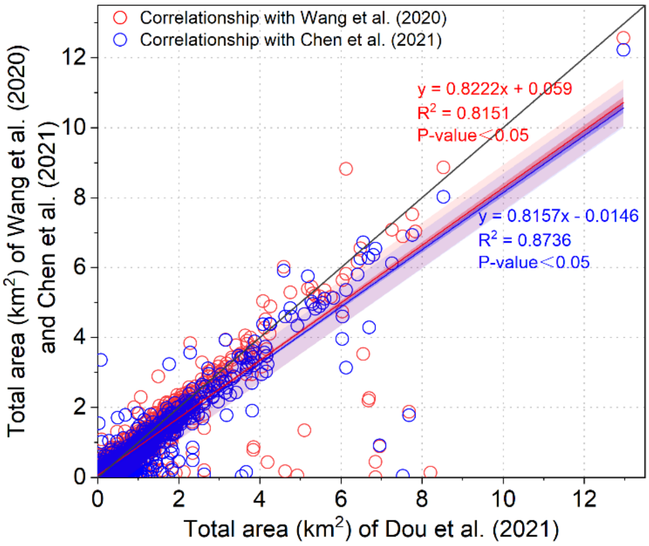


Figure 12. Total area co-relationship of our inventory with Wang et al. (2020) and Chen et al. (2021), respectively. The red and blue lines are the correlation fitting curves with each of them, the black line is the 1:1 diagonal line.

Reviewer comment 3:
Aggregation: what is the effect of digitizing lakes only from one image in a given year against an aggregate of images over an entire decade? What is the effect of consistently using images from one month against aggregating over a range of month in a given year? In this regard, the authors note that "During this period [July to November], the coverage of snow and ice is minimal, while the area of the glacial lake usually reaches its maximum, which does not change much due to factors such as glacier supply and precipitation". Others, however, do find that seasonality matters for the case of supraglacial lakes (Miles et al., 2017).

Response 3:

Thanks for your comment. As we said above, the aggregation of multiple images into a single image is the first time it has been used in mapping glacial lakes on the Tibetan Plateau. In this study, we made several attempts to select images and time period in the early stage, including aggregation of images from July to November of each year, aggregation of images every three years, every five years, every seven years, and every ten years. We found that when the time series is not long enough, the data cannot cover the whole Tibetan Plateau completely, and there will be a large number of blank striped regions. In addition, we found thorough literature search and preliminary experiments that the Tibetan Plateau has the highest temperature and the lowest ice coverage from July to November each year, and the area of glacial lakes tends to reach the maximum value in a year. If we use images from only one month (e.g., August), there are many places covered with snow that cannot be extracted from the glacial lakes, so we choose to use the aggregated images from July to November, considering the available images literature and data inventory. By using the GEE platform, we were able to more quickly select the portion of all the images that best fit our needs for aggregation. If we selected images from one year for extraction and then searched for other images from different years to fill the blank regions, this will result in inconsistent results due to different years of mapping and filling bases. By aggregation, we used a total of 42,833 images, in which 12,224 were used in the first period (1990-1999), 14,670 were in the second period (2000-2012), and 15,939 were in the third period (2013-2019). The starting time of the third period is 2013, which takes the Landsat 8 satellite images into account, successfully avoiding errors that may result from aggregating different satellite images within one time period (e.g., aggregating Landsat 5 and Landsat 8).

In the Section 4.5 of Miles et al. (2017) mentioned, the supraglacial lakes cover in the Langtang valley shows an increase during the pre-monsoon, rises to a peak in the early monsoon, drops during the post-monsoon and decreases to negligible during the winter months. And they also noted the seasonality change of the thawed glacial lakes on debris-covered glaciers for May-October. We choose July-November to extract glacial lakes also considering the seasonality of glacial lake changes. Glaciers on the Tibetan Plateau reach their melting peak in summer and become an important source of glacial lake recharge. Due to the relatively small proportion of supraglacial lakes among all glacial lake types, we do not deliberately consider the seasonality of glacial lake changes here. We will focus on this analysis of glacier lake response to climate change in the future.

Reviewer comment 4:
Methods: The processing chain for using NDWI thresholds in optical imagery is well established but has its known drawbacks, e.g., potential confusion of water with mountain or cloud shadows. Other studies have recently experimented with satellite missions with higher temporal repeat rates (Wu et al., 2020), radar data (Wangchuk et al., 2022), and image segmentation (Qayyum et al., 2020). I am aware that many resources such as Sentinel-1 data are not available for older time periods in the record. However, is there possibly potential for using the current high-resolution, high- repetition-rate data to improve our lake abundance models for earlier decades for which we only have Landsat imagery?

Response 4:

We agree with the reviewer that the processing chain for using NDWI thresholds has its known drawbacks, such as potential confusion of water with mountain or cloud shadows. In our study, we used GEE platform to deal with it through the methods we described in the second paragraph of *Section 3.1:*

"Since the original images may contain clouds and mountain shadows, essential preprocessing was carried out in GEE to mask clouds and cloud shadows (Beckschafer, 2017; Li et al., 2018; Skakun et al., 2019; Zhu and Woodcock, 2012). Here we used the code "cloudBitMask" and "cloudShadowBitMask" with the threshold of 1-5 and 1-3 to process the cloud and its shadow in GEE (Gomez-Chova et al., 2017; Mateo-Garcia et al., 2018). Then ALOS AW3D-30 m digital elevation model (DEM) was employed to eliminate the effects of slope and topographic shadows. We set 7º slope as the masking threshold to eliminate some pseudo glacial lakes (Li and Sheng, 2012; Quincey et al., 2007). Since the production time of ALOS DSM data was not consistent with the

acquisition time of Landsat SR images used for glacial lakes mapping, the resulting slope and terrain may not match the actual terrain completely, leading to minor errors in masking glacial lakes. These errors were corrected as much as possible in the subsequent cross-validation and manual correction steps (see Section. 3.4)."

By using cloud mask thresholds with reliability, and by using the AW3D30 DEM with high accuracy (Chen et al. 2022), we find the part of the tens of thousands of satellite images that are least affected by cloud and mountain shadows to be aggregated to minimize the error in this aspect. There are many methods and papers that use Sentinel satellite SAR data to extract glacial lakes, but most of them only have data from recent years and do not provide complete coverage of the entire Tibetan Plateau. We appreciate this excellent idea of using current high-resolution SAR data to improve the glacial lake abundance models of the past decades, but we think this technique needs to be studied and tested in-depth on a small regional scale in combination with machine learning etc. The Tibetan Plateau is a large area with significant topographic variation, and there is no perfect method to ensure accuracy across the entire large region.

Reviewer comment 5:
Classification of lake types: Apart from the supraglacial lake class, I find it difficult to assess the value of classes such as proglacial, ice-marginal, or unconnected lakes. What do we learn when a glacier is "unconnected" to its parent glacier in terms of its vulnerability or its use as a freshwater resource? Many researchers using this dataset would probably be more interested in a robust assessment of dam type. That is, whether a lake is impounded by a moraine or a glacier, or whether it is located in a rocky depression, cirque, or on a glacier. The study by Lesi et al. (2022), which is currently under review at ESSD, goes an important step forward and classifies lake types according to the formation mechanism of glacier lakes and dam material properties. This could be a strong contribution from this study, if this is accomplished for the entire study region

Response 5:

Thanks for your comment. Accurate identification of the formation mechanism and dam material properties is difficult to achieve with satellite images on the whole Tibetan Plateau, especially when some lakes are located in snow-covered mountainous areas or surrounded by rocky outcrops that are not easy to be observed. The proglacial lakes, ice-marginal lakes and unconnected glacial lakes are also of importance in the current study. These four glacial lake types also have the potential to convert to each other under conditions such as climate change, and we observed the phenomenon of proglacial lakes detaching from glaciers due to receding glacier tongues when assigning types to glacial lakes (Luo et al., 2020). In addition, our literature search revealed that the proglacial lake outburst triggered a considerable number of GLOFs (Cook et al., 2016; Emmer et al., 2020). Although ice-marginal lakes are relatively little distributed in the Tibetan Plateau, GLOF-related events have been studied in other regions (e.g., Alaska) for ice-marginal lake outbreaks (Carrivick and Quincey, 2014; Rick et al., 2022). In the currently published inventories of glacial lakes, unconnected glacial lakes or non-glacial lake direct contact glacial lakes are the representatives of all glacial lake types (Chen et al., 2021; Luo et al., 2020). In the northern region of the Tibetan Plateau, we have observed two lakes that are not connected by surface runoff, where the water level of one lake drops dramatically and the lake water enters the other lake through subsurface runoff and causing its water level to rise and the risk of failure to increase dramatically. The study in CPEC region of Lesi et al. (2022) goes a pretty step forward to this field, although it is currently not possible to accurately delineate the entire study area of glacial lake dam material through remote sensing imagery. We hope to achieve this goal through more advanced means and data in the future.

Specific Comments:

Q1： L8: "As the Third Pole of the Earth and the Water Tower of Asia": please stay objective in highlighting the relevance of this region in the abstract. Physically speaking, there is now "Third Pole" on Earth, and the role of a "Water Tower" might not equivalently strong in all regions of the Tibetan Plateau.

R1: Thanks for your comment. About the description of *"the Third Pole of the Earth and the Water Tower of Asia"*, this has become part of the current scientific consensus. Qiu (2008) published an article entitled "The Third Pole" in Nature, detailing the importance of the Tibetan Plateau as the Third Pole of the Earth and the roof of the world, which has 845 citations (Google Scholar, last access: 2 March 2022). Yao et al. (2012a) also reiterated the concept of the Third Pole of the Earth and its important significance in the study of the Tibetan Plateau environment, which was also cited 479 times (Google Scholar, last access: 2 March 2022). Immerzeel et al. (2010) studied in detail the possible impact of the Tibetan Plateau and adjacent mountain ranges as the source of the five major rivers in Asia on water resources available at the basin scale under climate change and determined the importance of the Tibetan Plateau as the Water Tower of Asia, which was published in Science and cited 2721 times and laid the foundation for the study of water resources on the Tibetan Plateau (Google Scholar, last access: 2 March 2022). In addition to the studies mentioned above, a thorough literature search reveals that the definition of the Tibetan Plateau as "the Third Pole of the Earth, the roof of the world, and the Water Tower of Asia" has been widely and universally recognized, and has been repeatedly confirmed and used in related studies (Chen et al., 2016; He et al., 2021; Immerzeel et al., 2020; Lu et al., 2010; Pandit et al., 2014; Qu et al., 2019; Yao et al., 2019; Zhang et al., 2015; Zheng et al., 2021).

Q2: L8: I am unsure whether "Tibetan Plateau" is the most suitable term for this region, as the glacier lakes that are investigated in this study are largely located in the mountain ranges fringing the TP, if I am not mistaken.

R2: The glacial lakes investigated in this study cover the entire range of the Tibetan Plateau, most of which are distributed in the mountains at the edge of the plateau. However, other regions (e.g., interior and northern Tibetan Plateau) also have some unconnected glacial lakes, as is shown in Figure 9 in the manuscript.

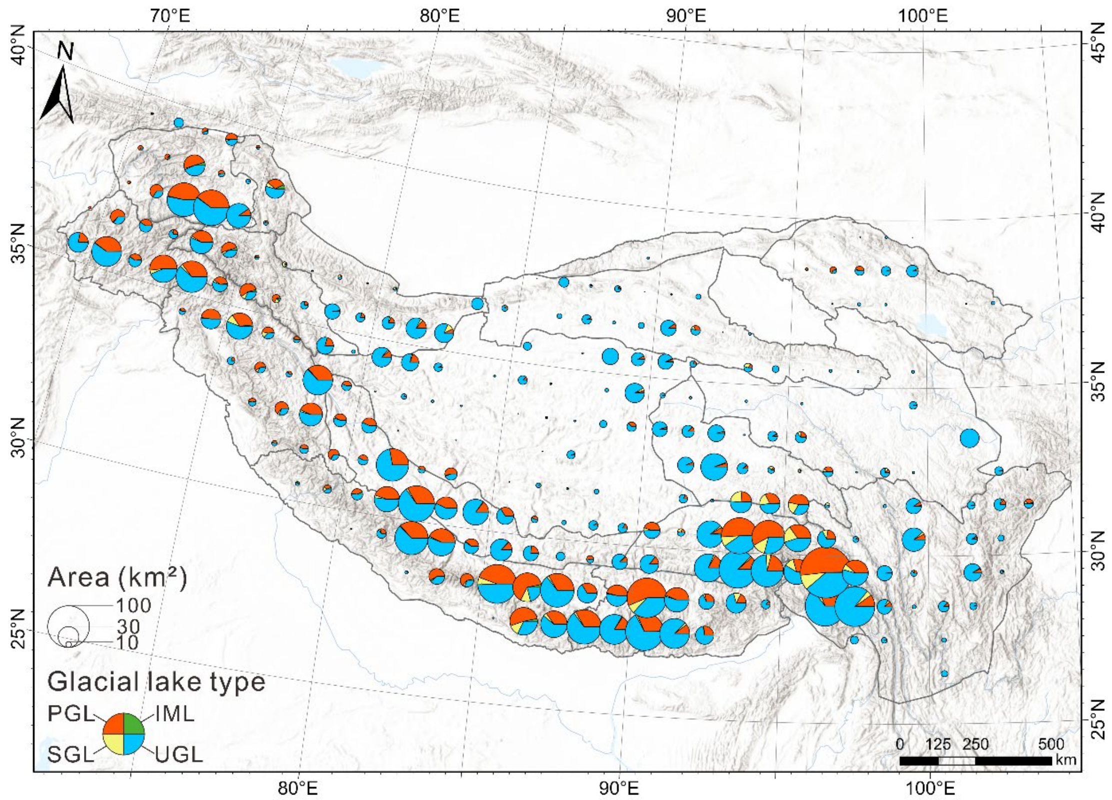


Figure 9. Proportional area distribution of four type glacial lakes in the last period (2013-2019) on 1°×1° grids. The circle size represents the total glacial lake area in the last period of each grid.

Q3: L12-14: This sentence needs to state how many time slices have been created in this study.

R3: Thanks for your comment. We modified this sentence in L14-15 with red and added the total number of images we used, and the modified sentence is as follows:

"Here, we created a multi-temporal inventory of glacial lakes in TP using 30 years record of 42833 satellite images (1990-2019)."

Q4: L15: "different regions of TP exhibited varying change rates in glacial lake size": ambiguous, please be more precise.

R4: We modified this sentence in L17-19 with red to make it more precise:

"We noticed that different regions of TP exhibited varying change rates in glacial lake size, most regions show a trend of expansion and increase in glacial lakes, while some regions show a trend of decreasing such as the western Pamir and the eastern Hindu Kush."

Q5: L16: "because of reduced rainfall rates": do the authors show this in this study?

R5: Thanks for your comment. Considering that the subject of this study aims to publish an updated and more complete inventory of glacial lake, and that the study on the response of glacial lake variability and climate change on the Tibetan Plateau is under preparation, we decided to remove this precipitation description here in order to avoid unnecessary controversy. The modified sentence in L17-19 is as follows:

"We noticed that different regions of TP exhibited varying change rates in glacial lake size, most regions show a trend of expansion and increase in glacial lakes, while some regions show a trend of decreasing such as the western Pamir and the eastern Hindu Kush."

Q6: L20: "Third Pole" instead of "third pole", yet suggest to remove this term entirely from this manuscript.

R6: Modified it with red fonts. Thanks for your suggestion of removing the term of the Third Pole entirely from this manuscript. As we replied in **R1**, "the Third Pole of the Earth" is an important description and definition of the Tibetan Plateau,, which demonstrates the importance and specialness of the Tibetan Plateau for the earth. Therefore, we believe that this description helps to express the importance and significance of our study.

Q7: L22: "the most significant number and area of glaciers outside polar regions": please be more precise. Also, it depends which regions are classified as 'polar'. Alaska has more ice the High Mountain Asia.

R7: Thanks for your comment. Here we clarify that polar regions refer to the Antarctic and the Arctic. Yao et al. (2012b) identified the Tibetan Plateau and surrounding areas as containing the largest number of glaciers outside of the polar regions with the map of *Glacial lakes in the Qinghai Tibet Plateau and adjacent areas 1:2 million (2008).* According to the data we collected, we examined only the glaciers cataloged within the Tibetan Plateau and found that the Randolph Glacier Inventory (RGI) 6.0 counted a total of 77325 glaciers with a total area of 90,035.335 km^2 (Arendt et al., 2017), GAMDAM glacier inventory counted a total of 105295 glaciers with a total area of 91,852.254 km^2 on the Tibetan Plateau (Nuimura et al., 2015). At the same time, according to "An updated ALASKA Glacier Inventory by using Landsat 8 OLI in 2018", there are a total of 27043 glaciers in the Alaska region with a total area of 81,285 km^2

(Shangguan, 2019). Therefore, We can confirm that the number of glaciers on the Tibetan Plateau is the largest apart from the Antarctic and the Arctic. Also we have modified the manuscript accordingly in L24-25, as follows :

"The Third Pole of the Earth, Tibetan Plateau (TP) consists the most significant number and area of glaciers outside the Antarctic and the Arctic."

Q8: L26-27: "glacier landmass": unclear, please revise.

R8: Thanks for your comment. We deleted this unclear description and revised this sentence with a more clear description in red fonts in L28-30 as follows:

"The melting snow and ice present a challenge for the development of glacial lakes. Many glacial lakes form in the low-lying land, such as depressions and troughs, and gradually expand with precipitation or glacial melt supply."

Q9: L31: "hidden dangers": please stay objective.

R9: We use the word *"potential"* instead of "hidden" to ensure the accuracy and objectivity of the description.

Q10: L33: "extremely important": please avoid subjective qualifiers and quantify instead, why the role is so important.

R10: As the water tower of Asia and the origin of the five major rivers in Asia, the Tibetan Plateau's lakes are the indicators of climate change (Zhang et al., 2019; Zhu et al., 2019). Existing studies have found that the glacial lakes on the Tibetan Plateau are sensitive to climate change and also have important research implications for ecological changes and hydrodynamic cycles in the region (Woolway et al., 2020; Yang et al., 2011; Zhang et al., 2020). We change the description as *"a great importance"* to highlight the value and significance of glacial lake research on the Tibetan Plateau, based on existing studies in L35.

Q11: L67: The minimum mapping unit is an important consideration, but also a weak motivation for another study, assuming that those previous studies remained consistent in their use of a minimum mapping unit. This introduction, and this section in particular, call for a much stronger motivation for this analysis.

R11: Thanks for your comment. About the minimum mapping unit, we add a much stronger motivation for the analysis in this introduction and Section 3.2:

In this part, we add some analysis in L71-78, the 5th paragraph of Section 1, as follows:
"According to the properties of the satellite images, the minimum pixel length used to extract the glacial lake is 30 m, which means that some glacial lakes cannot ideally occupy a complete number of pure pixels but are more likely to be partially surrounded by 1-8 mixed water body pixels (Wang et al., 2020). Studies have shown that applying a smaller minimum threshold area under the same spatial resolution will significantly increase the total number of glacial lakes, but the general area of the lakes will not change significantly (Nie et al., 2017). Nevertheless, choosing a minimum threshold area that is too small will lead to substantial uncertainty (see Sect. 4.1) and significantly increase the workload of meaningless cross-validation and manual correction (Salerno et al., 2012), resulting in a negative impact on extracting glacial lake in TP."
And in L163-165, the 3rd paragraph of Section 3.2, we add a more explicit and detailed description of the selection of the minimum mapping unit, as follows:
"Thus, based on the uncertainty and spatial resolution, this study set 0.0081 km^2 (3×3 pixels) as the minimum threshold area according to experience and multiple attempts in different regions of TP. Further cross-validation, manual vectorization, and correction were all based on this precondition."

Q12: L74-79: Instead of describing the workflow of this study, the introduction could rather end with a key research question.
R12: Thanks for your comment. We rewrote the closing line of the introduction in L83-85 as follows:
"In order to address the above problems of incomplete spatial and temporal coverage of glacial lake data on the TP, this study mapped an updated inventory of glacial lake covering the entire TP including three periods of data, aiming to solve the above problems and provide a data base for cryosphere studies."

Q13: L77-78: "This study mapped the glacial lakes in TP to the maximum": unclear.
R13: We have rewritten this sentence as **R12.**

Q14: L81: "Roof of the World": please stay objective. Suggest deleting.
R14: Thanks for your comment. We ensured the objectivity of our research. all the descriptions have reasonable citation sources and are accepted by the research

mainstream. We also responded to your query about "Roof of the World" in detail in **R1**, and we added authoritative citations to the manuscript to ensure the reliability of the sources in L87.

Q15: L90: "many countries": how many?

R15: The Amu Darya flows through 4 countries: Tajikistan, Afghanistan, Uzbekistan and Turkmenistan. The Indus River flows through 3 countries: China, India and Pakistan. The Ganges River flows through 2 countries, India and Bangladesh. The Yangtze River and Yellow River flow only through China. The Mekong River flows through 6 countries, including China, Laos, Myanmar, Thailand, Cambodia and Vietnam. The Salween flows primarily within southwest China and eastern Myanmar (Burma), with a short section forming the border of Burma and Thailand. The Brahmaputra flows through 4 countries: China, Bhutan, India and Bangladesh. And the Irrawaddy River flows through 2 countries: China and Myanmar. It is important to note that in the manuscript we mention *"These rivers, which pass through many countries in Asia…"* is meant to illustrate the importance of the Tibetan Plateau as the source of the major rivers in Asia, for the downstream hydrological role and billions of people, and therefore the specific countries through which these rivers flow, are not the focus of our discussion and study.

Q16: L93: "~1900s": given the rest of the sentence, it's rather the 1930? Furthermore, climate data are not assessed in the rest of the manuscript. Suggest tone down the effects of atmospheric warming / precipitation changes in this manuscript?

R16: According to Table 1 *(List of used stations above 2000 m a.s.l., including the station identification number (ID), station name, first year of record, latitude, longitude and elevation a.s.l.)* in Liu and Chen (2000), we found that some sites were established before ~1900s, but the vast majority of them were established in ~1950s, and five of them have data dating back to before the ~1930s. As you mentioned, we did not perform climate data assessment in the rest of the manuscript, but climate conditions are still part of the study area profile, and we have only briefly described and cited climate change conditions in TP here, deleting the climate statements in the rest of the manuscript.

Q17: L96: Is this "wetting trend" consistent in the entire study region?

R17: Thanks for your comment. Based on our search of the relevant literature, we know that TP has generally been warming and wetting over the past half century. In the last paragraph of chapter 3 of Kuang and Jiao (2016) in *Review on climate change on the Tibetan Plateau during the last half century*, it is stated that:

"The TP is overall getting warmer and wetter during the last half century. The precipitation on the TP is slightly increased, but the increase is not as pronounced as that of temperature. The spatial pattern of changes in precipitation is complicated, and the annual precipitation does not show a uniform increasing or decreasing trend across the TP. Precipitation in some subregions is increasing while in some other subregions decreasing. Due to the nonuniform changes in precipitation, some subregions in the TP are becoming warmer and wetter, while some subregions are becoming warmer and drier. There is also not a uniform change in precipitation in different seasons. The precipitable water in the atmosphere of the TP has been shown to increase since the 1990s and precipitation will increase in the future in most areas of the TP."

Also, after analyzing data from 66 meteorological stations in TP, Li et al. (2010) similarly concluded that *"the changes in climate over the Qinghai-Tibet Plateau present trends towards warm and wet conditions"*. We added citations to the relevant literature in L103-104.

Q18: L100: Figure 1: Suggest moving the inset to the main map.

R18: Modified as shown in Figure1 in the manuscript.

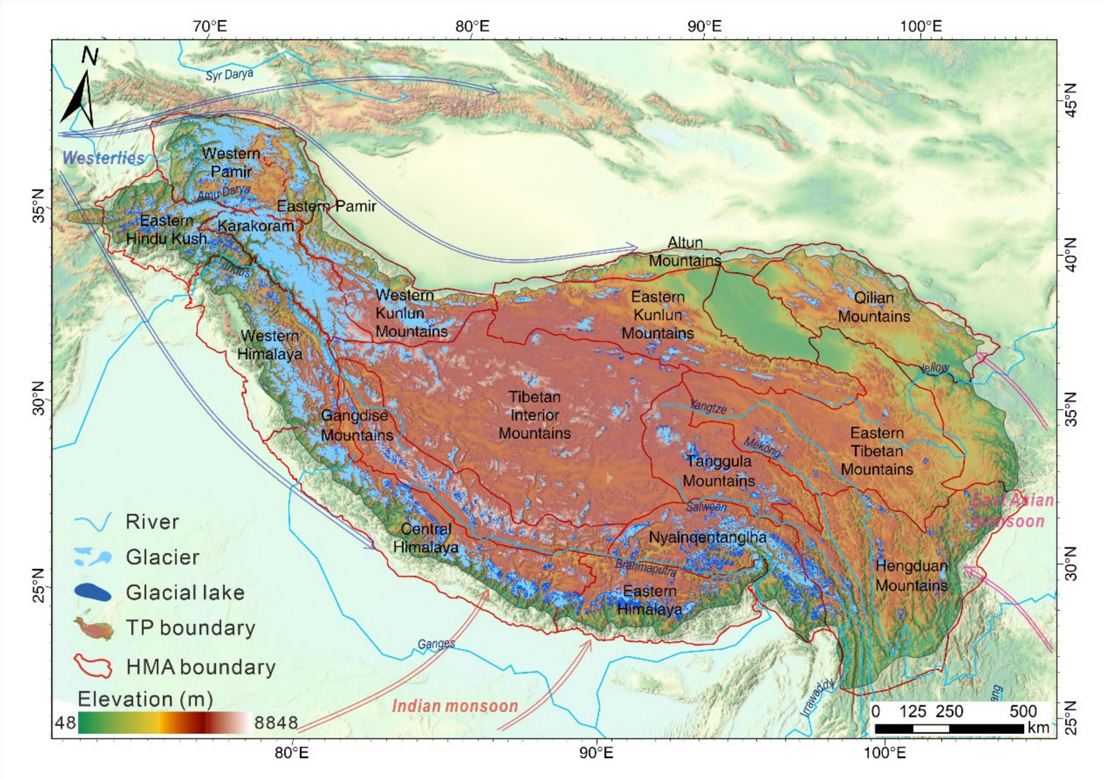


Figure 1. Distribution of glaciers, glacial lakes and major rivers on the Tibetan Plateau (TP). The TP was divided into 17 mountains (http://geo.uzh.ch/~tbolch/data/regions_hma_v03.zip). The large-scale atmospheric circulations are also included. The terrain basemap is sourced from Esri (© Esri 2013).

Q19: L116-117: "which does not change much": contradicts previous part of the sentence?

R19: This is an unclear statement. We rewrote the sentence as *"During this period, the coverage of snow and ice is minimal, while the glacial lake area usually reaches its maximum. Under the action of glacial meltwater and precipitation, the glacial lake area does not produce large fluctuations"* in L121-123.

Q20: L126-127: What is the effect of this thresholds on lakes adjacent to glaciers with steep tongues that melted since the generation of ALOS DEM?

R20: Thanks for your comment. We note that the choice of surface gradient varies from study to study. Quincey et al. (2007) obtains the Table 1 on surface gradient from Reynolds (2000)'s study and argues that where large glacial lakes currently exist, the glacier surface slope is always less than 2°. Chen et al. (2021) uses a slope larger than 10° of SRTM to mask the topographic shadows. Since we used a more accurate AW3D30 DEM (Chen et al., 2022), and we used a much larger number of images than those used in previous studies, we tried different slope values between 5° and 10°, and finally found that 7° yielded the most reliable results, capturing as much of the glacial lake as possible while substantially avoiding the interference caused by mountain shadows. After our cross-checking and manual review, we found that the use of multi-view image fusion techniques avoided some temporary small glacial lakes appearing on glacier with steep tongues to be mapped, such lakes arising on glacier with steep tongues are generally very small, similar to ponds. For such small glacial lakes, we randomly selected some single-view images to check, and found that they do not exist as stable as other glacial lakes for a long time. Therefore, the impact on the final data can be ignored. At the same time, we also added and improved the very few glacial lakes that can exist stably on steep tongues in the process of manual correction.

Table 1 Relationship between glacier surface gradients and supraglacial lake development in Bhutan, proposed by Reynolds (2000)

Surface gradient	Interpretation
<2°	Formation of large supraglacial lake over stagnant or very slow moving ice body forms from the merging of many smaller discrete ponds.
2°–6°	Supraglacial ponds form, may also be transient locally, but sufficiently large areas affected by presence of ponds.
6°–10°	Isolated small ponds may form, transient due to local drainage conduits opening and closing due to ice flow.
>10°	All melt water is able to drain away, no evidence of ponding.

Q21: L166-167: Why the reference to Alaska, and why talking about the distribution in the TP in the methods section?

R21: We present here our four different types of glacial lakes. IML is widely distributed in Alaska but sparsely distributed in TP. Thus, we cite it to illustrate the need for the existence of this glacial lake type.

Q22: L168-170: "maybe not": unclear.

R22: We modified this sentence in L177-178:

"but they may have evolved from a proglacial lake or supraglacial lake as glaciers retreat."

Q23: L182: "topography and location": ambiguous, please be more precise.

R23: Thanks for your comment. Taking into account the comments you have given, and considering that the study of the empirical formula of glacial lake area-volume is not applicable to the whole Tibetan Plateau, we have carefully considered and decided to delete the description of the glacial lake area-volume formula and all related contents of the glacial lake volume variation from the manuscript.

Q24: L184: "applied" instead of "applicable.

R24: As above.

Q25: L188: Where is the uncertainty in the parameters that were estimated from data that the authors have mentioned before?

R25: Thanks for your comment. In conjunction with **R23**, we are also fully aware that it is inappropriate to use a volumetric formula that has not been rigorously tested across the Tibetan plateau, and we have not yet determined the evaluation parameters regarding uncertainty, so we remove this aspect.

Q26: L211: style: report the mean first, then the min and max.

R26: Thanks for your comment. We adjust the presentation style in L211-212:

"The average uncertainty for all glacial lakes is 17.5%, with a standard deviation of 9.91% and overall uncertainty in the range of 0.2%-50%."

Q27: L213: yes, that's what the formula implies, given that the uncertainty is inversely proportional to the size of the lake. What does this tell relative measure of error tell us?

R27: This formula tells that the uncertainty is inversely proportional to the size of the lake. Therefore, based on the 30m spatial resolution Landsat satellite images we are currently using, pursuing too fine mapping of the glacial lake (e.g., setting the minimum mapping unit to 1×3 pixels) would cause great uncertainty in the mapping results and also affect the reliability of the data inventory, which is why we chose to use 3×3 pixels as the minimum mapping unit.

Q28: L216: Figure 4: What is the purpose of the normal curve? It is not mentioned in the text. In left plot (suggest using labels a and b), dots overlap and don't allow for a meaningful representation of mapping uncertainty.

R28: Thanks for your comment. After careful analysis, we believe that using the normal curve in the uncertainty swarm graph does not convey the meaning we want to convey well, but makes the graph complicated and difficult to understand. So we deleted the normal curve from the graph. We lost the label of graphs in Figure 4, and now we replaced it by a correct figure as the following figure. The overlapping dots in Figure 4 (a) imply that the data of these three periods have relatively consistent uncertainty, and there is no case that there is uncertainty heterogeneity in the data of one period.

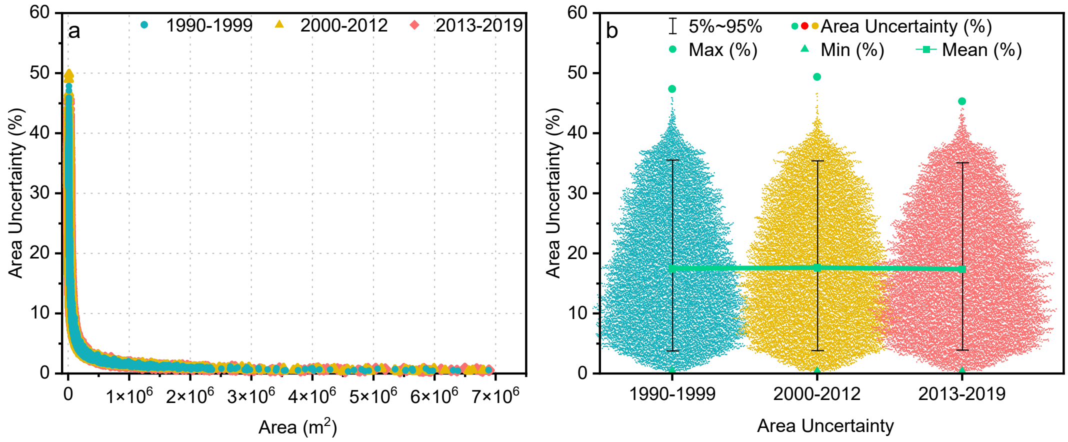


Figure 4. (a) Relationships of relative area uncertainty of glacial lakes in TP; (b) normal distribution of uncertainty of glacial lake area, the swarm plots for each time period represent the uncertainty distribution of all glacial lakes in that period.

Q29: L225: how "slow"?

R29: In the range from 5300m to 5900m a.s.l., the area of the glacial lake increased by 56.75 km^2, while in the range from 4000m to 5300m, the area of the glacial lake increased by 180.79 km^2. Therefore, in the range of 4000m-5900m, the increase in area of the former is relatively small. The expression "slow" is not clear enough here, so we revised this sentence in L215-216, as follows:

"Between 5300 m and 5900 m, the number of glacial lakes has increased as well but the area expansion was smaller compared to the range of 4000m to 5300m."

Q30: L226-227: "The increase of glacial lake number at higher elevations": I can't see this in this manuscript. "ultra-small": which size class is this?

R30: Thanks for your comment. The average elevation of the Tibetan Plateau is 4000m a.s.l. According to our data, the number of glacial lakes above 4000m has increased by 3145 in the past three decades, and the area has increased by 237.74 km^2. The minimum glacial lake area mapped by Salerno et al. (2012) is 0.001 km^2, here we define "ultra-small" glacial lake as an area between 0.001 and 0.0081 km^2. For clarity of presentation, we have rewritten this sentence in L217-220:

"The increase of glacial lake number at higher elevations (above than 4000m a.s.l.), as well as the number of ultra-small glacial lakes (the area is between 0.001-0.0081 km^2) that have been studied (Salerno et al., 2012) but not considered in this paper, suggests that glaciers start retreating at higher elevations (Chen et al., 2021; Nie et al., 2017)."

Q31: L230: "a relatively consistent trend with the increase of altitude": not sure what this means. Please rephrase.

R31: We rewrote this sentence in L221-222 as follows to make it clearer:

"Different glacial lake types have distinct characteristics in altitude distribution, and their numbers and areal distribution show the same increasing or decreasing trend with the increase of altitude."

Q32: L232: "are" instead of "account".

R32: Modified in L224.

Q33: L235: Figure 5: suggest avoiding a second y-axis, given that the scale of the two axis differ. Why are plots b and c in 3D? They partly overlap, especially in the tails that could be important to highlight changes in glacier lake elevation. Also, please list all abbreviations in the caption (PGL, UGL, etc.). This critique applies to all plot in the following.

R33: Thanks for your comment. In Figure 5(a), we tried using the same y-axes, but this would result in different data being mixed together and losing good display, so we chose to use a second y-axis. We modified Figure 5b and c by using two-dimensional line graphs to make the data clearer as shown. Besides, we add a section of abbreviations at the end of the manuscript to make it clear as follows:

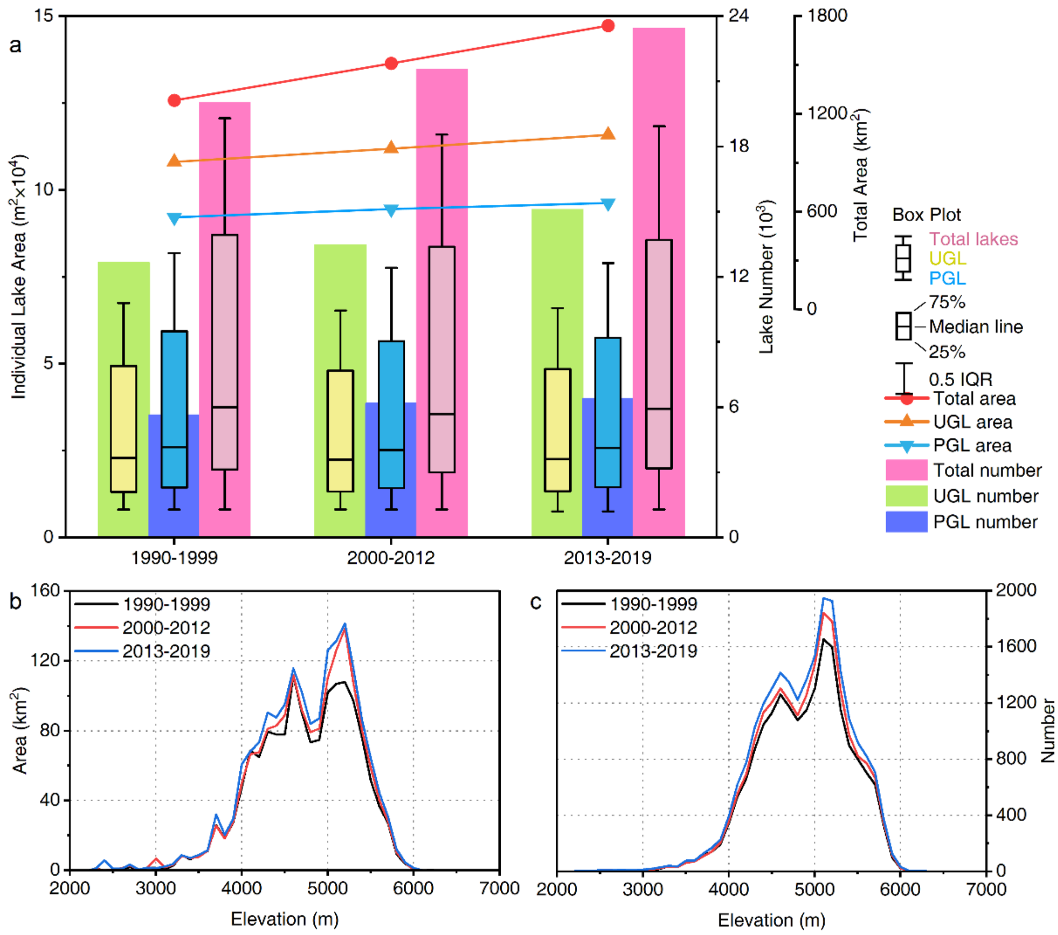


Figure 5. (a) Numbers and areas with three periods of all glacial lakes and PGL, UGL; (b) altitudinal distribution (100 m bin sizes) of lake areas; (c) altitudinal distribution (100 m bin sizes) of lake numbers.

Abbreviations

a.s.l.: above sea level;

CGI: First and Second Chinese Glacier Inventory;

CPEC: China-Pakistan Economic Corridor;

DEM: digital elevation model;

GAMDAM: Glacier Area Mapping for Discharge from the Asian Mountains;

GLIMS: Global Land Ice Measurements from Space;

GLOFs: glacial lake outburst floods;

IML: Ice-marginal lakes;

MNDWI: modified normalized difference water index;

NDWI: normalized difference water index;

PGL: Proglacial lakes;

RGI: Randolph Glacier Inventory;

SGL: Supraglacial lakes;

SR: Surface Reflectance;

TP: Tibetan Plateau;

TPGL: Tibetan Plateau Glacial Lake database;

UGL: Unconnected glacial lakes.

Q34: L247: How "significantly"?

R34: As you can see in Figure 8 in the manuscript, the color of the Western Kunlun Mountains, Eastern Kunlun Mountains, and Tibetan Interior Mountains are significantly darker than those in the other regions. These colors are a reflection of the rate of area change in the different regions, with darker colors implying a greater rate of the area change.

Q35: L252: "and selected typical glacial lakes expanded or contracted as examples". Unclear, please rephrase.

R35: We modified this sentence in L244-245 as follows to make it clearer:

"and six glacial lakes with significantly expanded or contracted changes were selected as examples to show their detailed outline changes…"

Q36: L253: "variation trend": unclear, please rephrase.

R36: We modified it as *"the number and area change trends of glacial lake areas in some places are contrary to the overall trend of the whole region"* in L246-247 to make it clearer.

Q37: L255: "did not provide an in-depth analysis": so, do the authors provide a more detailed analysis? I fear no.

R37: Thanks for your comment. As we said that the studies targeting TP glacial lakes usually did not provide an in-depth analysis, and our speculation in this regard is that, due to the small number of glaciers distributed in the interior Tibetan Plateau, the number and area of glacial lakes in the interior Tibetan Plateau, according to our data list, represent a low proportion of the glacial lakes in the whole Tibetan Plateau and do not affect the trend of glacial lake changes in the whole Tibetan Plateau, and therefore have not been studied in depth. Of course, the glacial lake changes in the interior

Tibetan Plateau also deserve more in-depth analysis and study in separate small regional glacial lake studies. We rewrite this sentence in L247-250 to convey a more correct expression:

"Current studies targeting TP glacial lakes did not provide an in-depth analysis of interior TP (Chen et al., 2021; Wang et al., 2020; Zhang et al., 2020) since there are fewer glaciers in the interior TP. Therefore, fewer glacial lakes are developed within 10 km of the glacial terminus compared to the entire TP, which does not have a dominant effect on the overall variability of all glacial lakes within the TP."

Q38: L257: "various": four?

R38: We use the exact number "the four" instead of various in L251.

Q39: L259-260: Content of this sentence is largely subjective and speculative. Suggest deleting.

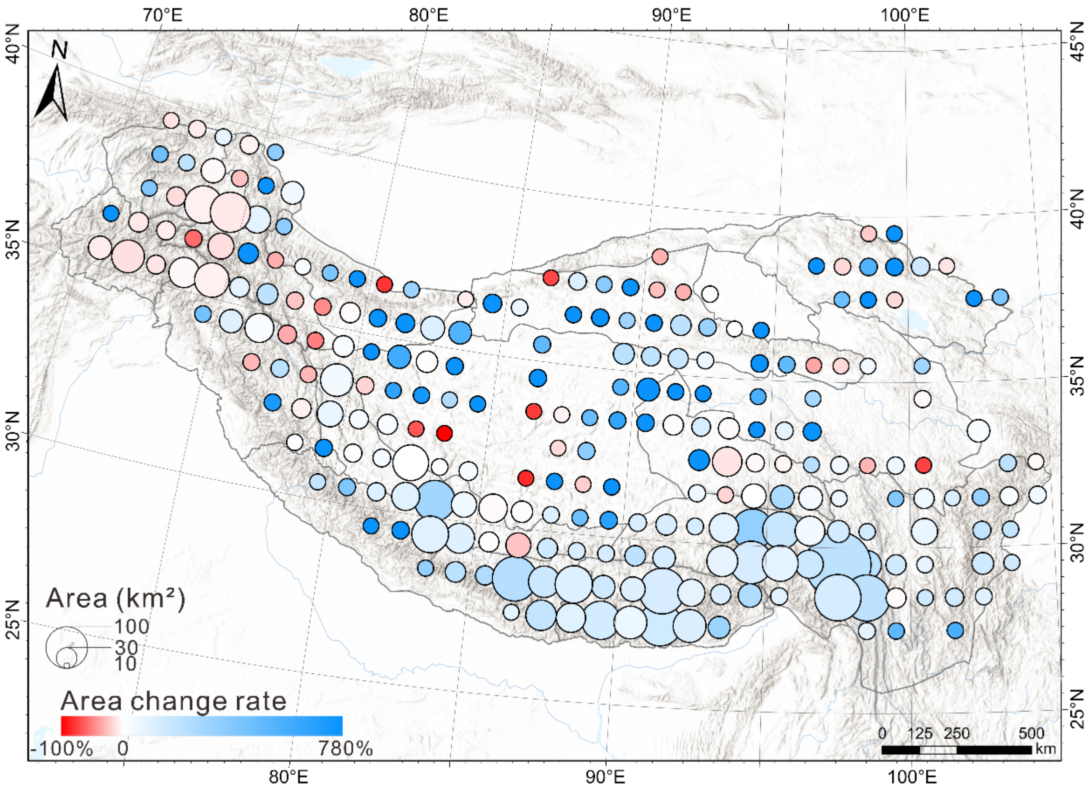
R39: Deleted.

Q40: L261: "is" instead of "was".

R40: Modified in L253.

Q41: L274: Legend of Figure 10: "Area change rate": is it %? Meters? Temporal reference period? Also, the color stretch is wrong, as it suggests that the value range from -1 to 0 is the same as for 0 to 7.8.

R41: We redrew the figures as the following shows.



Q42: L277-283: Suggest deleting the chapter on lake volumes, given that the volumes are a simple conversion of area and are not at the heart of this paper. This chapter also adds hardly any novel insights compared to the previous estimates on lake areas.

R42: As we reported in **R23** and **R25**, we delete this chapter on lake volumes.

Q43: L281: "which confirmed a frequency increase of GLOFs in the Himalayan region": NO, this is exactly opposite to what some of these studies have found.

R43: Thanks for your comment, We are sorry for this confusion. After reconsidering that the glacial lake volume chapter is unnecessary in this manuscript. Therefore, we deleted it.

Q44: L305: so, this study is a lumped sum over a longer period. Could this explain the higher abundance/area compared to previous studies?

R44: Thanks for your comment. Because we used images from many years of image aggregation, as we explained in Response 3, by setting parameters to select the images we needed, we were able to minimize the effects of clouds, mountain shadows, etc., allowing us to obtain images that contained more glacial lakes, so we extracted more of them than the rest of the data inventory.

Q45: L316: "Considering the difference in time coverage of the three datasets": Not sure how useful this comparison is then?

R45: Since these three datasets cover different times, we selected the most recent time of each dataset for comparison, which can also indicate our data is updated latest. This comparison method can also be seen in Chen et al. (2021) by using the data with the closest time for cross-sectional comparison and analysis.

Q46: L319: Not the 1° x 1° grids anymore? Why this resolution?

R46: Considering the significant differences in the number of glacial lakes in the three data lists (as shown in Table 2 in the manuscript), we chose to use a finer grid for the correlation analysis to bring the comparison results closer to those using the original glacial lake numbers. The points in the correlation figure (Figure 12 in the manuscript) will be too much to present if a 1° x 1° grid had been used. The grid unit of correlation analysis was not necessarily to the same with that of spatial analysis.

Q47: L326: Figure 12: Add years of publication to y-axis. Why not add a 1:1 line to the plot? It is important to mention that the trend is smaller than 1, hence the authors observe more lake area on average than previous studies. Figure caption needs to mention that the data have been aggregated on a grid.

R48: Thanks for your comment. We redraw figure 12 as shown following in L308-310 in the manuscript.

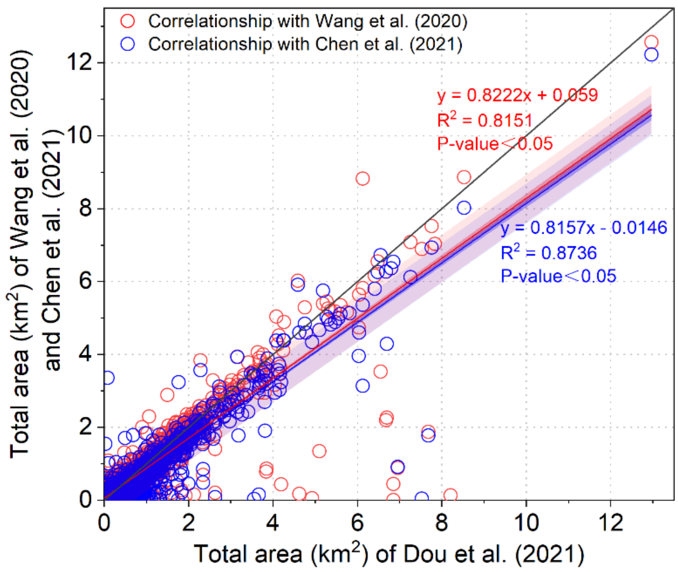


Figure 12. Total area summed over a 0.1° × 0.1° grid correlations with Wang et al.

(2020) and Chen et al. (2021). The red and blue lines are the correlation curves with each of them.

We appreciate the reviewer's suggestion to summarize some previous studies and analyze them in-depth in the form of a REVIEW, which is our next step to complete. We hope to publish this new inventory of Tibetan Plateau data to lay the data foundation for subsequent studies. At the same time, with the development of satellite technology and the improvement of image quality, we are ready to update the inventory of glacial lakes with higher accuracy and newer time span. We reiterate the editor's comments here: "As already indicated in your paper, the temporal evolution of glacial lakes across the Tibetan Plateau is a quite important research field and, hence, was already covered extensively by Wang et al. (2020) and Chen et al. (2021). Compared to those two studies, your data consists of temporal averages for three periods during 1990 to 2018 and therefore could be used for, e.g., trend analyses."

We would appreciate if the reviewer can re-review our manuscript wholeheartedly as a dataset paper which (we believe) is of great use to many works in this field.

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