Reply to reviewer #1

In its present form the paper lacks however clarity in language, structure and explanations, which make it difficult to follow the findings presented. The purpose of the study should be explained better and the results presented accordingly. As now, for some of the results it is unclear how they tie into the investigation of the collapse consequences. I recommend that at least the senior co-authors carefully revise the manuscript to make it clearer. This recommendation refers not only to language editing, but more important to the explanations given, precise language usage, and logical structure of presentation of results.

Reply: Thank you very much for the constructive comments and suggestions. The language, structure and explanations have been carefully revised according to these comments.
For the structure of the paper, we have made substantial revisions as following:
1, Add a new Section 4.3, which mainly focuses on the meltwater estimation of the two ice avalanches. The meltwater is mainly estimated by area of the ice mass and in-situ measurement of glacier mass balance (Tab. 1). This estimation is further validated by elevation changes of the two ice avalanches (Section 4.3).
2, Add a new Section 4.4, which mainly focuses on the impact of the meltwater on the seasonal lake level changes at Memar Co. Lake level seasonality and the hydraulic connection are moved to this part.
3, Add a discussion section (Section 5), which focuses on the response of the rapid lake expansion on the western TP to climate change and the potential risk of natural hazard on the TP.

For the purpose of the study, we have addressed it in more detail in the introduction (line 47-59). Although the mechanism of Aru glacier collapses has been investigated, its impact on the downstream lakes in the subsequent years (2016-2019) has still not been investigated until now. Based on comprehensive in-situ observations and satellite data, we investigate its impact of the two glacier collapses on the downstream lakes in the subsequent years when most of the ice mass has melted. This study not only provides us unique evidence of the impact of a large amount of glacier melting on the downstream lakes, but also helps to improve our understanding the relationship between glacier mass loss and lake behavior on the TP under a warming climate.

For the explanation of the result, we have added further discussion in the revision. For example, we added two new figures in the revision. One (Fig. 4) is about the dynamics of the intruding ice into Aru Co. High resolution (1 m resolution) GF-2 satellite image is used to detect the extent of the intruding ice and the floating ice over the lake surface. The dynamics of the intruding ice into Aru Co in summer 2016 is shown in this figure. The other (Fig. 10) is about the spatial distribution of lake surface temperature before and after the glacier collapses.

The paper lacks a discussion section and some discussions seem to be part of the results section. The authors should clearly separate results and their discussion/interpretation.

Uncertainties in the results are hardly mentioned.

Reply: A discussion section (Section 5) has been added in the revision. In this new section, we mainly discuss the response of the rapid lake expansion on the western TP to climate change and the potential risk of natural hazard on the TP.

Uncertainties of lake level changes, water storage and lake surface temperature are evaluated in the revision as well (Line 104, 150, Line 161).

The abstract and intro most urgently need revision of language. As an example (line 39), not the Aru glaciers are giant, but their collapses! Professional language editing will likely not capture such errors. Another example, the authors say the shoreline was pushed. Did the avalanche really move the shoreline? Or did the shoreline change due to deposition of sediments? Or (line 340), does "rapid lake expansion of 0.8m/yr" refer to the lake level increase or lateral expansion of lake area? Another example for lack of clarity: in line 48 the authors talk about lake increase due to glacier melt. A few lines later (53) they write about drastic precipitation changes as cause behind lake growth.

Reply: Thanks for pointing out these errors. We have carefully revised the abstract and make it more accurate.

Part of the third paragraph in the introduction is moved to discussion section (Section 5.2) in the revision.

Section 3.4: To my best knowledge, the most extensive study on lake volume changes in Tibet is Treichler et al. 2018 (https://tc.copernicus.org/articles/13/2977/2019/). The authors could compare their findings for Memar Co to the regional aggregations by Treichler et al.

Reply: Thanks for the good suggestions. In the discussion section, we now use the main result of Treichler et al. 2018 as the background of lake expansion on the western TP and discuss glacier-lake interaction in Memar Co basin.

Section 3.5: Any uncertainties behind the MODIS temperatures? For instance bias from undetected clouds, or lake ice?

Reply: We agree that MODIS derived lake surface temperature is easily affected by clouds and other factors, especially in summer. We evaluate the uncertainties of MODIS derived temperature in the method section (Line 161).

At line 161 the lake seasonality after 2016 is presented, but it would be important to relate that to seasonality before the collapses. This is then touched upon much later.

Reply: We added a new section (Section 4.4) about the impact of glacier collapses on lake level seasonality. Lake level seasonality before (2011-2015) and after (2016-2019) the glacier collapses is compared according to Cryosat-2 satellite data and in-situ measurement.

At several occasions the authors classify the changes as "drastic" or "dramatic", for instance the 2-week lake surface cooling by 2-4 deg (line 289). Why is such change, or the other changes dramatic?

Reply: Thanks for the good suggestion. We agree that using 'drastic' or 'dramatic' in some places are not accurate. We have deleted or replaced some of them in the revision.

Fig 3: what is the meaning of the colored areas in panels b and c?

Reply: The three different colors in figure 3 indicate monsoon season, post monsoon season and ice covered season. We have addressed this now in the caption of the figure.

The lines in Figs 7 and 8 are difficult to compare. Better have the lines for each year combined in one plot per area? I.e. not separate plots per year but per area.

Reply: Thanks again. We have changed this figure according to the suggestion.

Reply to reviewer #2

The purpose of the study is more like two downstream lakes observation after Aru glacier collapses events. Hence, I would suggest change the title as "How two downstream lakes responding to Aru glacier collapses and their changes based on in-situ and Remote sensing data " or others.

Reply: Thanks for the good suggestion. Following your suggestions, the title of the paper is revised as 'Response of downstream lakes to Aru glacier collapses on the Tibetan Plateau'.

From the abstract, I got the information that the glacier collapses have two impacts on two lakes, that is, short-term (LST and lake level) and long-term impacts (Lake level and others). So, I would suggest authors refine the rules and results.

Reply: Thanks for the suggestion. We have revised the abstract carefully according to this time line.

Specific comments:

Line 80 Aru co is : : here I would suggest add a sentence "Memar co and Aru Co are lagoons" then, "Aru co is : : :."

Reply: Thanks for the suggestion. We have revised this sentence according to this suggestion (line 78-79).

Line125 here, authors should give the methods how to get lake level changes and how to calculate the uncertainty of lake level changes.

Reply: We have addressed the method about lake level reconstruction in more detail in the revision (Line 143-153). The uncertainty of past lake level changes is also estimated (Line 150)

Line 130 The important feature of 2 degree decrease after collapse was success to be caught by using MODIS 8-days. And I also understood that it may be difficult to express the temperature field due to resolution (1km). But it is useful to compare between the records from AWS during Oct 2016 and Sep 2019 and LST.

Reply: Thanks for the good suggestion. We added a new Fig. 10 about the spatial distribution of lake surface temperature in the revision. We agree that it is difficult to express the temperature field because Aru Co is very narrow and long. There are no valid data in the central part of Aru Co.

We included a comparison between MODIS LST at Aru Co and air temperature from AWS in 2017 and 2018 in the revision (Fig. S5). Daily air temperature had larger fluctuation than water temperature and was always higher than lake surface temperature at Aru Co.

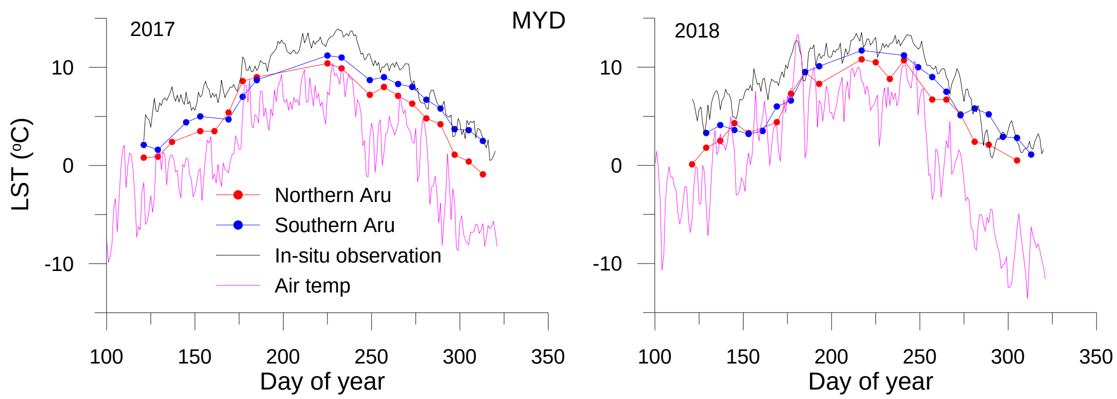

Fig. S5: Comparison of MODIS derived lake surface temperature with in-situ measurement at the shoreline and daily air temperature from AWS station.

Line 145 here, Authors can mark where is norther basin, south basin and center part of Aru Co/Memar Co in figure 1.

Reply: Thanks for the good suggestion. We have shown this in Figure 1.

Line 175 did you want to express that the water level of Aru Co was controlled by climate change and the water level of Memar Co was controlled by climate change in summer and ground water in winter?

Reply: Yes, we have addressed this more clearly in the revision (Line 266-272).

Line 180 did you want to express that the Aru co has a hydraulic connection with Memar Co. And the time lag was about half a month?

Reply: Yes, it should be hydraulic connection and we have revised this sentence in the revision (Line 266). From the seasonal pattern of lake level changes at the two lakes, there is about half a month lag.

Line 191 Sential 2->sentinel 2

Reply: Thanks for pointing out this error.

Line 208 section 4.3 this lake level and lake expansion are chaotic. It should be clear.

Reply: Thanks for the suggestion. The former Section 4.3 is now divided into three sections in the revision:

- Section 4.3, The meltwater estimation of the two ice avalanches;
- Section 4.4, The impact of the meltwater on the seasonal lake level changes of Memar Co;
- Section 4.5, The impact of the meltwater on the inter-annual lake level changes of Memar Co.

Line 230 "In 2016" could be omitted.

Reply: Thanks for pointing out this error. We have revised it (Line 223).

Line 261. I agree on your opinion that after collapse, the lake level increase in warm season *rapidly. Did you have any evidence from glacier ablation observations*

Reply: Meltwater from the two ice avalanches is estimated according to ice avalanche area and changes in ice thickness (Section 4.3). In-situ observation of thickness change was conducted in the first two years (2016 and 2017). Meltwater from the avalanche deposits is constrained using examination of satellite images and differencing of digital elevation models (DEMs). The contribution of meltwater to seasonal lake level change is further quantified (Line 279-281).

Line 270 the lake skin temperature? Water body temperature? Freeze up-?ice on is "Break up" melt on or melted?

Reply: Lake skin temperature derived from MODIS data is usually considered to be different from water body temperature. Lake skin temperature is the water temperature of the uppermost 10-20 μm deep molecular layer while water body temperature is water temperature of several cm to <1 m.

Yes, freeze up means that lake surface is covered by ice and break up means that lake ice melts.

Reply to reviewer #3

General comments: After reading the manuscript, I feel that the title is a bit too specific and does not contain what has been done in this work. I suggest rephrasing the title.

Reply: Thank you very much for the constructive comments and suggestions. We have revised the manuscript carefully according to these comments.

About the title, we change it as ‘Response of downstream lakes to Aru glacier collapses on the Tibetan Plateau’

The hydrological connection is very interesting in my point of view. However, the reasoning of the buffering effect of the Aru Co on the Memar Co is not very convincing. L175, “discharge from Aru Co only accounted for 20-30% of the lake volume increase at Memar Co in the cold season”. How is this conclusion made? Simply assume that the decline in water level completely attributes to outflow? From Lei et al. (2019 GRL), it seems the seasonality of 0.5 m is reasonable for endorheic lakes in the same region. It could be also possible for the Aru Co presenting a 0.5 m annual fluctuation without outflow. Outflow may happen in summer when the recharge is larger. But in cold season, whether outflow happens is questionable. It simply depends on the elevations of the Aru Co and the channel connecting the two lakes. So it needs to be careful when calculating the contribution of outflow of the Aru Co to the rising of the Memar Co by simply comparing the decline of the Aru Co and rising of the Memar Co.

Reply: Thanks for the comment. The hydraulic connection between the two lakes is investigated by comparing the seasonal lake level changes at Aru Co and Memar Co. ‘Lake level at Aru Co started to increase rapidly in early July, which was about half a month earlier than that at Memar Co. Meanwhile, the end of the rapid lake level increase at Aru Co was also about half a month earlier than that at Memar Co. The time lag of seasonal lake level changes at the two lakes indicates the buffering effect of Aru Co as an outflow lake. A large amount of water was stored in Aru Co in summer, and released to Memar Co in autumn. In early September, lake level at Aru Co decreased by about 10 cm, accounting for about 90% of the lake volume increase at Memar Co. This indicates that Aru Co, as an outflow lake, plays a significant role in regulating the water balance of Memar Co.’

As shown in the main text (Line 251-252), the two lakes are covered by lake ice between December and May. During the ice covered period, lake level of Aru Co decreased slightly while Memar Co increased dramatically. The decrease in lake storage at Aru Co only accounted for 20-30% of the lake volume increase at Memar Co during this period, so we believe that the lake surplus at Memar Co is not mainly contributed by the discharge from Aru Co. It is true that the seasonal lake level fluctuation is in a range of 0.5 m and we agree that it is questionable to compare the decline of the Aru Co and rising of the Memar Co when the lake does not freeze up.

Another concern is the altimetry data processing, which affects the reconstruction of historical lake levels. Current methodological description is very vague. What are the data sources? How is the water level generated? How is the bias between the two data sets handled? The results relating elevation changes are heavily dependent on the bias of the two data sets.

Reply: Thanks for the good suggestion. We have addressed altimetry data processing in more detail in the revision (Line 121-132). 'ICESat altimetry data was processed after Li et al (2014) and was used to examine water level variations between 2003 and 2009. CryoSat-2 data was processed after Xue et al (2018) and was used to investigate water level variations between 2010 and 2018. Both lakes were observed by ICESat satellite twice or three times a year (Phan et al., 2012), and by CryoSat-2 satellite every two or three months (Kleinherenbrink et al., 2015; Jiang et al., 2017). Notably, the two datasets are referenced to different ellipsoids and geoid height. The ICESat data contains corrected surface ellipsoidal heights referenced to TOPEX/Poseidon ellipsoid and geoid height referenced to Earth Gravity Model (EGM) 2008; while the CryoSat-2 data are referenced to WGS84 and EGM96 (Song et al., 2015). In order to make the two datasets comparable, lake elevation at Aru Co is compared because the lake is an outflow lake and inter-annual lake level changes are relatively small. At Aru Co, the lowest lake level in May is very stable from year to year as it is controlled by the elevation of the outlet. The ICESat and CryoSat-2 derived lake surface elevations of Aru Co were averaged to be 4936.67 m a.s.l. in April (n=2) during the period 2003-2009 and 4937.04 m a.s.l. in May (n=5) during the period 2011-2016, respectively. The small elevation difference of 0.37 m is considered to be the bias of the two datasets and used to correct satellite altimetry data.'

Specific comments: L21: "collapsed suddenly" suddenly is not necessary, I think.
Reply: We have deleted it in the revision.

L52: "dramatic increase", I do not think there is a dramatic increase in precipitation. Before 2014, the increasing of precipitation is not significant, and a plethora of studies debated the reason of lake expansion. Until recent years, the increasing of precipitation is much clear but not dramatic.
Reply: Thanks for the suggestion. 'Dramatic' is not accurate some places, so we replaced it with other words or deleted it in the revision.
The response of lake expansion to climate change is discussed in a new section (Section 5.1) because it is not closely related to the subject of this study. Yes, precipitation on the TP exhibited significant spatial difference and different precipitation dataset shows quite large difference. This is mainly due to lack of in situ measurement. On the interior TP, precipitation data is only available at several stations and exhibits large inter-annual fluctuations. It should be noted that lake can expand when precipitation is higher than the equilibrium value, so lake expansion does not need continual increase in precipitation. Generally, the precipitation was above average value on the interior TP after the late 1990s, so we can find that most lakes expanded rapidly during the past 20 years.

L65-69: Do you think the bathymetry have significant change?
Reply: The ice avalanches can influence lake bathymetry of Aru Co near the collapse fan, not the whole lake (Section 4.2).

L90: How was the snow measured?
Reply: The snow is measured by a T200B rain gauge (Line 87).

L177-178: This sentence is not clear to me. Please rephrase it.

Reply: Thanks, we have rephrased it in the revision (Line 264-265).

L191: "Sential" -> "Sentinel", please also change it in the caption of Figure 4.

Reply: Thanks for pointing out this error. We have revised it in the revision.

L192: Figure 3a should be Figure 4a.

Reply: Thanks for pointing out this. We have rephrased this sentence in the revision.

L209-214: How many pairs of level and area are used to build this regression model? Extrapolation based on data of six years could be problematic. This needs to be better explained.

Reply: In this study, six pairs of lake level and area are used, including 1972, 1994, 1999, 2004, 2014 and 2018. Since these data contains the lowest (~1997) and highest (2018) lake area and water level, we believed the regression model used in this study is reliable.

L217-218: It seems that the satellite data did not capture the sudden rise (pink dotted line) revealed in Figure 5b. Is the pink coded line indicating the reconstruction?

Reply: The pink dotted line is the satellite altimetry data. The dramatic increase of lake level change occurred during the whole period between 2016 and 2019. To be honest, the sudden rise in lake level at Memar Co shortly after the Aru-1 collapse can not be captured by CryoSat satellite data due to its temporal resolution.

L256-257: The seasonality revealed by satellite data is not very clear due to the course temporal resolution.

Reply: We agree with this. Because Memar Co also expanded rapidly before the glacier collapse, the lake level seasonality revealed by Cryosat-2 data did not exhibit big difference before and after the collapse. However, if we compare the average values between the two periods, we can find the considerable difference of lake level change in summer.

Conclusion: I would suggest the authors try to concise the conclusions, right now too many repetitive statements from the results.

Reply: Thanks, we have rephrased the conclusion carefully.

Reply to Short comments

(1) The organization of the Results part should be adjusted to focus on the evaluation of the glacier collapse influences. In Section 4.1, the description of Aru Co, Memar Co, and their hydrological connection can be moved to the part of the Study area.

Reply: Thank you very much for the constructive comments and suggestions. We re-organize the structure of the paper in the revision. Lake level seasonality and the hydraulic connection are moved to section 4.4, which is about the impact of the meltwater on the seasonal lake level changes of Memar Co. We do not move lake bathymetry and water storage at the two lakes to study area section because they belong to part of the result in this study. If we move them to the study area, readers may have question about how these results come from.

(2) In Section 4.4, the impact of glacier collapses and meltwater on surface temperature of two downstream lakes were analyzed. From the LST time series, it can be clearly observed that several degrees of temperature difference occurred before and after the collapse. It can be inferred that the LST differences may be revealed in the spatial pattern of MODIS-derived temperature image varying with the distance from the ice mass input place. It is thus suggested to add the maps showing the spatial pattern of LST effect responding to the glacier collapse.

Response: Thanks for the good suggestion. We add a new figure 10 in the revision about the spatial pattern of lake surface temperature (LST). The spatial patterns of LST before (11 July) and after (19 and 27 July) the first glacier collapse are investigated in Section 4.6. Before the first glacier collapse, the spatial pattern of lake surface temperature on 11 July 2016 is investigated based on MYD11A2 data. After the first glacier collapse, the spatial patterns of lake surface temperature on July 19^{th} and 27^{th}, 2016 are investigated. Because Aru Co is narrow (1.4 to 9 km) and only lake pixels beyond 1 km from shoreline were extracted, there was no valid data in the central part of Aru Co.

The spatial pattern of LST shows that the northern Aru Co was considerably cooler than the southern Aru Co after the glacier collapse (19 and 27 July 2016), which is in contrast with that before the glacier collapse (11 July 2016). This is because the ice avalanche was closer to the northern Aru Co. Similar pattern also occurred in Memar Co, where lake surface temperature increased from south to north. This spatial pattern may also indicate that the floating ice from the first ice avalanche also influenced the lake surface temperature of Memar Co through the 5 km long river (10~20 m wide) linking the two lakes.

(3) The estimation of the collapsed glacier contribution on the lake water storage increase assumes that all of the collapsed ice mass eventually entered the downstream lakes in the form of meltwater supply. However, the glacier melting in other forms, e.g., evaporation, may need to be discussed.

Reply: Thanks for the suggestion. In this study, we assume all the meltwater from the collapsed glaciers entered the downstream lakes. According to in-situ observation by Li et al. (2019), sublimation and/or evaporation at Guliya ice cap on the western TP were estimated to be 0.12 m in the year 2015/2016. Sublimation and evaporation is relatively small and negligible compared with the rapid melting of the avalanche deposit. Meanwhile, the two glacier collapses are very close to Aru Co. Therefore, we do not consider evaporation or other kinds of water loss in this study (Line 227-228).

Li, S., Yao, T., Yu, W., Yang, W., Zhu, M.: Energy and mass balance characteristics of the Guliya ice cap in the West Kunlun Mountains, Tibetan Plateau. Cold Reg. Sci. Technol., 159, 71–85, 2019.

~~**Tracking the impacts of the Aru glacier collapses on downstream lakes**~~

Response of ~~two~~ downstream lakes to Aru glacier collapses on the Tibetan Plateau

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Abstract The entire lower parts of two~~Two giant glaciers~~ glaciers ~~(termed Aru-1 and Aru-2)~~ ~~at the Aru range, western Tibetan Plateau,~~ at the Aru range on the western Tibetan Plateau (TP) ~~collapsed~~ collapsed ~~suddenly~~ unprecedentedly on 17 ~~17~~ July and 21 ~~21~~ September 2016, respectively, ~~, respectively,~~ causing fatal damage to local people and their livestock. The giant ice avalanches, with a total volume of 150×10^6 m^3, had almost melted by September 2019. How the two downstream lakes (i.e. the outflow Aru Co and the terminal Memar Co) responded to the glacier collapses is still not ~~unclear~~investigated. Based on in-situ observation, bathymetry survey and satellite data, here we show the impacts of the two ice avalanches~~glacier collapses~~ on the downstream lakes~~,~~ ~~the outflow Aru Co and the terminal Memar Co,~~ in terms of lake morphology, water level and water temperature in the subsequent four years (2016-2019). After the first glacier collapse, the ice avalanche slid into Aru Co along with a large amount of debris, which generated great wave at Aru Co and significantly modified the lake's shoreline and ~~bathymetry~~underwater topography. The intruding ice with a volume of at least 7.1×10^6 m^3 soon spread over the Aru Co's surface and dramatically lowered lake surface temperature (LST) by 2-4 °C in the first ~~1~~ 2 weeks after the first glacier collapse. Due to the large amount of meltwater input, ~~By comparing with long term lake level changes~~~~we found that~~ Memar Co exhibited more rapid expansion after the glacier collapses (2016-2019) than before (2003-

2014)~~ due to the large amount of meltwater input,~~., characterized by much larger l~~L~~ake level increase ~~in cold season did not exhibit considerable difference, but itbecame much larger~~ in warm season. ~~Assuming all the meltwater could be transferred into Memar Co, t~~The melting of ice avalanches was found to contribute to about 26.4% ~~30%~~ of the increase in lake storage between 2016 and 2019~~26.4~~. Out results ~~Assuming all the meltwater could be transferred into Memar Co, its contribution to the annual lake level increase was estimated to be 41.9%, 34.3%, 14.2% and 10.3%, respectively, between 2016 and 2019. Lake surface temperature (LST) at Aru Co and Memar Co exhibited a significant decrease of 2-4 °C in the first 1-2 weeks after the first glacier collapse due to the intruding ice into Aru Co and its melting. Memar Co significantly deepened by 12.5 m between 2000 and 2018, with accelerated lake level increase after the glacier collapses. Memar Co expanded rapidly at a rate of 0.80 m/yr between 2016 and 2019, which is about 30% higher than the average rising rate between 2003 and 2014. Lake surface temperature (LST) at Aru Co and Memar Co exhibited a significant decrease of 2-4 °C in the first 1-2 weeks after the first glacier collapse due to the intruding ice into Aru Co and its melting. The meltwater from ice avalanches was found to contribute to about 26.4% of the increase in lake storage between 2016 and 2019. This study implie~~indicates that ~~the~~ Aru glacier collapses had long-term and dramatic impacts on the downstream lakes~~. .This study~~ and ~~may further shed light~~may be helpful ~~on~~in ~~the~~ ~~potential effect~~understanding the relationship between glacier ~~melting~~mass loss ~~on~~ and lake ~~expansion~~behaviour on the ~~inner~~ TP under a warming climate.

带格式的: 非突出显示

1 Introduction

Potential risk of natural hazards in the Third Pole region has increased in the last decades (Cui et al., 2015; Cook et al., 2018; Liu et al., 2019). Glaciers in the Third Pole region have changed heterogeneously due to rapid climate warming and different patterns of precipitation changes (Yao et al., 2012). Most glaciers have experienced significant negative mass balance, except for the slight mass gain on the Karakoram and western Kunlun Mountains (Gardelle et al., 2012; Kääb et al., 2015; Brun et al., 2017). Due to the rapid glacier retreat, most glacial lakes expanded rapidly and many new glacial lakes appeared (Li et al., 2012; Nie et al., 2017), which together increased the risk of glacial lake outburst floods (Cook et al., 2018; Wang et al., 2018). Meanwhile, ice avalanche as a new form of glacier instability appeared on the western Tibetan Plateau. The low parts of two ~~giant~~ glaciers ~~(Aru-1 and Aur-2)~~ at the Aru range on the western TP~~,~~ collapsed unprecedentedly~~suddenly~~ on 17 July and 21 September 2016, leading to fatal damage to local people and their livestock (Tian et al., 2017). Main causes of the two glacier collapses were identified as the unusually high water input from melting and precipitation, as well as soft-bed properties of the glaciers (~~Tian et al., 2017;~~ Kääb et al., 2018; Gilbert et al., 2018).

Although the two giant ice avalanches have caused serious ecological and environmental problems, its impacts on the downstream lakes (i.e. the outflow Aru Co and the terminal Memar Co) in the successive years is still not ~~evaluated~~investigated. The two ice avalanches may influence~~d~~ the downstream lakes ~~at least~~ in ~~two~~several ways. First of all, a large amount of ice avalanche slid into Aru Co at high speed ~~after running out 6-7 km beyond the glacier terminus~~ and generated huge impact wave at Aru Co (Kääb et al., 2018), which could affect shoreline and ~~lake morphology~~underwater topography. Secondly, the melting of the fragmented ice mass, with a total volume of ~150×10^6 m^3, could supply the downstream lakes and affect lake level changes of Memar Co in subsequent years. ~~Secondly~~Thirdly, the ice avalanches could ~~have impact on~~affect lake ~~water~~surface temperature through floating ice and cold water input. ~~To what extent the fragmented ice melting can influence the lake level and surface water temperature still needs to be investigated.~~ In fact, there are many studies about the impact of glacier melting on rapid lake growth on the interior TP (e.g. Yao et al., 2010, 2018; Lei et al., 2012; Song et al., 2015; ~~Tong et al., 2015;~~ Li et al., 2017; Zhang et al., 2017; Zhou et al., ~~2017,~~ 2019; Yao et al., 2018; Treichler et al., 2019). However, the process of how glacier melting regulates lake level changes is largely unknown due to a lack of in-situ observation. Therefore, the observation of lake level changes in the downstream lakes of the Aru glacier collapses will provides us unique evidence of the impact of a large amount of glacier melting on the downstream lakes. Clarifying how the two downstream lakes respond to the two ice avalanches is also helpful in understanding the relationship between glacier mass loss and lake behaviour on the TP under a warming climate.

~~Most endorheic lakes in the Third Pole region have expanded significantly since the late 1990s due to a dramatic increase in precipitation (e.g. Lei et al., 2014), which led to serious ecological and environmental problems (Yao et al., 2010). For example, rapid lake expansion in the northern Tibet inundated a large area of grassland and destroyed infrastructures such as roads and bridges (Yao et al., 2011). A case study occurred in Hol Hil Nature Reserve, where a significant overflow suddenly occurred at Zhuonai Lake (255 km²) in late August 2011 due to continuous expansion since the 2000s. The flood subsequently induced the overflow of Kusai Lake (260 km²) and rapid expansion of the downstream lakes, Haidingnuoer Lake and Salt Lake (Yao et al., 2012; Liu et al., 2019). This sudden process was captured by Cryosat satellite, which shows that there was 12.6 m lake level drop at Zhuonai Lake after the outburst (Hwang et al., 2019; Li et al., 2019). The newly formed riverbanks caused by the outburst flood obstructed the traditional migration route of antelopes and had serious ramifications for antelope survival (Pei et al., 2019).~~

In September 2016, two months after ~~the~~ Aru-1~~first~~ glacier collapse and one week after ~~the second~~Aru-2 glacier collapse, we conducted a field campaign and installed instruments to monitor lake level changes at the two downstream lakes, Aru Co and Memar Co (Fig. 1). In July 2017 and October 2018, we further conducted lake bathymetry survey at both lakes. A comprehensive ~~dataset of~~ hydro-meteorology monitoring has been established ~~near~~ about the two glacier collapses. In this study, the impact of the two glacier collapses on the downstream lakes is investigated in terms of lake morphology, lake level changes and lake surface temperature. We first investigate ~~characteristics of lake bathymetry~~the instantaneous impact of the avalanches on the morphology of Aru Co, then evaluate ~~and~~ the impact of the meltwater on ~~-~~lake level changes at Memar Co on seasonal to inter-annual time scales, ~~at both lakes~~ and ~~then~~ finally ~~analyze~~ analyse the impact of the meltwater on changes in ~~of the two glacier collapses on the downstream lakes, the outflow Aru Co and the terminal Memar Co, in terms of lake bathymetry,~~ lake surface ~~water~~ temperature ~~and lake level changes~~at both lakes. ~~(The structure of the paper)~~ 带格式的: 突出显示

2 ~~General description of the s~~Study area

Aru Co and Memar Co are located in an endorheic basin on the western Tibetan Plateau (Fig. 1). According to the second glacier inventory (Guo et al., 2015), 105 pieces of glaciers are located in the basin with a total area of ~184 km^2. Studies showed that glaciers in this region had been rather stable in the past decades (Tian et al., 2017; Zhang et al., 2018). Two adjacent glaciers (Aru-1 and Aru-2) to the west of Aru Co collapsed suddenly on July 19th and September 21st, 2016, respectively, killing nine people and hundreds of livestock. The fragmented ice mass of the ~~first~~ Aru-1 glacier collapse reached Aru Co at high speed after running out 6-7 km beyond the glacier terminus, generating huge impact wave at Aru Co (Kääb et al., 2018). ~~Fieldwork a~~At ~~the first~~Aru-1 glacier collapse fan, ~~showed that~~ the depth of the ~~collapsed~~ fragmented ice mass varied from 3 m at the glacier snout to 13 m at the far end of the deposit (Tian et al., 2017). The two ice avalanches covered an area of 9.4 and 6.7 km^2, and the~~ir~~ volumes of the detached glacier were estimated to be 68 and 83×10^6 m^3, respectively (Tian et al., 2017; Kääb et al., 2018).

Aru Co and Memar Co are ~~located in~~ the two downstream ~~of~~ lakes of the ~~two~~ glacier collapses (Fig. 1). Both lakes are lagoons and share a catchment area of 2310 km^2. Aru Co is an outflow lake with salinity of 0.56g/L, and Memar Co is the terminal lake of Aru Co with salinity of 6.22 g/L. The surface elevation of Aru Co (4937 a.s.l.) was about 14 m higher than Memar Co (4923 a.s.l.) in 2003, according to ICESat satellite altimetry data (Li et al., 2014). There are dozens of visible paleo-shorelines around Memar Co. The highest shoreline around Memar Co is ~40 m above the modern lake level, indicating Aru Co and Memar Co used to be one large lake on a geological time scale.

are lagoons and The two lakes share a catchment area of 2310 km^2. Aru Co is an outflow lake with salinity of 0.56g/L, and Memar Co with salinity of 6.22 g/L is the terminal lake of Aru Co. The surface elevation of Aru Co (4937 a.s.l.) was about 14 m higher than Memar Co (4923 a.s.l.) in 2003, according to ICESat satellite altimetry data (Li et al., 2014). There are dozens of visible paleo-shorelines around Memar Co. The highest shoreline around Memar Co is ~40 m above the modern lake level, indicating Aru Co and Memar Co used to be one large lake on a geological time scale.

The climate in this area is cold and dry most of the year. Automatic weather station (AWS) data collected between Oct 2016 and Sep 2019 near the glacier collapse (~5000 a.s.l.) show that mean annual air temperature is -3.6 ^{o}C, with the lowest value of -14.0 ^{o}C in January and the highest value of 7.2 ^{o}C in August. A T200B rain gauge data ~~during the same period~~ indicated that mean annual precipitation near the glacier collapse is 333 mm between October 2016 and September 2019, which is much higher than that at Nagri meteorological station (Tian et al., 2017). Precipitation in this region is mainly concentrated in the warm season from June to September, accounting for more than 80% of annual precipitation. Snowfall in the cold season between October and May only accounts for 10-15% of annual precipitation.

>>Fig. 1<<

>>Fig. 2<<

3 ~~Study m~~Methods

3.1 Lake bathymetry

Bathymetric survey at Aru Co and Memar Co was conducted in July 2017 and October 2018, respectively. Water depth was determined using a 500 watt duel frequency depth sounder interfaced with a Garmin GPSMAP 421S chart plotter. Latitude, longitude, and water depth were acquired at 3-second interval during each bathymetric survey. At Aru Co, a total of 16,100 water depth points were acquired, with a focus on the underwater topography near the first glacier collapse. A detailed bathymetry survey at Aru Co was conducted at an interval of 100-200 m near the first glacier collapse fan. At Memar Co, a total of 18,000 water depth points were acquired. The horizontal position of each point was recorded with an accuracy of 3 m or better. The lake boundary in July 2017 and October 2018 was used to calculate lake water storage at Aru Co and Memar Co, respectively. The water depth was interpolated to the whole lake to acquire the lake isobaths and then lake volume was calculated in ArcGIS 9.2. ~~At~~ Memar Co was composed of two lakes in the late 1990s when the lake level was much lower than present. In this study, lake water depth of the shoreline in 1994 was reconstructed according to bathymetry survey and also used to calculate the lake isobaths because this is a year of low lake level.

3.2 Lake water level monitoring

Lake level at Aru Co and Memar Co was monitored since September 2016 using HOBO water level loggers (U20-001-01) or Solist water level loggers, which were installed in the littoral zone of the lake. Because water levels were recorded as changes in pressure (less than 0.5 cm water level equivalent), air pressure data was subtracted from the level loggers to get pressure changes related to water column variations. Daily lake level changes between October 2016 and September 2019 were used in this study at Aru Co. At Memar Co, lake level is only available from October 2017 to September 2019 because the logger was lost in the first year. Water depth of the loggers was measured during fieldwork to calibrate the logger data.

3.3 Satellite observation

Multi-sources of satellite data, including Landsat images, ICESat and ~~Cryosat~~CryoSat-2 satellite altimetry~~ data~~, were explored to detect long-term changes in lake extent and water level. Landsat images downloaded from the USGS website (http://glovis.usgs.gov) were used to investigate changes in lake area since the 1970s. A total of ~~32~~ 30 satellite images between September and November, ~~1977~~ 1972 to 2018, were selected. Before 1990, only ~~one~~ two images (~~1977~~1972 and 1976) ~~was~~ were available. After 1990, almost annual changes in lake area (no data in 1991, ~~1993,~~ 1995 and 1998) were extracted. Lake boundaries were extracted in false color image by manual delineation using ArcGIS 9.2 software.

~~ICESat and Cryosat-2 satellite altimetry data were used to detect lake level changes between 2003 and 2017 (Li et al., 2014; Xue et al., 2018). Memar Co was monitored by ICESat satellite twice a year (pre-monsoon and post-monsoon seasons) between 2003 and 2009 (Phan et al., 2012; Zhang et al., 2011). Since 2010, Memar Co was monitored by Cryosat-2 satellite every two or three months (Kleinherenbrink et al., 2015; Jiang et al., 2017).~~

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Dynamics of the two ice avalanches were investigated through different kind of satellite images (Sentinel-2, Gaofen~~F~~-2, Landsat-8 OLI). A Sentinel-2 satellite image on July 21st, 2016 was acquired to detect the largest extent of the intruding ice into Aru Co. A G~~F~~aofen-2 satellite image~~s~~ on July 25th, 2016 was acquired to detect the floating ice at the surface of Aru Co because of its high resolution of ~1 m. The extent of the two ice avalanches was extracted based on Landsat images between 2016 and 2019 and used to calculate meltwater every year.

ICESat and ~~Cryosat~~CryoSat-2 satellite altimetry data were used to detect lake level changes between 2003 and 2017 ~~(Li et al., 2014; Xue et al., 2018). Memar Co was monitored by ICESat satellite twice a year (pre-monsoon and post monsoon seasons) between 2003 and 2009 (Phan et al., 2012; Zhang et al., 2011). Since 2010, Memar Co was monitored by Cryosat-2 satellite every two or three months (Kleinherenbrink et al., 2015; Jiang et al., 2017).~~ In this study, ICESat altimetry data, which was processed according to Li et al (2014), was used to examine water level variations between 2003 and 2009. CryoSat-2 data, which was processed according to Xue et al (2018), were used to investigate water level variations between 2010 and 2018. The two lakes was observed by ICESat satellite ~~detected the two lakes~~ twice or three times a year (Phan et al., 2012), and by CryoSat-2 satellite ~~observed the two lakes~~ every two or three months (Kleinherenbrink et al., 2015; Jiang et al., 2017). Notably, the two datasets are referenced to different ellipsoids and geoid height. The ICESat data contains corrected surface ellipsoidal heights referenced to TOPEX/Poseidon ellipsoid and geoid height referenced to Earth Gravity Model (EGM) 2008; while the CryoSat-2 data are referenced to WGS84 and EGM96 (Song et al., 2015). In order to make the two datasets comparable, lake elevation at Aru Co is compared because the lake is an outflow lake and inter-annual lake level changes are relatively small. ~~As shown in Fig. 5~~At~~,~~ ~~lake level at~~ Aru Co, ~~was in its~~the lowest lake level in May ~~and it~~ is very stable from year to year determined by the outlet. The ICESat and CryoSat-2 derived lake surface elevations of Aru Co were averaged to be 4936.67 m a.s.l. in April (n=2) during the period 2003-2009 ~~(n=2). The CryoSat-2 derived lake surface elevations of Aru Co were averaged to be~~ and 4937.04 m a.s.l. in May (n=5) during the period 2011-2016, respectively ~~(n=5)~~. This elevation difference of 0.37 m is considered to be the bias of the two datasets ~~at~~in this study.

3.4 Long-term lake level reconstruction

Lake level variations before 2003 were determined based on the current ~~water depths~~lake bathymetry and the position of past shorelines, which is derived from Landsat satellite images ~~(Lei et al., 2012)~~. ~~The primary objective of b~~Bathymetric survey was used to determine the current water depth over shorelines that were previously exposed (Lei et al., 2012). To minimize errors, more than 10 bathymetry lines across Memar Co were acquired and used to reconstruct past lake level changes. ~~In this study, l~~Lake level changes in 197~~7~~2, 1994, ~~1997,~~ 1999, 2004 and 2014 relative to October 2018 were reconstructed ~~by bathymetry survery~~. ~~We used as many as~~ ~~More than 10 bathymetry lines across Memar Co were acquired and used to reconstruct past lake level changes.~~ ~~Memar Co exhibited shrinkage from 1972 to 1999, and then expanded significantly since 2000. Therefore, different stages of lake level changes are included in this reconstruction.~~ Uncertainty of lake level changes is mainly determined by the resolution of satellite images, which is considered as~~estimated using~~ the standard deviation of all the reconstructed lake levels. In this study, uncertainty of changes in lake level and water storage ~~changes~~ was estimated to be ±0.3 m~~,~~ and ~~the uncertainty of lake storage changes was estimated to be~~ ±0.05 Gt, respectively. ~~For Memar Co, t~~The relationship between lake area and the reconstructed lake levels was developed using a 2-order polynomial regression~~a linear regression~~ model.

Continual lake level changes at Memar Co since 1972 were reconstructed using this relationship and the corresponding lake area.

3.5 Lake surface temperature derived from MODIS satellite data

~~In this study,~~ MODIS 8-day land surface temperature products (i.e. MOD11A2 and MYD11A2) were used to investigate changes in lake surface temperature at Aru Co and Memar Co. The MODIS 8-day data is the averaged lake surface temperature of daily MODIS product over eight days. In both platforms (Terra and Aqua), two instantaneous observations were collected every day (Terra: approximately 10:30 and 22:30 local time, Aqua: approximately 13:30 and 01:30 local time). ~~The MODIS 8-day data is the averaged lake surface temperature of daily MODIS product over eight days.~~ Only nighttime data was used in this study because there was less cloud cover at night (Zhang et al., 2014; Wan et al., 2018). MOD11A2 and MYD11A2 products are produced at a spatial resolution of about 1 km~~.~~ with ~~The~~an accuracy of ~~MODIS LST data is~~ 1 K ~~in most cases~~ under clear sky conditions (Wan, 2013). MODIS lake surface temperature data ~~are~~ is pre-processed to account for atmospheric and surface emissivity effects. The cloud mask (MOD35) used for inland water provides a surface temperature measurement when there is a 66 % or greater confidence of clear-sky conditions (Wan, 2013), otherwise no temperature is produced. To reduce the contamination from land pixels, only lake pixels beyond 1 km from shoreline were extracted (Ke et al., 2014) ~~(Fig. S3)~~. Because the two ice avalanches were closer to ~~At~~the northern Aru Co (Fig. 2), ~~lake~~ lake surface temperature at the southern half ~~(29 pixels)~~ and northern half ~~(7 pixels)~~ of the lake was extracted to investigate its spatial difference. At Memar Co, lake surface temperature at the northern half of the lake ~~(81 pixels)~~ was extracted. Anomalous lake surface temperature was examined and removed if there was big difference between ~~the two~~ MOD11A2 and MYD11A2 datasets. To confirm the reliability of MODIS products, nighttime lake surface temperature was compared with in-situ observation at the shoreline.

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4 Results

4.1 Bathymetry survey at Aru Co and Memar Co

Aru Co has a surface area of 105 km^2 with a length of 27 km and a width of 1.4 to 9 km. The bathymetry survey shows that Aru Co is composed of two sub-basins. The northern basin accounts for less than 30% of the total lake area with a maximum water depth of 20 m. The southern basin is the main body of Aru Co, with a maximum water depth of 35 m (Fig. 2). The central part of Aru Co is narrow and shallow, with a width of ~1.5 km and a maximum water depth of ~11 m. The entire Aru Co has an average water depth of 17.6 m and total water storage of 17.9×10^8 m^3.

>>Fig. 2<<

Memar Co has a surface area of 177 km^2 with a length of 36 km and a width of 2 to 7 km. Similar to Aru Co, Memar Co is also composed of two sub-basins. The northern basin is the main body of the lake with a maximum depth of 42.6 m. The southern basin only accounts for less than 20% of total lake area, with a maximum water depth of 20.5 m (Fig. 2). The south-central part of Memar Co is narrow and shallow, with a width of 2-3 km and a maximum depth of ~12.5 m. Satellite images show that the southern and northern parts were separated in the 1990s when the lake level was low. The two parts have been connected since 2000 due to the rapid lake expansion. According to lake bathymetry in October 2018, Memar Co has an average water depth of 20 m and total water storage of 34.9×10^8 m^3, about twice as large as Aru Co.

~~4.2~~ 4.2 The instantaneous ~~Impact~~ impact of ~~the~~Aru-1 ~~first~~ glacier collapse on the morphology of Aru Co

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Aru-1 glacier collapse ran into Aru Co at high speed after running out 6-7 km beyond the glacier terminus (Tian et al., 2017; Kääb et al., 2018). A Sentinel-2 satellite image acquired on July 21st, 2016 showed that the ice avalanche ran into Aru Co as far as ~800 m and the intruding ice into Aru Co had an area of ~0.89 km^2 with a width of ~2250 m and an average length of 400 m. ~~about 0.89 km² of ice intruded into Aru Co. The shoreline of Aru Co was pushed eastward ~400 m on average (Fig. 3a).~~ The intruding ice generated great wave impact at the northern Aru Co due to its high speed and large volume, which inundated the opposite shore of Aru Co (Kääb et al., 2018). Fieldwork in October 2016 showed that there was clear footprint of wave erosion at the opposite shore of the northern Aru Co, which extended up to 240 m inland and 9 m above the lake level along 10 km long shoreline distance (Fig. 3a).

Bathymetry survey in July 2017 showed that water depth at the east margin of the intruding ice ~~into Aru Co~~ was about 8 m~~,~~. Because the intruding ice was obviously higher than the lake surface, ~~indicating that it~~the water depth of 8 m was probably the least thickness of the ice mass into ~~the lake~~Aru Co ~~as the intruding ice are obviously higher than the lake surface~~. Therefore, regardless of the floating ice over the lake surface, the volume of ice mass into Aru Co is estimated to be at least 7.1×10^6 m^3, accounting for ~10% of the total ice volume of ~~the first~~Aru-1 glacier collapse. Due to the influence of lake water, the intruding ice melted quickly in less than two months as indicated by ~~Comparison with~~ Landsat satellite image on September 20th, 2016 ~~on 20th September, 2016 shows that~~ ~~most of the ice mass into Aru Co melted in two months~~(Fig. 4).

~~We conducted a d~~Detailed bathymetry survey at Aru Co ~~near the first glacier collapse fan~~showed that the underwater topography near Aru-1 ice avalanche was largely modified~~.~~ du~~Du~~e to a large amount of debris input along with the fragmented ice mass~~, the lake bathymetry was largely modified~~. Fig. ~~4~~ 3b shows that the ~~uneven~~ bathymetry near the ice avalanche~~glacier collapse~~ ~~fan~~ became uneven, which is quite different from the adjacent areas~~,~~. The extent of the uneven lake bathymetry was slightly larger than that of the intruding ice on July 21st, 2016 (Fig. 3b), indicating that part of the intruding ice had spread over the surface of Aru Co or melted in four days after the glacier collapse. The uneven underwater topography indicated that a large amount of debris was transported into Aru Co or the lake bed was significantly eroded~~which indicates that the lake bed was greatly eroded~~. The lake bottom stays unchanged in areas deeper than 15 m or far from the glacier collapse fan.

An investigation of Aru-1 ~~the first~~ ice avalanche in October 2019 gave further evidence of debris input into Aru Co. ~~>>Fig. 4<<~~

~~The >>Fig. 4<<~~

Clear deposit with a thickness of 0.2-1.0 m ~~of the first glacier collapse fan~~ was ~~investigated in October 2019~~left after the fragmented ice mass had completely melted~~when the fragmented ice mass had completely melted~~. ~~We found that t~~The original road was no longer accessible because ~~the glacier collapse fan~~it was covered by thick ~~a large amount of~~ debris~~ with a thickness of 0.2-1.0 m~~. Boulders with a diameter of 1-2 m ~~-~~were found even near the ~~lake~~ shoreline (Fig. ~~4d~~3d). The uneven land surface may explain~~s~~ well why the lake bottom became uneven. Fieldwork also showed that ~~Due to the large amount of debris input, the~~ Aru Co's shoreline near the northern and southern sides of the ice avalanche dramatically ~~at the northern and southern sides of the glacier collapse fan was pushed~~ moved ~~eastward~~ offshore for about 100-120 m, which was probably due to the deposit of debris transported by glacier collapse and afterwards meltwater. ~~This indicates that the debris of first glacier collapse significantly modified the land surface and the lake bathymetry of Aru Co.~~

>>Fig. ~~4~~3<<

>>Fig. 4<<

4.~~2~~3 The melt~~ing~~water estimation of the two ~~ice avalanches~~ice avalanches~~ (degree day model)~~

According to the areas and volumes reported by Kääb et al (2018), ~~Both satellite images and fieldwork showed that the first glacier collapses have almost melted by October 2019.~~ the average thickness of Aru-1 and Aru-2 ice avalanches was estimated to be 7.6 m and 15.2 m, respectively. Different thickness of the fragmented ice mass determined the duration of its melting. ~~The~~ Aru-1~~first~~ glacier collapse had ~~completely~~almost melted in two summers as indicated by ~~b~~Satellite images~~y October 2018~~ in October 2017 (only some scattered ice mass left)~~Fig. 1~~. ~~(Supplementary). Areal changes?~~The melting of Aru-2 glacier collapse lasted longer due to its larger thickness. In October 2019,

~~Only less than 0.5 km^2 of~~ the fragmented ice had~~remained~~ an area of about 1.9 km^2, accounting for about 29% of the total area. ~~at~~ The remaining ice mass mainly occurred in the upper part of Aru-2 ~~second~~ ice avalanche~~glacier collapse fan~~, where the fragmented ice ~~i~~was thicker (Kääb et al., 2018)~~ by October 2019~~. ~~Areal changes? DEM difference of ice left.~~

Here we ~~made a~~ roughly estimat~~ion~~e the yearly meltwater of the fragmented ice mass according to the area and in-situ measurements of ice mass balance~~ in the first two years~~. In 2016, in-situ measurements at 9 sites show that Aru-1 ~~the~~ ice ~~mass~~avalanche thinned about 2.84 m on average between August 13th 2016 and Oct 24th 2016, which corresponded to ~~about~~a volume of ~~30.6~~24.4×10^6 m^3~~ of meltwater (assuming the ice density of 900 kg/m^3)~~. Considering the intruding ice into

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Aru Co (7.1×10^6 m^3), the total meltwater of the first ice avalanche is estimated to be 28.4×10^6 m^3 in 2016 (assuming the ice density of 900 kg/m^3). The meltwater of Aru-2 ice avalanche is not considered in 2016 because air temperature was already close to zero degree in the late September. The largest melting of the fragmented ice mass occurred in summer 2017 ~~according to Landsat satellite images and in-situ observation~~. In-situ measurements show Aru-1 and Aru-2 ice avalanches melted down 6.5 m and 5.5 m on average, respectively, between September 2016 and September 2017. Most of the first ice avalanche had melted by October 2017 and~~.~~ it ~~In-situ measurements show the first and second glacier collapses melted down 6.5 m and 5.5 m on average, respectively, between September 2016 and September 2017,~~ meltwater in 2017 is considered to be 26.6 $\times10^6$ m^3, which is also the remaining part of Aru-1 ice avalanche. Meltwater of the second ice avalanche is estimated to be 33.2 $\times10^6$ m^3. Thus, the total meltwater in 2017 is estimated to be 59.7~~which corresponds to 63.9~~ $\times10^6$ m^3 ~~of meltwater in total~~. ~~By~~In October 2018 and 2019, ~~only a small portion of~~ the second glacier collapse ~~remained~~only had an area of 3.0 and 1.9 km^2, respectively. We assumed that the ~~rate~~meltdown of the ice ~~melting~~mass ~~at the second glacier collapse~~ in 2018 and 2019 w~~as~~ere same as in 2017, and the total volume of meltwater is estimated to be 2~~5.2~~4.0 $\times10^6$ m^3~~.~~ and 18.2×10^6 m^3 in 2018 and 2019, respectively (Tab. 1). Thus, about 3.1×10^6 m^3 of the fragmented ice was left at Aru-2 ice avalanche according to the above calculation.~~By October 2019, the second glacier collapse had also completely melted, with the remaining meltwater of 18.2×10^6 m^3 (Tab. 1).~~

>>Tab. 1<<

4.~~3~~4

~~4.3~~ Impact of the ~~ice avalanches~~meltwater on the seasonal lake level changes of Memar Co ~~of Memar Co~~

~~5~~ The impact of the ~~two~~meltwater ~~ice avalanches~~ on ~~seasonal and inter-annual~~ lake level changes ~~of~~mainly occurred at Memar Co ~~was investigated~~ because ~~their meltwater finally went into Memar Co via~~ Aru Co is an outflow lake. Here we first Compared to Aru Co, the lake level at Memar Co did not exhibit ~~clear~~distinct seasonality during the study period. There was an overall lake level increase throughout the year. Lake level increase not only occurred in the warm season, but also in the cold season (Lei et al., 2017). During the cold season, lake level increased dramatically by ~30 cm (1.4-2.0 mm/day) between November and May, which was comparable or even larger than that in the warm season between June and August (Fig. ~~3~~5). The rate of lake level increase in the cold season was very stable, indicating that the water supply is also very stable. Lake level increase in the warm season was mainly associated with high summer rainfall and glacier melting, while the lake level increase in the cold season was probably related to groundwater discharge because there is almost no surface ~~discharge~~runoff during this period. Notably, ~~discharge~~ lake volume decrease ~~from~~at Aru Co only accounted for 20-30% of the lake volume increase at Memar Co ~~in~~during the ~~cold~~ice covered season (November to May), indicating that the significant lake water surplus at Memar Co was not mainly contributed by the discharge from Aru Co, but by other sources of groundwater discharge. The in-situ observation of seasonal lake level changes at Memar Co also confirms the unique lake level seasonality on the western Tibetan Plateau~~, which is derived from Cryosat-2 data~~ (Lei et al., 2017).

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The hydraulic~~hydrological~~ connection between Aru Co and Memar Co can be indicated by the different seasonal lake level changes~~ between Aru Co and Memar Co~~. Lake level at Aru Co started to increase dramatically in early July, which was about half a month earlier than that at Memar Co. Meanwhile, the end of the rapid lake level increase at Aru Co was also about half a month earlier ~~relative to~~than that at Memar Co (Fig. 5b, c). The time lag of seasonal lake level changes at the two lakes indicates the buffering effect of Aru Co as an outflow lake. A large amount of water was detained at Aru Co in the summer, and was released to Memar Co in autumn. In early September, lake level at Aru Co decreased by about 10 cm, accounting for about 90% of the lake volume increase at Memar Co. This indicates that Aru Co, as an outflow lake, plays a significant role in regulating the water balance of Memar Co.

The impact of the two glacier collapses on lake level changes can be seen from the seasonal lake level changes derived from CryoSat-2 satellite data and in-situ observations between 2011 and 2019. The lake level increase in cold season (October to May) did not vary much from year to year, with an average value of 0.35 m and 0.36 m before (i.e. 2011-2015) and after (i.e. 2016-2019) the glacier collapses (Fig. ~~6~~6a). However, lake level increase in the warm season (May to September) increased dramatically after the glacier collapses (Fig. ~~6~~6b). Before the glacier collapses, lake level increase in the warm season varied in a range of -0.2~0.36 m, with an average of 0.12 m. After the glacier collapses, the lake level increase in the warm season varied in a range of 0.24~0.54 m, with an average of 0.39 m. Since the glacier collapses mainly melted in summer, the contribution of meltwater to the lake level increase in summer is estimated to be 48.7% on average between 2016 and 2019. We can see that the melting of the fragmented ice mass played an important role in the ~~accelerated~~dramatic ~~-~~lake level increase ~~after the glacier collapses~~in summer at Memar Co~~ was mainly contributed by the melting of the fragmented ice mass~~.

>>Fig. ~~6~~6<<

~~6~~

4.~~4~~5 Impact of the meltwater on the inter-annual lake level changes of Memar Co

~~L>>Fig.6<<~~

According to lake area and water level changes, lake dynamics of Memar Co between 1972 and 2018 were quantified and divided into two distinct periods. Between 1972 and 1999, Memar Co exhibited gradual shrinkage with lake level decrease of ~~3~~2.1 ±0.~~6~~3 m. Since 2000, Memar Co experienced dramatic expansion with lake level increase of 12.5 ±0.3 m between 2000 and 2018. The gradual shrinkage before 1999 and dramatic expansion at Memar Co since 2000 were similar to most endorheic lakes on the TP (e.g. Lei et al., 2014). Many studies showed that precipitation increased significantly on the interior TP since the late 1990s (Yang et al., 2014; Treichler et al., 2019), which led to the significant lake expansion (Lei et al., 2014). Between 1977 and 2018, lake level and water storage of Memar Co increased by ~~9~~10.4 ±0.3 m and 1.50 ±0.05 Gt (from 1.~~99~~86 to 3.~~49~~35 Gt), respectively.

After the Aru glacier collapses in 2016, Memar Co ~~changed~~ expanded ~~significantly before and~~~~at a~~more rapidly than before~~n accelerated speed~~ ~~after the Aru glacier collapses in 2016~~. Between 2003 and 2014, the lake level of Memar Co increased

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steadily at a rate of 0.59 m/yr. The lake expansion paused in 2015, in response to the widespread drought over the TP during the strong 2015/2016 El Niño event (Lei et al., 2019). Between 2016 and 2019~~After the first glacier collapse~~, the lake level of Memar Co ~~expanded~~ increased ~~more rapidly~~ with an average rate of 0.80 m/yr~~ between 2016 and 2019~~, which was about 30% higher than that between 2003 and 2014. The lake level and the water storage ~~and storage at~~ of Memar Co accumulatively increased by 3.0 m and ~~and~~ 0.38 Gt, respectively~~,, respectively,~~ between 2016 and 2019. Assuming all the meltwater can be transferred into Memar Co, the total melting of ice avalanches contributed to 26.4% of increase in lake storage between 2016 and 2019. We can see that without the melting of ice avalanches, the rate of lake level increase ~~at~~ of Memar Co after the glacier collapses could be similar to that between 2003 and 2014 (Fig. ~~3a~~7a).

The contribution of the ice avalanches melting on inter-annual lake level changes of Memar Co is ~~further~~ also quantitatively evaluated. In 2016, when ice melting mainly occurred in the first glacier collapse, Memar Co expanded slightly with lake level increase of 0.43 m. In 2017, when the ice melting reached its peak, Memar Co exhibited the most dramatic expansion, with lake level increase of 1.07 m. In 2018 and 2019, when the ice melting slowed down, the ~~Memar Co expanded~~ expansion of Memar Co also ~~slightly~~slowed down, with lake level increase of 0.8 m and 0.69 m, respectively. Assuming all the meltwater could be transferred into Memar Co, its contribution to the lake level increase of Memar Co is estimated to be ~~41.9~~38.8%, ~~34~~32.~~3~~1%, ~~14~~17.~~2~~0% and ~~10~~15.~~3~~0% ~~of the total lake level increase~~ in the subsequent 4 years (2016~~, 2017, 2018 and~~ -2019)~~, respectively~~.

>>Fig. 7<<

4.~~5~~6 The impact of Aru glacier collapses on lake surface temperature

The two ~~ice avalanches~~glacier collapses may ~~impact~~affect the lake surface temperature at Aru Co~~ and Memar Co~~ and Memar Co due to the input of a large amount of cold water. MODIS 8-day products (MOD11A2 and MYD11A2) are used to detected changes in lake surface temperature at ~~Aru Co and Memar Co~~the two lakes. Seasonal variations of lake surface temperature at Aru Co~~ and Memar Co~~ and Memar Co are shown in Fig. ~~7~~8~~ and 8~~. ~~At~~ Aru Co~~, the lake surface~~ usually freezes up in early November and breaks up in early May. After lake ice break up in May, the nighttime lake surface temperature increases rapidly from 2 °C to 10 °C between May and August. Then the lake water cools gradually from September to October. Seasonal lake surface temperature at Memar Co shows similar seasonal cycle with Aru Co, but different lake ice phenology (Fig. 8). Memar Co usually freezes up in late November and breaks up ~~about two to three weeks later than Aru Co~~in early June. A comparison of MODIS LST with in situ observation shows that although there are similar seasonal cycles, in situ lake surface temperature at the shoreline is considerably higher than MODIS LST (Fig. 9). This is because MODIS sensors measured the lake skin temperature at the lake centre while HOBO logger measured lake water temperature at the depth of 30-70 cm at the shoreline.

The ~~impact of~~ Aru-1 ice avalanche~~s~~ significantly ~~on~~affected lake surface temperature~~ mainly occurred~~ of Aru Co and Memar Co in summer 2016~~ shortly after the glacier collapses~~. Both MYD11A2 and MOD11A2 datasets showed that lake surface temperature decreased abruptly by 2-4 ^{o}C at Aru Co in the first two weeks after ~~the first~~Aru-1 glacier collapse (Fig. ~~7~~8~~b~~). A similar decrease in lake surface temperature also occurred at Memar Co, but its magnitude and duration were less than that at Aru Co (Fig. ~~8b~~9). We attribute the dramatic decrease in lake surface temperature to the floating ice over the surface of Aru Co. As shown in Section 4.1, a large amount of ice ~~avalanches~~mass slid into Aru Co after Aru-1 glacier collapse and generated great wave impact at Aru Co. A lot of floating ice ~~soon~~ spread over the surface of Aru Co and its melting may cool the lake surface temperature~~,~~. ~~which~~This can be confirmed by Gaofen-2 satellite image (1 m resolution) on July 25th 2016 (Fig. 4), which clearly shows the floating ice over the surface of Aru Co. Notably, lake surface temperature returned to normal status about two weeks later. ~~High resolutionGF-2spreadnear the glacier collapse fanFig. 4~~

The spatial patterns of lake surface temperature before and after the first glacier collapse are further investigated by using MYD11A2 data (Fig. ~~10??~~10). Before and after the ~~first~~Aru-1 glacier collapse, the spatial pattern of lake surface temperature on July 11th~~, 2016~~ 19th and 27th, 2016 is investigated. ~~After the first glacier collapse, the spatial patterns of lake surface temperature on July 19th and 27th, 2016 are investigated. There is no valid data in the central part of the lake of Aru Co because it is very narrow.~~ The results show that lake surface temperature at the northern Aru Co is dramatically lower than that at the southern Aru Co on July 27th, 2016 (also on July 19th)~~.~~ and the ~~From north to south,~~ lake surface temperature increased gradually from north to south, ~~gradually after the glacier collapse,~~ which ~~is~~further confirms the influence of ~~probably due to the influence of~~ the floating ice ~~over the lake surface of Aru Co~~on lake surface temperature. This spatial pattern is in contrast with that before the glacier collapse (Fig. 10~~July 11th, 2016~~). Similar pattern also occurred in Memar Co, where lake surface temperature increased from south to north after the glacier collapse. This spatial pattern may ~~also~~ indicate that the floating ice may ~~further~~ flow into Memar Co through the 5 km long river (10~20 m wide) between the two lakes.

Lake surface temperature ~~from~~at the southern and northern Aru Co was ~~extract~~compareded to examine the spatial heterogenity ~~(Fig. S2 and S3),~~ since the northern Aru Co was closer to the two glacier collapses. Before the glacier collapses (e.g., 2015), water temperature between the southern and northern Aru Co did not exhibit considerable difference in July and August ~~(Fig. 7a)~~. After the glacier collapse, the lake surface temperature in August 2016 ~~at the northern Aru Co~~ was about 1-2 ^{o}C lower at the northern Aru Co ~~in August 2016~~ than that at the southern Aru Co (Fig. ~~7~~9~~b~~). ~~We attribute t~~This spatial difference ~~temperature difference to~~may indicate the long term impact of the melt~~ing~~water on lake surface temperature in summer~~of the intruding ice~~. ~~Satellite images~~As showe~~d~~n in section 4.1, most of ~~that~~ the intruding ice into Aru Co, with a volume of 7.1×10^{6} m^{3}, melted ~~by September 20th, 2016~~in two months ~~(two months after the first glacier collapses)~~. Since the meltwater of the intruding ice ~~of the intruding ice~~ was considerably coo~~l~~der than the lake water, ~~the melting~~it ~~of the intruding ice~~ may ~~cool~~decrease the lake water temperature at the northern Aru Co more significantly. Similar condition can also be found in summer 2017 and 2018.

~~Although MODIS derived lake surface temperature can be affected by cloud cover and other factors (Ke et al., 2014), both confirmedimpact of ice avalanches on MOD11A2 and MYD1A2 products recorded a dramatic decrease of lake surface temperature.~~ However, the detailed process of changes in lake surface temperature after the glacier collapses is still unclear

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because there is no data available due to influence of cloud cover and other factors.~~We attribute the dramatic decrease in lake surface temperature to the floating ice over the surface of Aru Co. Since the meltwater of the intruding ice was considerably colder than the lake water, The dramatic decrease in lake surface temperature at Aru Co indicates that although the volume of the ice avalanches only account for a small portion of lake water storage at Aru Co (less than 8%), its melting could have dramatic impact on lake surface temperature. Notably, M~~ More work is ~~still~~ needed to demonstrate this process ~~the detailed process of changes in lake surface temperature after the glacier collapses~~by using more intensive satellite data.

>>Fig. ~~7~~8<<

>>Fig. ~~8~~9<<

>>Fig. 10<<

5 Discussion

5.~~2~~1 ~~Attribution of~~Response of the rapid lake expansion on the western TP to climate change

Widespread lake expansion occurred on the interior TP during the past two decades (e.g. Lei al., 2014). Although there are many studies about changes in lake area and water level, ~~Most endorheiclson the western TP significantly dedsince the late 1990s. Lei et al (2014) showed that the total area of 10 large lakes on the western TP increased by 18.2% between 1976 and 2010. The lake level increased at an average rate of 0.3 m/yr according to ICESat satellite altimetry data between 2003 and 2008. The extent of lake area and water level increase on the wester TP is similar with lakes in other regions of the TP. Yao showed that the total water storage at ?? lakes increased at a rate of (??) between 2003 and 2008. However, changes in total lake volumeB~~bathymetry survey ~~are~~is still less ~~investigated~~conducted at lakes on the western TP due to its harsh natural condition and remoteness. Qiao et al (201~~0~~7) conducted bathymetry survey at four lakes on the western TP, including Guozha Co, Longmu Co, Aksai Chin Lake and Bangdag Co. ~~-~~Their results showed that ~~lake volume~~water storage at Aksai Chin Lake and Bangdag Co was almost doubled during the past 40 years. At Aksai Chin Lake and Bangdag Co, water storage ~~of at~~ increased from 1.3~~28~~3 to 2.5~~68~~7 Gt and from 1.23 to 2.60 Gt, respectively, ~~from~~between 1996 ~~to~~and 2015. ~~At Bangdag Co, wincreased from 1.226 to 2.598 Gt during the same period.~~ In this study, our result showed that water storage at Memar Co increased from 1.~~99~~58 to 3.49 Gt ~~at Memar Co~~ between 19~~77~~99 and 2018, which was similar with the two reported lakes. Meanwhile, ~~B~~based on more intense ~~inter-annual lake level changes~~satellite data ~~(Fig. ?)~~, we ~~also found~~also found that the turning point from shrinkage to expansion at Memar Co occurred at 2000, which is about1-2 years later than lakes in other regions of the TP (Lei et al., 2014).

Since most glaciers ~~are widely distributed~~ on the TP experienced dramatic mass loss during the past decades, its impact on the rapid lake expansion on the TP ~~is often connected with regional glacier melting~~was investigated in many studies (e.g.

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Yao et al., 2010, 2018; Lei et al., 2012; Song et al., 2015; Li et al., 2017; Zhang et al., 2017; Zhou et al., 2019; Treichler et al., 2019). For example, glacier mass loss was estimated to contribute to ~10.5% of lake expansion at Nam Co on the central TP (Li et al., 2017). In Hol Xil region, glacier mass loss contribution to lake expansion was estimated to be ~~10~~9.9 and 11.1% at LexieWudan Lake and KekeXili Lake (Zhou et al., 2019). However, more and more studies shows that glaciers in the Karakoram and western Kunlun Mountains are very stable or even exhibited positive mass balance (Kääb et al., 2015~~Yao et al~~). ~~For example,~~ Kääb et al (2018) showed that ~~both~~ the two Aru glaciers experienced a slight ~~thickness increase~~mass gain of 0.2-0.3 m/yr water equivalent (w.e.) since the early 2000s, despite there ~~i~~was ~~slight~~ glacier retreat of 520-460 m. ~~(Kääb et al., 2018)~~This indicates that the glacier mass changes played a limited role in the rapid lake expansion of Memar Co since the 2000s~~was not mainly contributed by the glacier mass changes~~.

Treichler et al (2019) suggested that ~~both~~ the glacier thickening ~~on the western TP~~ and rapid lake growth on the western TP were mainly attributed to the stepwise increase in precipitation ~~in~~since the late 1990s. Dramatic increase in precipitation since the 2000s is visible from meteorological station data and reanalysis data (Lei et al., 2014; Treichler et al., 2019). This indicates that rapid lake expansion on the western TP, including Memar Co, ~~may~~~~cantaken~~ was a ~~a~~ response to climate change, especially climate wetting (Lei and Yang, 2017).

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5.2 Potential risk caused by lake expansion on the TP

~~DramaicWidespread lake expansion occurred was widely found for most closed lakes on the interior TP during the past two decades (e.g. Lei al., 2014).~~ Lake expansion on the interior TP inundated grassland and infrastructures (e.g. road and bridges) in the surrounding area, which not only led to enormous economic loss, but also serious ecological and environmental problems (Yao et al., 2010; Liu et al., 2019; Pei et al., 2019). For example, rapid lake expansion in the northern Tibet inundated a large area of grassland and destroyed infrastructures such as roads and bridges (Yao et al., 2011). A case study occurred in Hol Hil Nature Reserve, where a significant overflow suddenly occurred at Zhuonai Lake (255 km^2) in late August 2011 due to continuous expansion since the 2000s. The flood subsequently induced the overflow of Kusai Lake (260 km^2) and rapid expansion of the downstream lakes, Haidingnuoer Lake and Salt Lake (Yao et al., 2012; Liu et al., 2019). This sudden process was captured by ~~Cryosat~~CryoSat satellite, which shows that there was 12.6 m lake level drop at Zhuonai Lake after the outburst (Hwang et al., 2019; Li et al., 2019). The newly formed riverbanks caused by the outburst flood obstructed the traditional migration route of antelopes and had serious ramifications for antelope survival (Pei et al., 2019).
~~The rapid lake expansion of Memar Co ismay also lead to serious ecological problem no exception.~~ The ~~rapid~~continual lake expansion of Memar Co may further lead to its combination with Aru Co in near future, which ~~will~~will have significant impact on the regional geomorphology and ecosystem. In 2003, the surface elevation of Aru Co (4936.8 m a.s.l) was about 14 m higher than that of Memar Co (4923.2 m a.s.l), as indicated by ICESat satellite altimetry data. In 2014, CryoSat-2 data show that the elevation difference between the two lakes decreased to ~8 m due to continual lake expansion of Memar Co. After the glacier collapses, Memar Co expanded at an accelerated speed and the elevation difference became even smaller. In

October 2019, the surface elevation of Memar Co reached 4931.3 m a.s.l and the elevation difference between the two lakes decreased to only 5.5 m. According to the increasing rate of 0.5-0.8 m/yr between 2003 and 2019, the surface elevation of Memar Co could reach that of Aru Co in 7-11 years. ~~If Memar Co continued to expand as before, the surface elevation of Memar Co could reach that of Aru Co in 7-11 years.~~ According to the reconstructed relationship between lake area and lake level in section 4.4, when the lake level of Memar Co increases by 5 m, the lake area and water storage will increase by 10.6% and 0.65 Gt, relative to 2019.

As has been shown, Memar Co is a saline lake while Aru Co is a freshwater lake. If the two lakes are merged, lake salinity and ion composition will exchange freely. Memar Co will be diluted while Aru Co will be significantly salted. The habitat of the phytoplankton and zooplankton in the lake will also change significantly in response to changes in lake salinity and ion composition. Therefore, it is necessary to carry out comprehensive monitoring at Aru Co and Memar Co in the next years, including lake hydrology, meteorology, water quality and ecology, etc.

~~5~~6 Conclusions

The fragmented ice mass ~~from~~ of the Aru ~~ice avalanches~~glacier collapses on 17 July and 21 September 2016 had almost melted by September 2019. A comprehensive investigation of the two downstream lakes, the outflow lake Aru Co and the terminal lake Memar Co, was ~~carried out~~conducted since 2016, including meteorology, ice mass balance, lake bathymetry, lake level changes, etc. Based on in-situ observation and satellite data, how the two downstream lakes responded to the ice avalanches in the successive years (2016-2019) is evaluated in this study. ~~A comprehensive investigation of the two downstream lakes, the outflow lake Aru Co and the terminal lake Memar Co, was carried out since 2016, including meteorology, ice mass balance, lake bathymetry, lake level changes, etc.~~ ~~How~~ We found that the ice avalanches~~the two downstream lakes, Aru Co and Memar Co,~~ can significantly affect the two downstream lakes~~responded The impact of~~to at least in the following aspects~~the ice avalanches on the~~~~in the successive years (2016-2019) downstream lakes is evaluated in this study based on in-situ observation in combination with~~and ~~satellite data.~~: ~~The main conclusion is as the following:~~

~~Lake bathymetry shows that Aru Co and Memar Co have water storage of 17.9 ×10^8 m^3 and 34.9 ×10^8 m^3, respectively. Although the total volume of the two glacier collapses only accounts for ~8% of the water storage of Aru Co, it exert great impacts on the two downstream lakes in terms of lake bathymetry, water temperature and lake level.~~ After Aru-1 glacier collapses, ~~a large amount of~~the ~~-~~fragmented ice mass ~~debris was transported~~slid into Aru Co along with a large amount of ~~the~~debris ~~fragmented ice~~, which generated great surges at Aru Co and further modified the shoreline and bathymetry ~~near the glacier collapse fan~~. The Aru Co shoreline was pushed ~~inwards~~offshore about 100-120 m along the two sides of the first glacier collapse fan. Lake bathymetry near Aru-1 ice avalanche became much uneven, which is quite different from the adjacent areas. The intruding ice into Aru Co, with an area of ~0.89 km^2 and a volume of at least 7.1×10^6 m^3, melted in less than two months.

The spread of ~~intrud~~floating ice ~~soon spread~~ over the surface of Aru Co~~'s surface and~~ dramatically lowered lake surface temperature (LST) by 2-4 °C in the first 2 weeks after ~~the first~~Aru-1 glacier collapse. ~~The Aru Co shoreline was pushed inwards about 100-120 m along the two sides of the first glacier collapse fan. Lake surface temperature at Aru Co decreased significantly by 2-4 °C in the first two weeks after the first glacier collapse.~~ A similar condition also occurred at Memar Co, but its magnitude and duration were much less than that at Aru Co. The dramatic difference of lake surface temperature across Aru Co is investigated before and after Aru-1 glacier collapse. The ~~spatial patterns of lake surface temperature before and after the first glacier collapse shows that~~ lake surface temperature in summer 2016 ~~at the northern Aru Co~~ is dramatically lower at the northern Aru Co than that at the southern Aru Co ~~due to~~due to influence of meltwater ~~the floating ice over the surface of Aru Co~~. ~~The ice avalanches melting may also cause a considerable decrease in lake surface temperature at Aru Co in summer 2016, 2017 and 2018, but its impact on Memar Co was not obvious due to longer distance.~~

After the first glacier collapse (2016-2019), Memar Co ~~significantly deepened by 12.5 m between 2000 and 2018, with accelerated lake level increase after the glacier collapses. After the first glacier collapse, Memar Co~~ expanded more rapidly ~~at a rate of 0.80 m/yr, which is about 30% higher than the average rising rate between 2003 and 2014~~than before (2003-2014), characterized by much larger~~.~~ lake level increase in summer. Between 2016 and 2019, the ice avalanche melting contributed about 26.4% of the increase in lake storage at Memar Co. ~~This study implies that the two glacier collapses have significant impacts on the downstream lakes in the subsequent years.~~ If Memar Co continues to expand steadily, it~~s water level could reach as high as Aru Co~~ will combine with Aru Co in 7-11 years~~7-11 years~~, which could have significant impact on the regional geomorphology and ecosystem. This study also suggests the necessity for more comprehensive monitoring at Aru Co and Memar Co as significant changes may occur at the two lakes in the near future.

Author contribution

Lei Y., Yao T., Tian L., and Sheng Y. conceived and designed the experiments; Lei Y.B., Yao T., Tian L., Zhao H., Yang W., Zhu M., and Wu G. performed the fieldwork; Lei.Y., Yao T., Tian L., Sheng Y., Lazhu, Yang K., Berthier E., and Brun F. analyzed the data; Liao J., and Gao Y. processed the satellite data~~,~~; All the authors wrote the paper.

Competing interests

The authors declare that they have no conflict of interest.

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~~Zhou, J., Wang, L., Zhang Y., Guo, Y., Li, X., and Liu, W. Exploring the water storage changes in the largest lake (Selin Co) over the Tibetan Plateau during 2003–2012 from a basin-wide hydrological modeling. Water Resour. Res., 51, doi:10.1002/2014WR015846, 2015~~

~~**Table 1: Annual rainfall, ice avalanche melting and lake level increase at Memar Co between 2016 and 2019**~~

~~Duration~~	~~Rainfall (mm)~~	~~Ice avalanche melting (10^6 m^3)~~	~~Lake level increase at Memar Co (m)~~	~~Contribution of ice melting to lake expansion (%)~~
~~2016.8-2016.10~~	~~--~~	~~30.6~~	~~0.43~~	~~41.9%~~
~~2016.10-2017.9~~	~~420~~	~~63.9~~	~~1.07~~	~~34.3%~~
~~2017.10-2018.9~~	~~239~~	~~25.2~~	~~0.80~~	~~14.2%~~
~~2018.10-2019.9~~	~~342~~	~~18.2~~	~~0.69~~	~~10.3%~~

Table 1: Ice avalanche melting and its contribution to lake level increase at Memar Co between 2016 and 2019

Year/month	Meltdown (m)		Area (km^2)		Meltwater (10^6 m^3)		Total meltwater (10^6 m^3)	Contribution to lake level (%)
	Aru-1	Aru-2	Aru-1	Aru-2	Aru-1	Aru-2		
2016/07		9.31						
2016/10	2.84	8.58	33.5404		6.54		26.83232	36.7
2017/10	6.55	0	48	5.5	4.85	35.97	67.176	36.1
2018/10				5.5	2.98	21.5325	17.226	12.2
2019/10				5.5	1.9	13.42	10.736	8.8

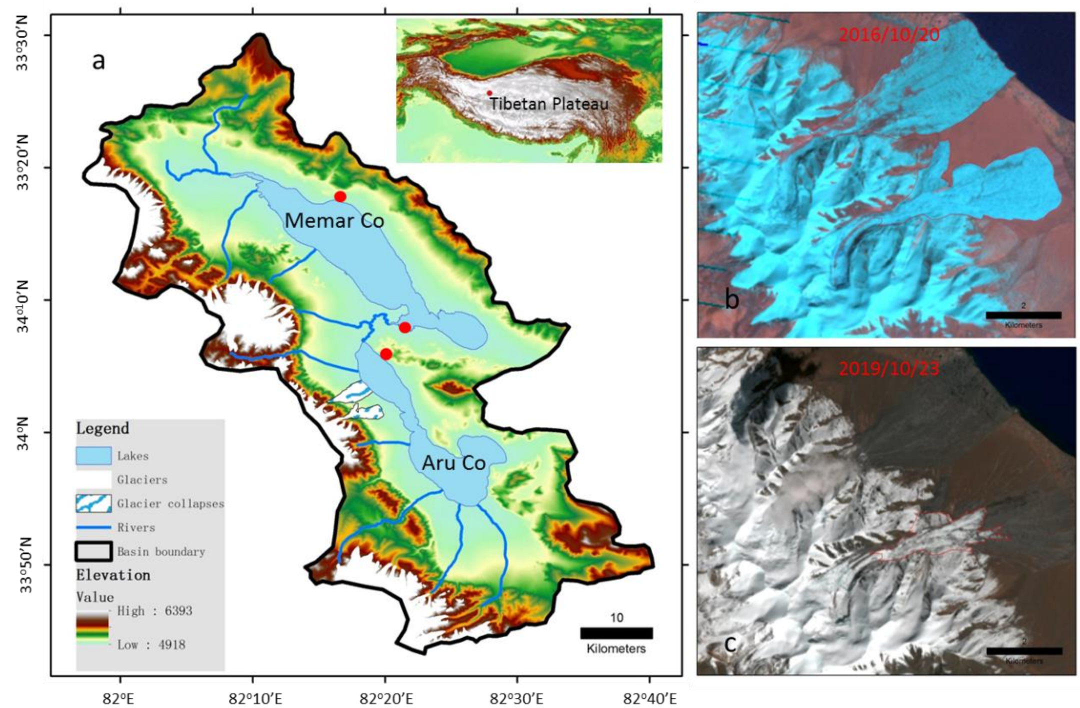


Figure 1: General description of the study area (a) and Landsat satellite images of the two glacier collapses on 20 October, 2016 (b) and 23 October, 2019 (c). The red dots denote the locations of lake level monitoring at Aru Co and Memar Co.

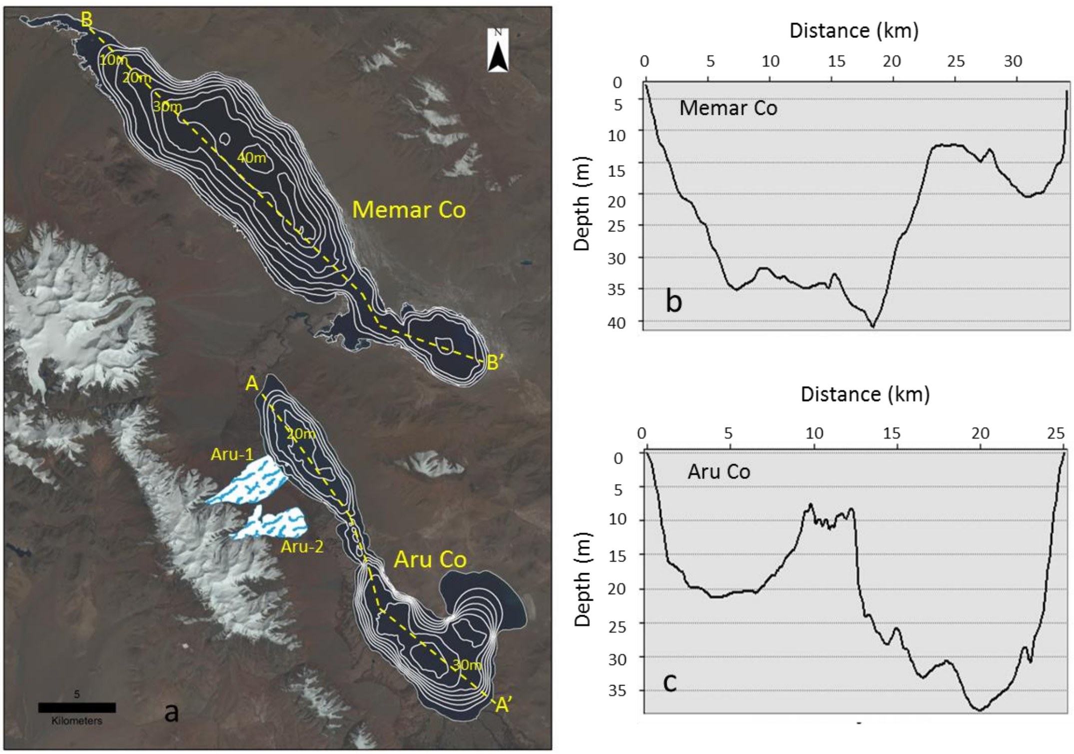


Figure 2: The 5 m interval isobaths (a) and the water depth profiles (b, c) on NW-SE direction (the yellow dashed lines) at Aru Co and Memar Co. Landsat satellite image (a) is used to indicate the location of the lakes and glacier collapses.

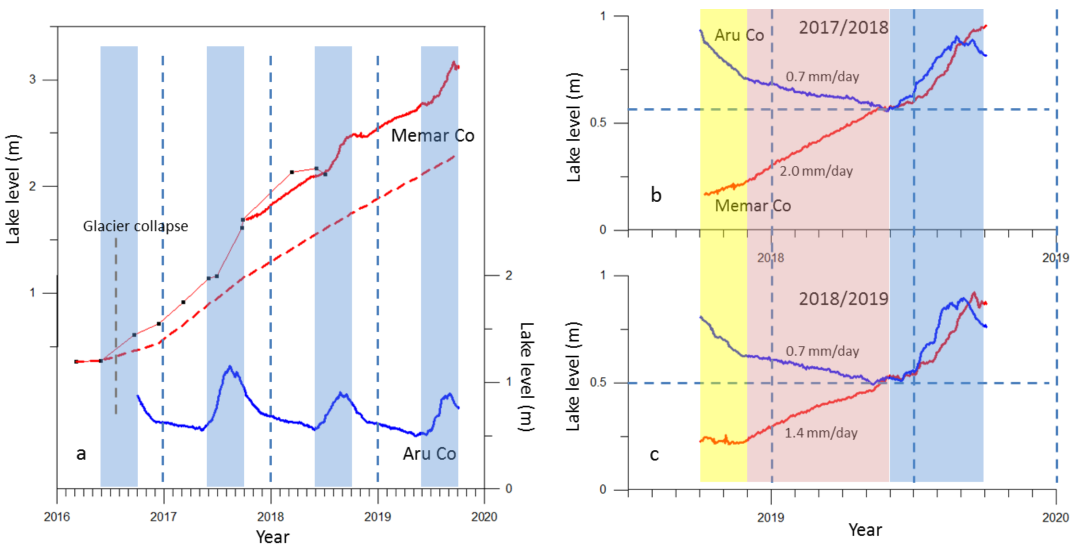


Figure 3: In-situ lake level observations at Aru Co (blue line) and Memar Co (red line) between 2016 and 2019. ~~(~~a~~:)~~ A comparison of lake level changes between 2016 and 2019. ~~and~~ b, c: ~~c~~Comparisons of lake level changes at the two lakes ~~at the two lakes (b, c)~~in 2017/2018 and 2018/2019. The dashed red line ~~(~~(a)~~)~~ indicates lake level changes at Memar Co without the fragmented ice melting. The black dots ~~in~~ (a) represents lake level derived from ~~Cryosat~~CryoSat-2 altimetry data. The coloured strips in b and c indicate different periods of lake level changes in a year, namely post monsoon season, ice covered season and monsoon season.

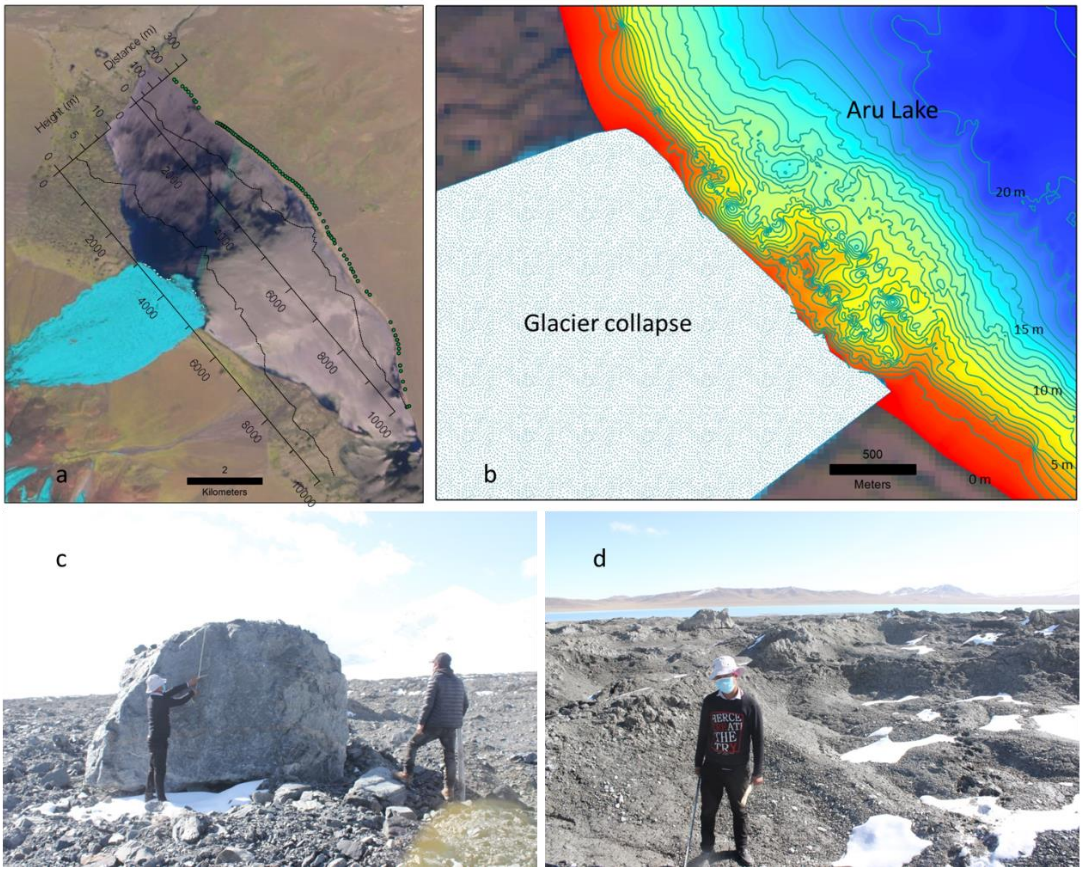
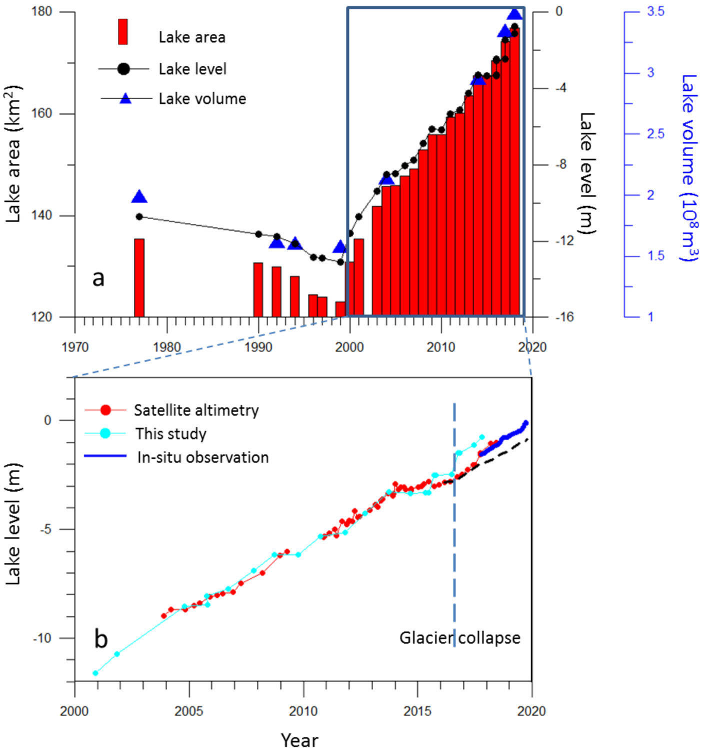


Figure 4: The impact of Aru glacier collapse on Aru Co. a: The extent of the first glacier collapse (~~Sential~~Sentinel-2 image on 21 July, 2016) and the impact wave at the opposite shore of Aru Co (green dots). b: The uneven lake bathymetry at Aru Co near the first glacier collapse. c, d: A large amount of debris left after the fragmented ice mass melting (photos taken on 3 October, 2019 by Yanbin Lei).



Lake area
Lake level
Lake volume
Lake area (km²)
Lake level (m)
Lake volume (10⁸ m³)
a
180
160
140
120
0
-4
-8
-12
-16
3.5
3
2.5
2
1.5
1
1970
1980
1990
2000
2010
2020
Satellite altimetry
This study
In-situ observation
Lake level (m)
b
Glacier collapse
0
-5
-10
2000
2005
2010
2015
2020
Year

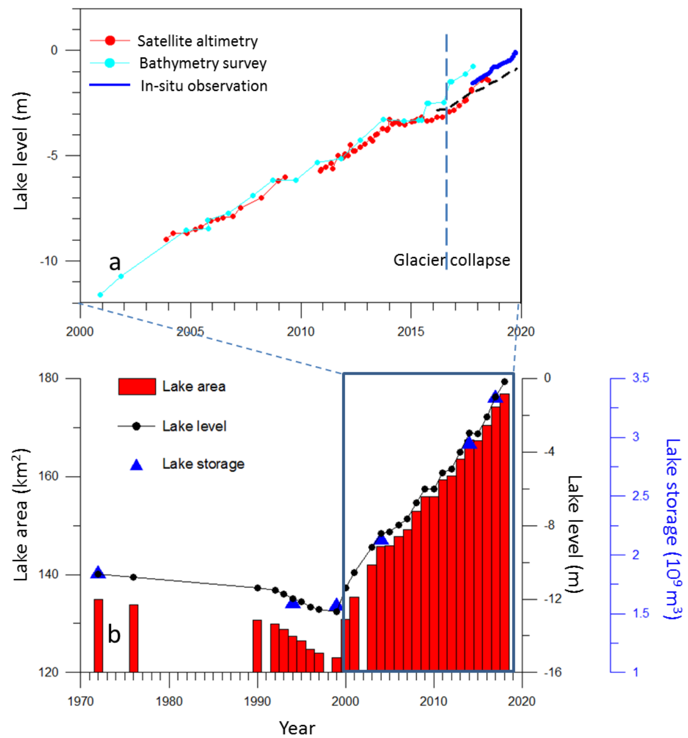


Figure 5: Lake dynamics of Memar Co between 1976 and 2018. a: Changes in lake area~~ and~~, water level and water storage of Memar Co between 1976 and 2018~~ (a),~~. ~~and~~ b: ~~a~~ A comparison of reconstructed lake level changes in this study (blue cycles) ~~derived from~~with satellite altimetry data (red cycles) ~~(b)~~. The dashed line in (b) indicates lake level changes without the ~~fragmented~~ ice avalanche melting.

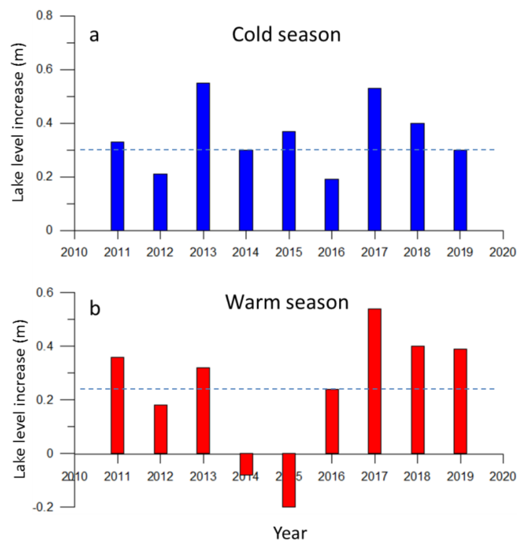


Figure 6: Seasonal ~~L~~lake level changes at Memar Co derived CryoSat-2 satellite altimetry data ~~and Aru Co in the cold (a) and warm (b) seasons~~ between 2011 and 2019. a: Cold season (Nov. to Jun.). b: Warm season (Jun. to Oct.).

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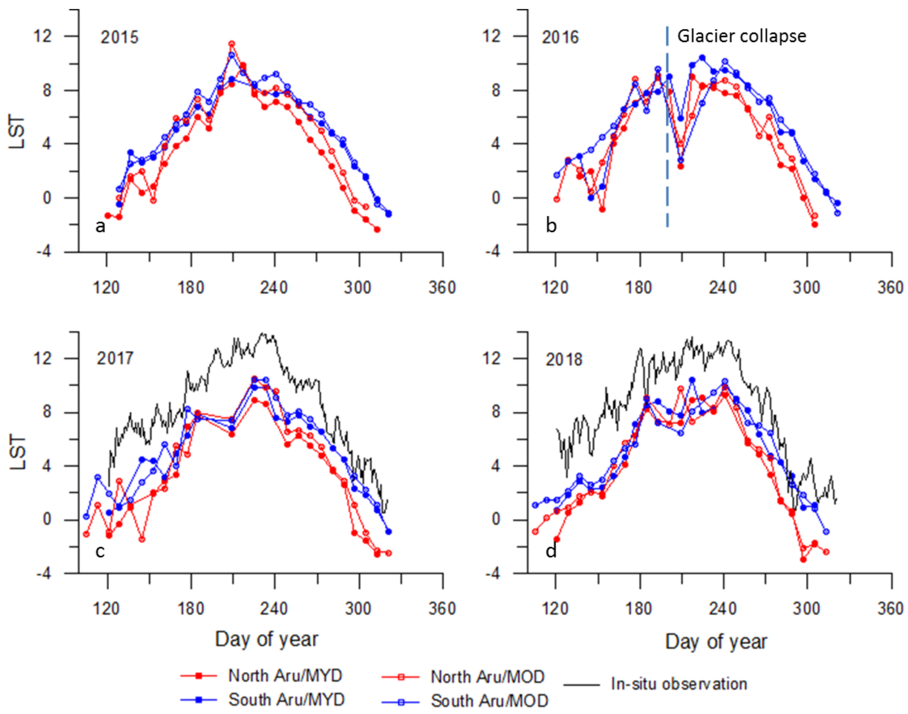

Figure 7: Time series of lake surface temperature (LST) derived from MYD11A2 (solid cycles) and MOD11A2 (hollow cycles) at the northern (red cycles) and southern Aru Co (blue cycles) between 2015 and 2018. The thin line represents in-situ lake water temperature at the shoreline. The dashed line in 2016 is the time of the first glacier collapse.

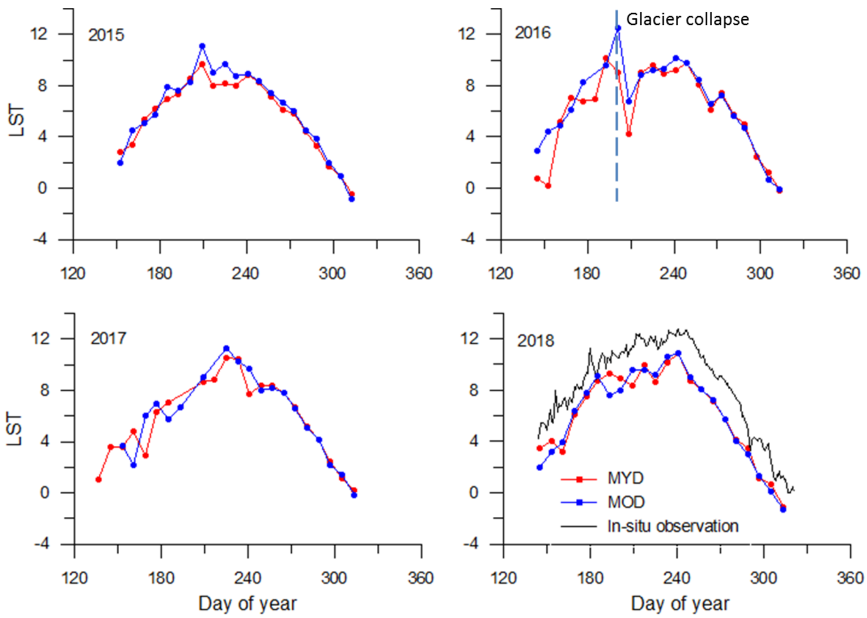

Figure 8: Time series of lake surface temperature (LST) derived from MYD11A2 (red cycles) and MOD11A2 (blue cycles) at Memar Co between 2015 and 2018. The thin line represents in-situ lake water temperature at the shoreline. The dashed line in 2016 is the time of the first glacier collapse.

Reply to reviewer #1

In its present form the paper lacks however clarity in language, structure and explanations, which make it difficult to follow the findings presented. The purpose of the study should be explained better and the results presented accordingly. As now, for some of the results it is unclear how they tie into the investigation of the collapse consequences. I recommend that at least the senior co-authors carefully revise the manuscript to make it clearer. This recommendation refers not only to language editing, but more important to the explanations given, precise language usage, and logical structure of presentation of results.

Reply: Thank you very much for the constructive comments and suggestions. The language, structure and explanations have been carefully revised according to these comments.
For the structure of the paper, we have made substantial revisions as following:
1, Add a new Section 4.3, which mainly focuses on the meltwater estimation of the two ice avalanches. The meltwater is mainly estimated by area of the ice mass and in-situ measurement of glacier mass balance (Tab. 1). This estimation is further validated by elevation changes of the two ice avalanches (Section 4.3).
2, Add a new Section 4.4, which mainly focuses on the impact of the meltwater on the seasonal lake level changes at Memar Co. Lake level seasonality and the hydraulic connection are moved to this part.
3, Add a discussion section (Section 5), which focuses on the response of the rapid lake expansion on the western TP to climate change and the potential risk of natural hazard on the TP.

For the purpose of the study, we have addressed it in more detail in the introduction (line 47-59). Although the mechanism of Aru glacier collapses has been investigated, its impact on the downstream lakes in the subsequent years (2016-2019) has still not been investigated until now. Based on comprehensive in-situ observations and satellite data, we investigate its impact of the two glacier collapses on the downstream lakes in the subsequent years when most of the ice mass has melted. This study not only provides us unique evidence of the impact of a large amount of glacier melting on the downstream lakes, but also helps to improve our understanding the relationship between glacier mass loss and lake behavior on the TP under a warming climate.

For the explanation of the result, we have added further discussion in the revision. For example, we added two new figures in the revision. One (Fig. 4) is about the dynamics of the intruding ice into Aru Co. High resolution (1 m resolution) GF-2 satellite image is used to detect the extent of the intruding ice and the floating ice over the lake surface. The dynamics of the intruding ice into Aru Co in summer 2016 is shown in this figure. The other (Fig. 10) is about the spatial distribution of lake surface temperature before and after the glacier collapses.

The paper lacks a discussion section and some discussions seem to be part of the results section. The authors should clearly separate results and their discussion/interpretation. Uncertainties in the results are hardly mentioned.

Reply: A discussion section (Section 5) has been added in the revision. In this new section, we mainly discuss the response of the rapid lake expansion on the western TP to climate change and the potential risk of natural hazard on the TP.

Uncertainties of lake level changes, water storage and lake surface temperature are evaluated in the revision as well (Line 104, 150, Line 161).

The abstract and intro most urgently need revision of language. As an example (line 39), not the Aru glaciers are giant, but their collapses! Professional language editing will likely not capture such errors. Another example, the authors say the shoreline was pushed. Did the avalanche really move the shoreline? Or did the shoreline change due to deposition of sediments? Or (line 340), does "rapid lake expansion of 0.8m/yr" refer to the lake level increase or lateral expansion of lake area? Another example for lack of clarity: in line 48 the authors talk about lake increase due to glacier melt. A few lines later (53) they write about drastic precipitation changes as cause behind lake growth.

Reply: Thanks for pointing out these errors. We have carefully revised the abstract and make it more accurate.

Part of the third paragraph in the introduction is moved to discussion section (Section 5.2) in the revision.

Section 3.4: To my best knowledge, the most extensive study on lake volume changes in Tibet is Treichler et al. 2018 (https://tc.copernicus.org/articles/13/2977/2019/). The authors could compare their findings for Memar Co to the regional aggregations by Treichler et al.

Reply: Thanks for the good suggestions. In the discussion section, we now use the main result of Treichler et al. 2018 as the background of lake expansion on the western TP and discuss glacier-lake interaction in Memar Co basin.

Section 3.5: Any uncertainties behind the MODIS temperatures? For instance bias from undetected clouds, or lake ice?

Reply: We agree that MODIS derived lake surface temperature is easily affected by clouds and other factors, especially in summer. We evaluate the uncertainties of MODIS derived temperature in the method section (Line 161).

At line 161 the lake seasonality after 2016 is presented, but it would be important to relate that to seasonality before the collapses. This is then touched upon much later.

Reply: We added a new section (Section 4.4) about the impact of glacier collapses on lake level seasonality. Lake level seasonality before (2011-2015) and after (2016-2019) the glacier collapses is compared according to Cryosat-2 satellite data and in-situ measurement.

At several occasions the authors classify the changes as "drastic" or "dramatic", for instance the 2-week lake surface cooling by 2-4 deg (line 289). Why is such change, or the other changes dramatic?

Reply: Thanks for the good suggestion. We agree that using ‘drastic’ or ‘dramatic’ in some places are not accurate. We have deleted or replaced some of them in the revision.

Fig 3: what is the meaning of the colored areas in panels b and c?

Reply: The three different colors in figure 3 indicate monsoon season, post monsoon season and ice covered season. We have addressed this now in the caption of the figure.

The lines in Figs 7 and 8 are difficult to compare. Better have the lines for each year combined in one plot per area? I.e. not separate plots per year but per area.

Reply: Thanks again. We have changed this figure according to the suggestion.

Reply to reviewer #2

The purpose of the study is more like two downstream lakes observation after Aru glacier collapses events. Hence, I would suggest change the title as "How two downstream lakes responding to Aru glacier collapses and their changes based on in-situ and Remote sensing data " or others.

Reply: Thanks for the good suggestion. Following your suggestions, the title of the paper is revised as 'Response of downstream lakes to Aru glacier collapses on the Tibetan Plateau'.

From the abstract, I got the information that the glacier collapses have two impacts on two lakes, that is, short-term (LST and lake level) and long-term impacts (Lake level and others). So, I would suggest authors refine the rules and results.

Reply: Thanks for the suggestion. We have revised the abstract carefully according to this time line.

Specific comments:

Line 80 Aru co is : : here I would suggest add a sentence "Memar co and Aru Co are lagoons" then, "Aru co is : : :."

Reply: Thanks for the suggestion. We have revised this sentence according to this suggestion (line 78-79).

Line125 here, authors should give the methods how to get lake level changes and how to calculate the uncertainty of lake level changes.

Reply: We have addressed the method about lake level reconstruction in more detail in the revision (Line 143-153). The uncertainty of past lake level changes is also estimated (Line 150)

Line 130 The important feature of 2 degree decrease after collapse was success to be caught by using MODIS 8-days. And I also understood that it may be difficult to express the temperature field due to resolution (1km). But it is useful to compare between the records from AWS during Oct 2016 and Sep 2019 and LST.

Reply: Thanks for the good suggestion. We added a new Fig. 10 about the spatial distribution of lake surface temperature in the revision. We agree that it is difficult to express the temperature field because Aru Co is very narrow and long. There are no valid data in the central part of Aru Co.

We included a comparison between MODIS LST at Aru Co and air temperature from AWS in 2017 and 2018 in the revision (Fig. S5). Daily air temperature had larger fluctuation than water temperature and was always higher than lake surface temperature at Aru Co.

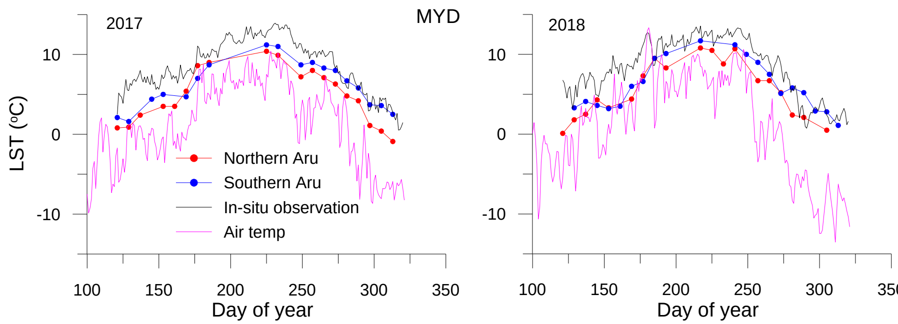

Fig. S5: Comparison of MODIS derived lake surface temperature with in-situ measurement at the shoreline and daily air temperature from AWS station.

Line 145 here, Authors can mark where is norther basin, south basin and center part of Aru Co/Memar Co in figure 1.

Reply: Thanks for the good suggestion. We have shown this in Figure 1.

Line 175 did you want to express that the water level of Aru Co was controlled by climate change and the water level of Memar Co was controlled by climate change in summer and ground water in winter?

Reply: Yes, we have addressed this more clearly in the revision (Line 266-272).

Line 180 did you want to express that the Aru co has a hydraulic connection with Memar Co. And the time lag was about half a month?

Reply: Yes, it should be hydraulic connection and we have revised this sentence in the revision (Line 266). From the seasonal pattern of lake level changes at the two lakes, there is about half a month lag.

Line 191 Sential 2->sentinel 2

Reply: Thanks for pointing out this error.

Line 208 section 4.3 this lake level and lake expansion are chaotic. It should be clear.

Reply: Thanks for the suggestion. The former Section 4.3 is now divided into three sections in the revision:

- Section 4.3, The meltwater estimation of the two ice avalanches;
- Section 4.4, The impact of the meltwater on the seasonal lake level changes of Memar Co;
- Section 4.5, The impact of the meltwater on the inter-annual lake level changes of Memar Co.

Line 230 "In 2016" could be omitted.

Reply: Thanks for pointing out this error. We have revised it (Line 223).

Line 261. I agree on your opinion that after collapse, the lake level increase in warm season rapidly. Did you have any evidence from glacier ablation observations

Reply: Meltwater from the two ice avalanches is estimated according to ice avalanche area and changes in ice thickness (Section 4.3). In-situ observation of thickness change was conducted in the first two years (2016 and 2017). Meltwater from the avalanche deposits is constrained using examination of satellite images and differencing of digital elevation models (DEMs). The contribution of meltwater to seasonal lake level change is further quantified (Line 279-281).

Line 270 the lake skin temperature? Water body temperature? Freeze up-?ice on is "Break up" melt on or melted?

Reply: Lake skin temperature derived from MODIS data is usually considered to be different from water body temperature. Lake skin temperature is the water temperature of the uppermost 10-20 μm deep molecular layer while water body temperature is water temperature of several cm to <1 m.

Yes, freeze up means that lake surface is covered by ice and break up means that lake ice melts.

Reply to reviewer #3

General comments: After reading the manuscript, I feel that the title is a bit too specific and does not contain what has been done in this work. I suggest rephrasing the title.

Reply: Thank you very much for the constructive comments and suggestions. We have revised the manuscript carefully according to these comments.

About the title, we change it as 'Response of downstream lakes to Aru glacier collapses on the Tibetan Plateau'

The hydrological connection is very interesting in my point of view. However, the reasoning of the buffering effect of the Aru Co on the Memar Co is not very convincing. L175, "discharge from Aru Co only accounted for 20-30% of the lake volume increase at Memar Co in the cold season". How is this conclusion made? Simply assume that the decline in water level completely attributes to outflow? From Lei et al. (2019 GRL), it seems the seasonality of 0.5 m is reasonable for endorheic lakes in the same region. It could be also possible for the Aru Co presenting a 0.5 m annual fluctuation without outflow. Outflow may happen in summer when the recharge is larger. But in cold season, whether outflow happens is questionable. It simply depends on the elevations of the Aru Co and the channel connecting the two lakes. So it needs to be careful when calculating the contribution of outflow of the Aru Co to the rising of the Memar Co by simply comparing the decline of the Aru Co and rising of the Memar Co.

Reply: Thanks for the comment. The hydraulic connection between the two lakes is investigated by comparing the seasonal lake level changes at Aru Co and Memar Co. 'Lake level at Aru Co started to increase rapidly in early July, which was about half a month earlier than that at Memar Co. Meanwhile, the end of the rapid lake level increase at Aru Co was also about half a month earlier than that at Memar Co. The time lag of seasonal lake level changes at the two lakes indicates the buffering effect of Aru Co as an outflow lake. A large amount of water was stored in Aru Co in summer, and released to Memar Co in autumn. In early September, lake level at Aru Co decreased by about 10 cm, accounting for about 90% of the lake volume increase at Memar Co. This indicates that Aru Co, as an outflow lake, plays a significant role in regulating the water balance of Memar Co.'

As shown in the main text (Line 251-252), the two lakes are covered by lake ice between December and May. During the ice covered period, lake level of Aru Co decreased slightly while Memar Co increased dramatically. The decrease in lake storage at Aru Co only accounted for 20-30% of the lake volume increase at Memar Co during this period, so we believe that the lake surplus at Memar Co is not mainly contributed by the discharge from Aru Co. It is true that the seasonal lake level fluctuation is in a range of 0.5 m and we agree that it is questionable to compare the decline of the Aru Co and rising of the Memar Co when the lake does not freeze up.

Another concern is the altimetry data processing, which affects the reconstruction of historical lake levels. Current methodological description is very vague. What are the data sources? How is the water level generated? How is the bias between the two data sets handled? The results relating elevation changes are heavily dependent on the bias of the two data sets.

Reply: Thanks for the good suggestion. We have addressed altimetry data processing in more detail in the revision (Line 121-132). 'ICESat altimetry data was processed after Li et al (2014) and was used to examine water level variations between 2003 and 2009. CryoSat-2 data was processed after Xue et al (2018) and was used to investigate water level variations between 2010 and 2018. Both lakes were observed by ICESat satellite twice or three times a year (Phan et al., 2012), and by CryoSat-2 satellite every two or three months (Kleinherenbrink et al., 2015; Jiang et al., 2017). Notably, the two datasets are referenced to different ellipsoids and geoid height. The ICESat data contains corrected surface ellipsoidal heights referenced to TOPEX/Poseidon ellipsoid and geoid height referenced to Earth Gravity Model (EGM) 2008; while the CryoSat-2 data are referenced to WGS84 and EGM96 (Song et al., 2015). In order to make the two datasets comparable, lake elevation at Aru Co is compared because the lake is an outflow lake and inter-annual lake level changes are relatively small. At Aru Co, the lowest lake level in May is very stable from year to year as it is controlled by the elevation of the outlet. The ICESat and CryoSat-2 derived lake surface elevations of Aru Co were averaged to be 4936.67 m a.s.l. in April (n=2) during the period 2003-2009 and 4937.04 m a.s.l. in May (n=5) during the period 2011-2016, respectively. The small elevation difference of 0.37 m is considered to be the bias of the two datasets and used to correct satellite altimetry data.'

Specific comments: L21: "collapsed suddenly" suddenly is not necessary, I think.

Reply: We have deleted it in the revision.

L52: "dramatic increase", I do not think there is a dramatic increase in precipitation. Before 2014, the increasing of precipitation is not significant, and a plethora of studies debated the reason of lake expansion. Until recent years, the increasing of precipitation is much clear but not dramatic.

Reply: Thanks for the suggestion. 'Dramatic' is not accurate some places, so we replaced it with other words or deleted it in the revision.

The response of lake expansion to climate change is discussed in a new section (Section 5.1) because it is not closely related to the subject of this study. Yes, precipitation on the TP exhibited significant spatial difference and different precipitation dataset shows quite large difference. This is mainly due to lack of in situ measurement. On the interior TP, precipitation data is only available at several stations and exhibits large inter-annual fluctuations. It should be noted that lake can expand when precipitation is higher than the equilibrium value, so lake expansion does not need continual increase in precipitation. Generally, the precipitation was above average value on the interior TP after the late 1990s, so we can find that most lakes expanded rapidly during the past 20 years.

L65-69: Do you think the bathymetry have significant change?

Reply: The ice avalanches can influence lake bathymetry of Aru Co near the collapse fan, not the whole lake (Section 4.2).

L90: How was the snow measured?

Reply: The snow is measured by a T200B rain gauge (Line 87).

L177-178: This sentence is not clear to me. Please rephrase it.

Reply: Thanks, we have rephrased it in the revision (Line 264-265).

L191: "Sential" -> "Sentinel", please also change it in the caption of Figure 4.

Reply: Thanks for pointing out this error. We have revised it in the revision.

L192: Figure 3a should be Figure 4a.

Reply: Thanks for pointing out this. We have rephrased this sentence in the revision.

L209-214: How many pairs of level and area are used to build this regression model? Extrapolation based on data of six years could be problematic. This needs to be better explained.

Reply: In this study, six pairs of lake level and area are used, including 1972, 1994, 1999, 2004, 2014 and 2018. Since these data contains the lowest (~1997) and highest (2018) lake area and water level, we believed the regression model used in this study is reliable.

L217-218: It seems that the satellite data did not capture the sudden rise (pink dotted line) revealed in Figure 5b. Is the pink coded line indicating the reconstruction?

Reply: The pink dotted line is the satellite altimetry data. The dramatic increase of lake level change occurred during the whole period between 2016 and 2019. To be honest, the sudden rise in lake level at Memar Co shortly after the Aru-1 collapse can not be captured by CryoSat satellite data due to its temporal resolution.

L256-257: The seasonality revealed by satellite data is not very clear due to the course temporal resolution.

Reply: We agree with this. Because Memar Co also expanded rapidly before the glacier collapse, the lake level seasonality revealed by Cryosat-2 data did not exhibit big difference before and after the collapse. However, if we compare the average values between the two periods, we can find the considerable difference of lake level change in summer.

Conclusion: I would suggest the authors try to concise the conclusions, right now too many repetitive statements from the results.

Reply: Thanks, we have rephrased the conclusion carefully.

Reply to the Short Comment

(1) The organization of the Results part should be adjusted to focus on the evaluation of the glacier collapse influences. In Section 4.1, the description of Aru Co, Memar Co, and their hydrological connection can be moved to the part of the Study area.

Reply: Thank you very much for the constructive comments and suggestions. We re-organize the structure of the paper in the revision. Lake level seasonality and the hydraulic connection are moved to section 4.4, which is about the impact of the meltwater on the seasonal lake level changes of Memar Co. We do not move lake bathymetry and water storage at the two lakes to study area section because they belong to part of the result in this study. If we move them to the study area, readers may have question about how these results come from.

(2) In Section 4.4, the impact of glacier collapses and meltwater on surface temperature of two downstream lakes were analyzed. From the LST time series, it can be clearly observed that several degrees of temperature difference occurred before and after the collapse. It can be inferred that the LST differences may be revealed in the spatial pattern of MODIS-derived temperature image varying with the distance from the ice mass input place. It is thus suggested to add the maps showing the spatial pattern of LST effect responding to the glacier collapse.

Response: Thanks for the good suggestion. We add a new figure 10 in the revision about the spatial pattern of lake surface temperature (LST). The spatial patterns of LST before (11 July) and after (19 and 27 July) the first glacier collapse are investigated in Section 4.6. Before the first glacier collapse, the spatial pattern of lake surface temperature on 11 July 2016 is investigated based on MYD11A2 data. After the first glacier collapse, the spatial patterns of lake surface temperature on July 19th and 27th, 2016 are investigated. Because Aru Co is narrow (1.4 to 9 km) and only lake pixels beyond 1 km from shoreline were extracted, there was no valid data in the central part of Aru Co.

The spatial pattern of LST shows that the northern Aru Co was considerably cooler than the southern Aru Co after the glacier collapse (19 and 27 July 2016), which is in contrast with that before the glacier collapse (11 July 2016). This is because the ice avalanche was closer to the northern Aru Co. Similar pattern also occurred in Memar Co, where lake surface temperature increased from south to north. This spatial pattern may also indicate that the floating ice from the first ice avalanche also influenced the lake surface temperature of Memar Co through the 5 km long river (10~20 m wide) linking the two lakes.

(3) The estimation of the collapsed glacier contribution on the lake water storage increase assumes that all of the collapsed ice mass eventually entered the downstream lakes in the form of meltwater supply. However, the glacier melting in other forms, e.g., evaporation, may need to be discussed.

Reply: Thanks for the suggestion. In this study, we assume all the meltwater from the collapsed glaciers entered the downstream lakes. According to in-situ observation by Li et al. (2019), sublimation and/or evaporation at Guliya ice cap on the western TP were estimated to be 0.12 m in the year 2015/2016. Sublimation and evaporation is relatively small and negligible compared with the rapid melting of the avalanche deposit. Meanwhile, the two glacier collapses are very close to Aru Co. Therefore, we do not consider evaporation or other kinds of water loss in this study (Line 227-228).

Li, S., Yao, T., Yu, W., Yang, W., Zhu, M.: Energy and mass balance characteristics of the Guliya ice cap in the West Kunlun Mountains, Tibetan Plateau. Cold Reg. Sci. Technol., 159, 71–85, 2019.