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Tracking the impacts of the Aru glacier collapses on downstream lakes

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Abstract Two giant glaciers at the Aru range, western Tibetan Plateau, collapsed suddenly on 17 July and 21 September 2016, respectively, causing fatal damage to local people and their livestock. The ice avalanches, with a total volume of 150×10^6 m^3, had almost melted by September 2019. Based on in-situ observation, bathymetry survey and satellite data, here we show the impacts of the two 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 significantly modified the lake's shoreline and bathymetry. 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. 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 implies that the Aru glacier collapses had long-term and dramatic impacts on the downstream lakes.

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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; 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. Two giant glaciers at the Aru range, collapsed suddenly on 17 July and 21 September 2016, leading to fatal damage to local people and their livestock. 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).

The two ice avalanches influenced the downstream lakes at least in two ways. First, 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 in subsequent years. Secondly, the ice avalanches could have impact on lake water temperature through 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 (Lei et al., 2012; Song et al., 2015; Tong et al., 2015; Li et al., 2017; Zhou et al., 2017, 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.

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 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 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 first glacier collapse and one week after the second glacier collapse, we conducted a field campaign and installed instruments to monitor lake level changes at 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

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monitoring has been established near the two glacier collapses. In this study, the impact of the two glacier collapses on the downstream lakes is investigated. We first investigate characteristics of lake bathymetry and lake level changes at both lakes and then analyze the impact of the two glacier collapses on the downstream lakes, the outflow Aru Co and the terminal Memar Co, in terms of lake bathymetry, lake water temperature and lake level changes.

2 General description of the 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 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 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 at the first glacier collapse showed that the depth of the collapsed ice 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 their volumes 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 downstream of the two glacier collapses (Fig. 1). 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 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<<

3 Study method

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, lake water depth of the shoreline in 1994 was reconstructed and used to calculate the lake isobaths.

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-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 satellite images between September and November, 1977 to 2018, were selected. Before 1990, only one image (1977) was 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).

3.4 Long-term lake level reconstruction

Lake level variations before 2003 were determined based on the current water depths and the position of past shorelines (Lei et al., 2012). In this study, lake level changes in 1994, 1997, 1999, 2004 and 2014 relative to October 2018 were reconstructed. We used as many as bathymetry lines to reconstruct past lake level changes. Uncertainty of lake level changes is estimated using the standard deviation of all the reconstructed lake levels. For Memar Co, the relationship between lake area and reconstructed lake levels was developed using a linear regression model. Continual lake level changes 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. 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. MODIS lake surface temperature data are 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 (Fig. S3). At Aru Co, lake surface temperature at the southern half (29 pixels) and northern half (7 pixels) of the lake was extracted. 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 datasets. To confirm the reliability of MODIS products, nighttime lake surface temperature was compared with in-situ observation at the shoreline.

4 Results

4.1 Lake bathymetry and seasonal lake level changes 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<<

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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.

Seasonal lake level changes at both lakes and their hydrological connections are investigated through in-situ observations and satellite altimetry data between 2016 and 2019. Aru Co exhibited dramatic seasonal fluctuations with the lowest lake level in late May and the highest in late August (Fig. 3). Its lake level increased dramatically by 30-50 cm between June and August in response to the relatively high summer rainfall and glacier runoff. After the end of monsoon rainfall, the lake level decreased considerably by 20-30 cm due to river discharge and lake evaporation between September and October. When Aru Co is frozen between November and the following April, the lake level exhibited a slight drop by 10-15 cm. After the lake ice broke up in early May, the lake level continued to decrease slightly due to very limited runoff and low evaporation.

>>Fig. 3<<

Compared to Aru Co, the lake level at Memar Co did not exhibit clear seasonality. 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). 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 during this period. Notably, discharge from Aru Co only accounted for 20-30% of the lake volume increase at Memar Co in the cold season, indicating that the significant lake water surplus at Memar Co was mainly contributed by other sources of groundwater discharge. The in-situ observation of seasonal lake level changes at Memar Co confirms the unique lake level seasonality on the western Tibetan Plateau, which is derived from Cryosat-2 data (Lei et al., 2017).

The hydrological connection 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 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 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.

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4.2 Impact of the first glacier collapse on the morphology of Aru Co

After the first glacier collapse, part of the fragmented ice slid rapidly into Aru Co at a speed of 30-40 m/s and generated great wave impact at Aru Co, 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 Aru Co, which extended up to 240 m inland and 9 m above the lake level along 10 km long shoreline distance (Fig. 4a).

A Sential-2 satellite image acquired on July 21, 2016 indicated that about 0.89 km^2 of ice intruded into Aru Co. The shoreline of Aru Co was pushed eastward ~400 m on average (Fig. 3a). Bathymetry survey in July 2017 showed that water depth at the margin of the intruding ice into Aru Co was about 8 m, indicating that it was the least thickness of the ice mass into the lake as the intruding ice are obviously higher than the lake surface. Therefore, 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 volume of the first glacier collapse. Comparison with Landsat image on 20th September, 2016 shows that most of the ice mass into Aru Co melted in two months.

We conducted a detailed bathymetry survey near the first glacier collapse fan. Due to a large amount of debris input along with the fragmented ice mass, the lake bathymetry was largely modified. Fig. 4 shows that the uneven bathymetry near the glacier collapse fan is quite different from the adjacent areas, 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.

>>Fig. 4<<

The deposit of the first glacier collapse fan was investigated in October 2019 when the fragmented ice mass had completely melted. We found that the original road was no longer accessible because the glacier collapse fan was covered by a large amount of debris with a thickness of 0.2-1.0 m. Boulders were found even near the lake shoreline (Fig. 4d). The uneven land surface explains well why the lake bottom became uneven. Due to the large amount of debris input, the shoreline at the northern and southern sides of the glacier collapse fan was pushed eastward for about 100-120 m. This indicates that the debris of first glacier collapse significantly modified the land surface and the lake bathymetry of Aru Co.

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

Lake level changes of Memar Co were investigated through ICSESat and Cryosat-2 satellite altimetry data between 2003 and 2018. We further extended the long-term lake level changes to 1977 according to the bathymetry survey and past shorelines (Lei et al., 2013). The results showed that the lake level of Memar Co was 9.4±0.6 m, 12.3±0.3 m, 12.5±0.3 m, 8.3±0.3 m, 3.1±0.3 m lower in 1977, 1994, 1999, 2004 and 2014 relative to October 2018. According to the lake area and the corresponding water level in the six years, the relationship between lake area and water level was developed by using 2-order polynomial regression (R^2=0.9881):

$$y = -0.0302 \times x^2 + 3.7702 \times x + 177.55$$

Here, y is lake area (km^2), and x is lake water level (m). Using this relationship, long-term lake level changes since the 1970s were reconstructed according to the corresponding lake area (Fig. 5). To validate the results, we compare the reconstructed

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lake level changes with ICSESat and Cryosat-2 satellite altimetry data. Fig. 5a shows that there is a good correspondence between the two datasets, indicating our reconstructed lake level changes at Memar Co are reliable.

>>Fig.5<<

According to lake area and water level changes, lake dynamics of Memar Co during the past 40 years were quantified and divided into two distinct periods. Between 1977 and 1999, Memar Co exhibited gradual shrinkage with lake level decrease of 3.1 m. Since 2000, Memar Co experienced dramatic expansion with lake level increase of 12.5 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), which led to the significant lake expansion (Yang et al., 2014; Zhou et al., 2015). Between 1977 and 2018, lake level and water storage of Memar Co increased by 9.4 m and 1.5 Gt (from 1.99 to 3.49 Gt), respectively.

Fieldwork showed that the fragmented ice mass has almost melted by October 2019 (only less than 0.5 km^2 remained from the second ice avalanche). It is difficult to directly quantify the amount of ice melting every year because it was controlled by many factors. Here we made a rough estimation according to in-situ measurements of ice mass balance in the first two years. In 2016, in-situ measurements at 9 sites show that the ice mass thinned about 2.84 m on average between August 13th 2016 and Oct 24th 2016, which corresponded to about 30.6×10^6 m^3 of meltwater (assuming the ice density of 900 kg/m^3). The largest melting of the fragmented ice mass occurred in 2017. According to Landsat satellite images and in-situ observation, most of the first ice avalanche had melted by October 2017. 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, which corresponds to 63.9×10^6 m^3 of meltwater in total. By October 2018, only a small portion of the second glacier collapse remained. We assumed that the rate of ice melting at the second glacier collapse in 2018 was same as in 2017, and the total volume of meltwater is estimated to be 25.2×10^6 m^3. 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<<

The expanding rate of Memar Co changed significantly before and after the glacier collapses. Between 2003 and 2014, the lake level of Memar Co increased 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). After the first glacier collapse, Memar Co expanded 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 storage at Memar Co increased by 3.0 m and 0.38 Gt, 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 Memar Co after the glacier collapses could be similar to that between 2003 and 2014 (Fig. 3a).

The contribution of the ice avalanches melting on inter-annual lake level changes of Memar Co is further 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, Memar Co expanded slightly, 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 is estimated to be 41.9%, 34.3%, 14.2% and 10.3% of the total lake level increase in 2016, 2017, 2018 and 2019, respectively.

The impact of the two glacier collapses on lake level changes can also be seen from the seasonal lake level changes derived from Cryosat-2 satellite data and in-situ observations between 2011 and 2019. The result shows that 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. 6a). However, lake level increase in the warm season (May to September) increased dramatically after the glacier collapses (Fig. 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. We can see that the accelerated lake level increase after the glacier collapses was mainly due to larger lake level increase in summer when the melting of the fragmented ice mass occurred.

>>Fig. 6<<

4.4 Impact of the glacier collapses on lake surface temperature

Two MODIS datasets (MYD11A2 and MOD11A2) were used to investigate the impact of glacier collapses on lake surface temperature at Aru Co and Memar Co. Figures 7c and 7d show that although there are similar seasonal cycles, in situ lake surface temperature at the shoreline is considerable higher than that derived from MODIS data. 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. 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 ^{o}C in May to 10 ^{o}C in August. During this period, the lake surface temperature does not exhibit much difference between the southern and northern parts of Aru Co. The lake water cools gradually in September and October. During this period, the southern Aru Co is usually 1-2 ^{o}C warmer than the northern Aru Co, which is mainly due to different lake heat storage. The larger lake heat storage at the southern Aru Co leads to slower decrease in lake surface temperature in autumn. 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 and breaks up about two to three weeks later than Aru Co.

After the glacier collapses, significant changes in lake surface temperature occurred at Aru Co and Memar Co. Both MYD11A2 and MOD11A2 datasets showed that lake surface temperature decreased abruptly by 2-4 ^{o}C at the southern and northern Aru Co in the first two weeks after the first glacier collapse (Fig. 7b). Lake surface temperature returned to normal status about two weeks later. 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). We attribute the dramatic decrease in lake surface temperature to the floating ice over the surface of Aru Co. As shown in Section 4.2, ice avalanches slid into Aru Co and generated great wave impact at Aru Co. A lot of floating ice soon spread over the surface of Aru Co and its melting cooled the lake surface temperature in the subsequent two weeks. This part of the floating ice flowed into Memar Co through the 5 km long river (10~20 m wide) between the two lakes. The dramatic decrease in lake surface temperature at Aru Co and Memar Co also 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.

Lake surface temperature from the southern and northern Aru Co was extracted to examine the spatial heterogenity since the northern Aru Co was closer to the two glacier collapses (Fig. 7). 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 at the northern Aru Co was about 1-2 ^{o}C lower in August 2016 than that at the southern Aru Co (Fig. 7b). We attribute this temperature difference to the melting of the intruding ice. Satellite images showed that the intruding ice into Aru Co, with a volume of 7.1×10^{6} m^{3}, melted by September 20th, 2016 (two months after the first glacier collapses). Since the meltwater of the intruding ice was considerably colder than the lake water, the melting of the intruding ice cooled the lake water at the northern Aru Co more significantly.

>>Fig. 7<<

>>Fig. 8<<

Lake surface temperature at Aru Co still exhibited a slight decrease in summer 2017 and 2018 (Fig. 7c and 7d), indicating that the melting of the ice avalanches may still have impact on the lake water temperature. The decrease in lake surface temperature occurred at Aru Co in July and August when ice melting from the collapse fan was high, but its magnitude was considerably smaller than that in summer 2016. Lake surface temperature at Memar Co did not exhibited considerable decrease as Aru Co in summer 2017 and 2018 (Fig. 8c, d), which was probably due to its longer distance from the glacier collapses. However, in situ lake surface temperature at Aru Co shoreline did not exhibit considerable decrease in summer 2017 and 2018, indicating its impact on lake surface temperature was very limited. More work is still needed to demonstrate the detailed process of changes in lake surface temperature after the glacier collapses using more intensive satellite data.

4.5 Implications of lake expansion at Memar Co

Dramaic expansion was widely found for most closed lakes on the interior TP during the past two decades (e.g. Lei al., 2014). Lake expansion 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). Memar Co is no exception. 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

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October 2019, the surface elevation of Memar Co reached 4931.3 m a.s.l and there was only 5.5 m elevation difference between the two lakes. 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. According to the reconstructed relationship between lake area and lake level (section 4.3), 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, compared with those of 2019. This will have significant impact on the regional geomorphology and ecosystem. 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 Conclusions

The fragmented ice from the Aru ice avalanches 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 since 2016, including meteorology, ice mass balance, lake bathymetry, lake level changes, etc. The impact of the ice avalanches on the downstream lakes is evaluated in this study based on in-situ observation in combination with satellite data. Lake bathymetry shows that Aru Co and Memar Co have water storage of 17.9 $\times 10^8$ m^3 and 34.9 $\times 10^8$ 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. A large amount of debris was transported into Aru Co along with the 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 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 ^{o}C in the first two weeks after the first glacier collapse. 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. 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 rapidly at a rate of 0.80 m/yr, which is about 30% higher than the average rising rate between 2003 and 2014. 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, its water level could reach as high as Aru Co in 7-11 years. 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.

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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., and Wu G. performed the fieldwork; Lei.Y., Yao T., Tian L., Sheng Y., Lazhu, Yang K. 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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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%

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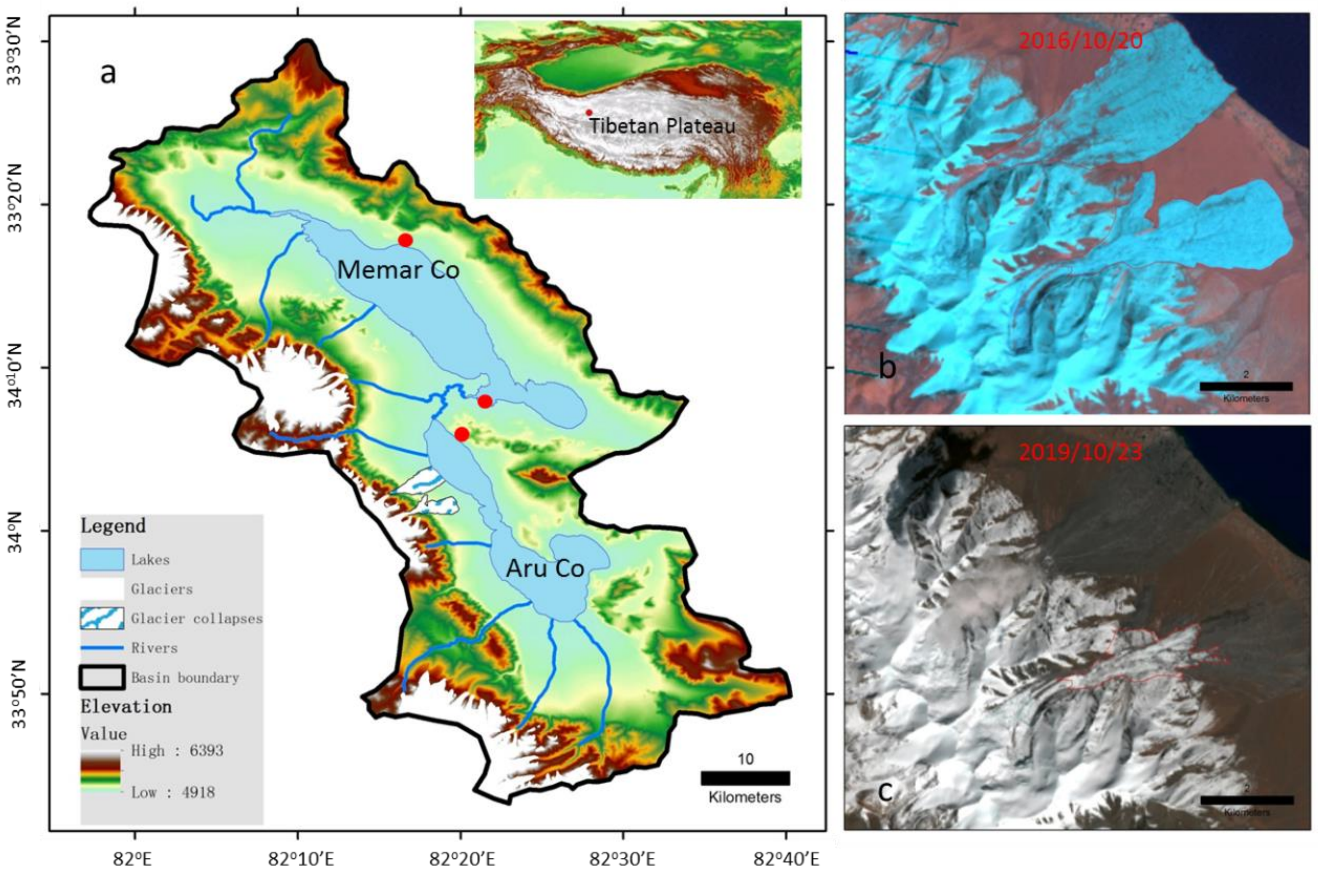

Figure 1: General description of the study area (a) and Landsat satellite images of the two glacier collapses on 20 October, 2016 (b) and 23 October, 2019 (c). The red dots denote the locations of lake level monitoring at Aru Co and Memar Co.

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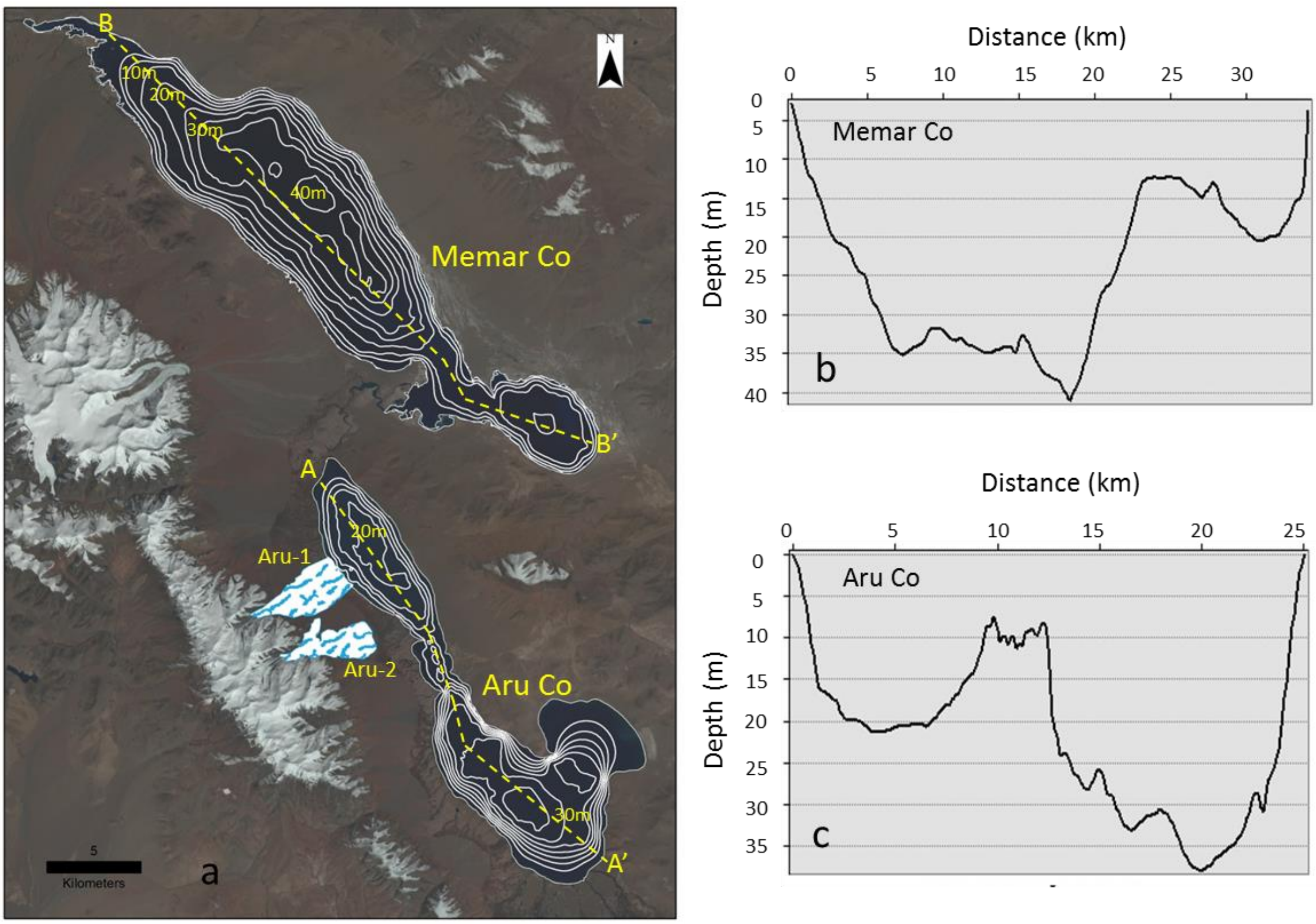

Figure 2: The 5 m interval isobaths (a) and the water depth profiles (b, c) on NW-SE direction (the yellow dashed lines) at Aru Co and Memar Co. Landsat satellite image (a) is used to indicate the location of the lakes and glacier collapses.

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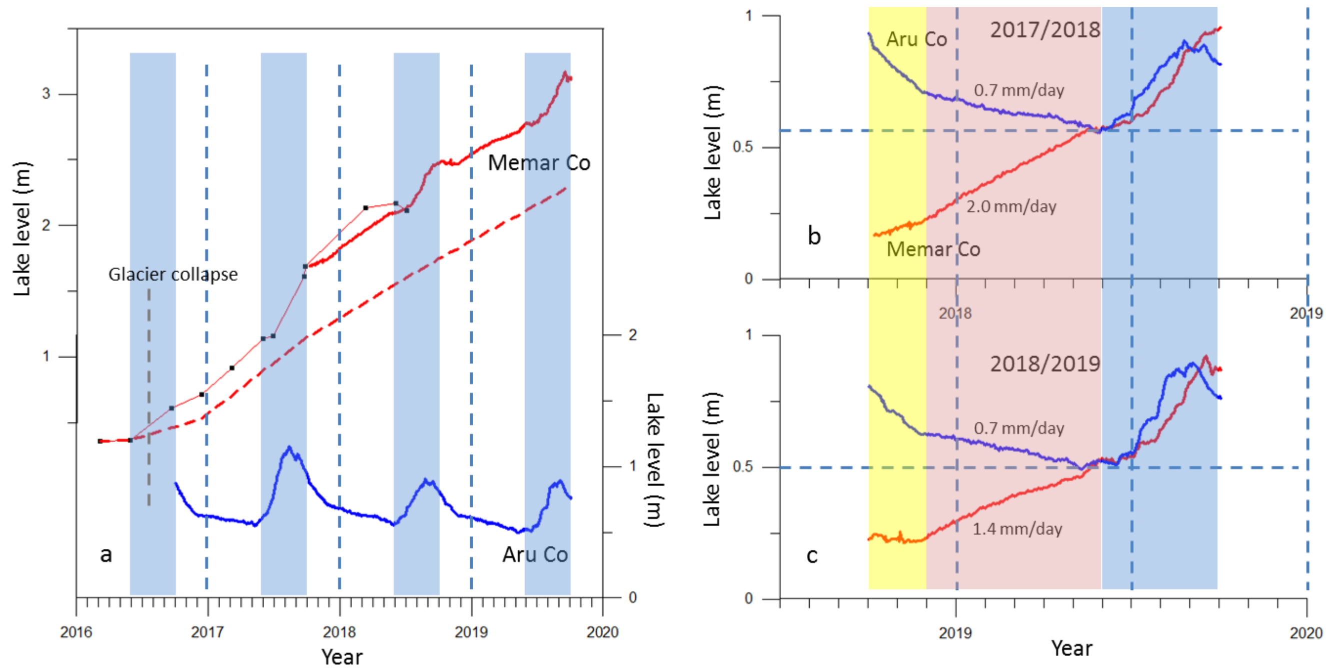

515 **Figure 3: In-situ lake level observations at Aru Co (blue) and Memar Co (red) between 2016 and 2019 (a) and comparisons of lake level changes at the two lakes (b, c). The dashed red line (a) indicates lake level changes at Memar Co without the fragmented ice melting. The black dots in (a) represents lake level derived from Cryosat-2 altimetry data. The strips indicate different periods of lake level changes in a year.**

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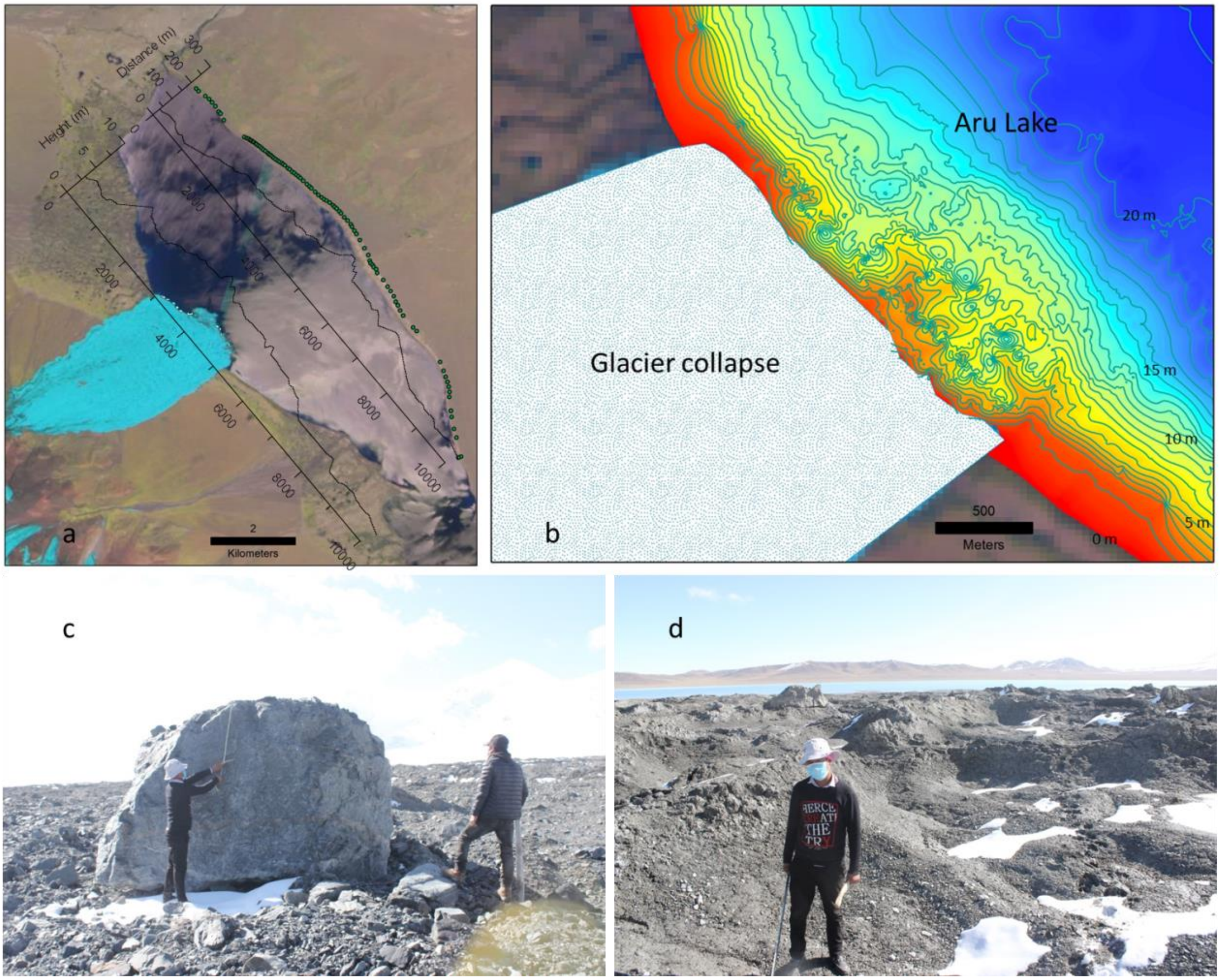

Figure 4: a: The extent of the first glacier collapse (Sential-2 image on 21 July, 2016) and the impact wave at the opposite shore of Aru Co (green dots). b: The uneven lake bathymetry at Aru Co near the first glacier collapse. c, d: A large amount of debris left after the fragmented ice mass melting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

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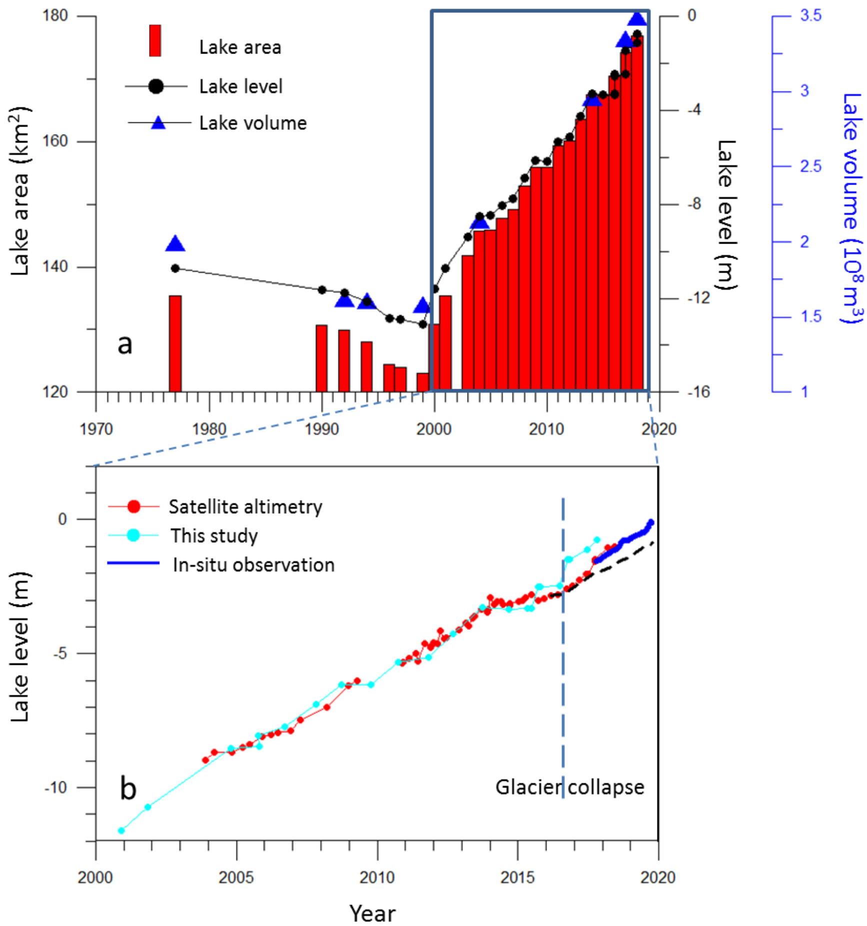

Figure 5: Changes in lake area and water level of Memar Co between 1976 and 2018 (a), and a comparison of lake level changes derived from satellite altimetry (b). The dashed line (b) indicates lake level changes without the fragmented ice melting.

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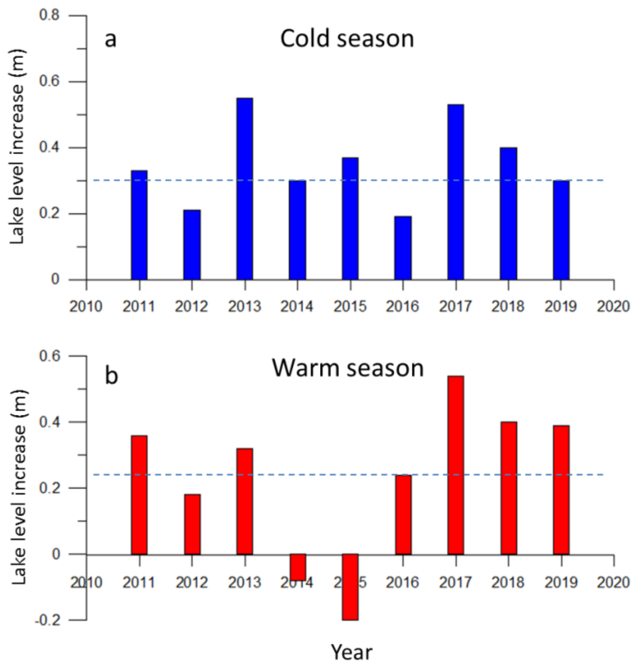

Figure 6: Lake level changes at Memar Co and Aru Co in the cold (a) and warm (b) seasons between 2011 and 2019.

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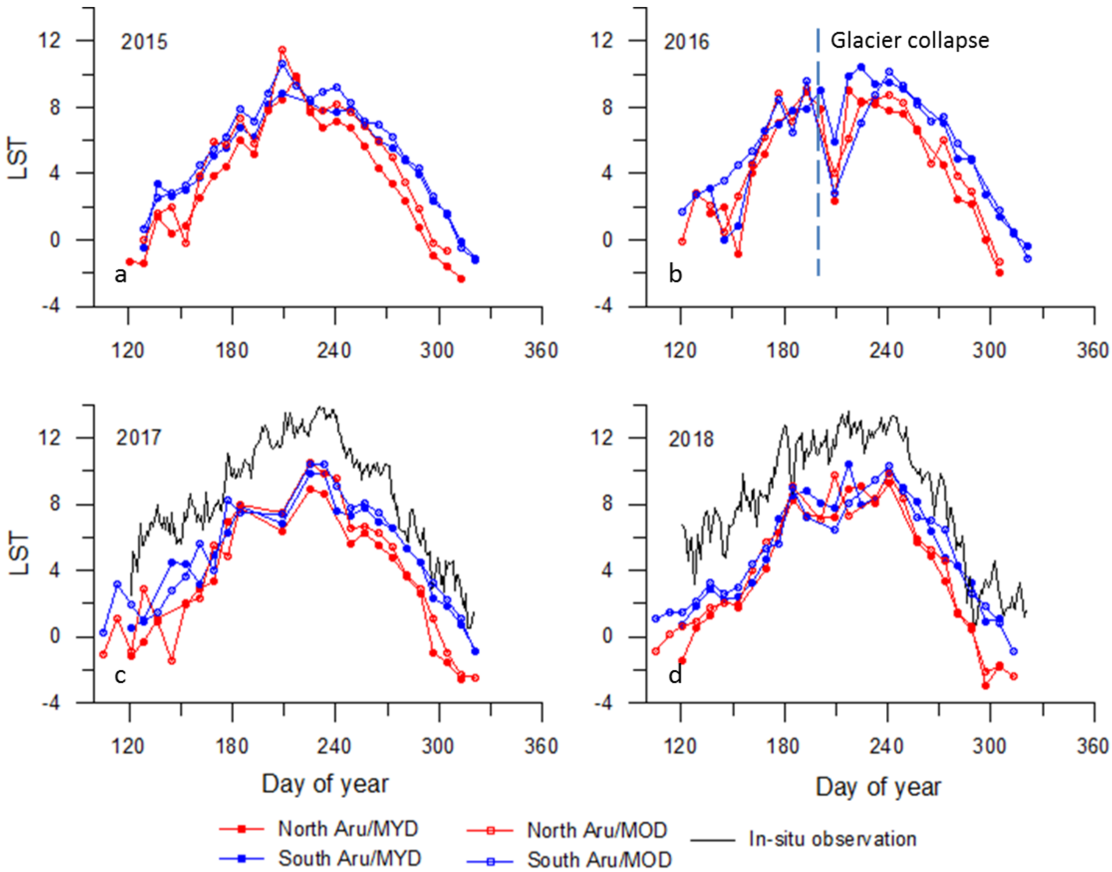

Figure 7: Time series of lake surface temperature (LST) derived from MYD11A2 (solid cycles) and MOD11A2 (hollow cycles) at the northern (red cycles) and southern Aru Co (blue cycles) between 2015 and 2018. The thin line represents in-situ lake water temperature at the shoreline. The dashed line in 2016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

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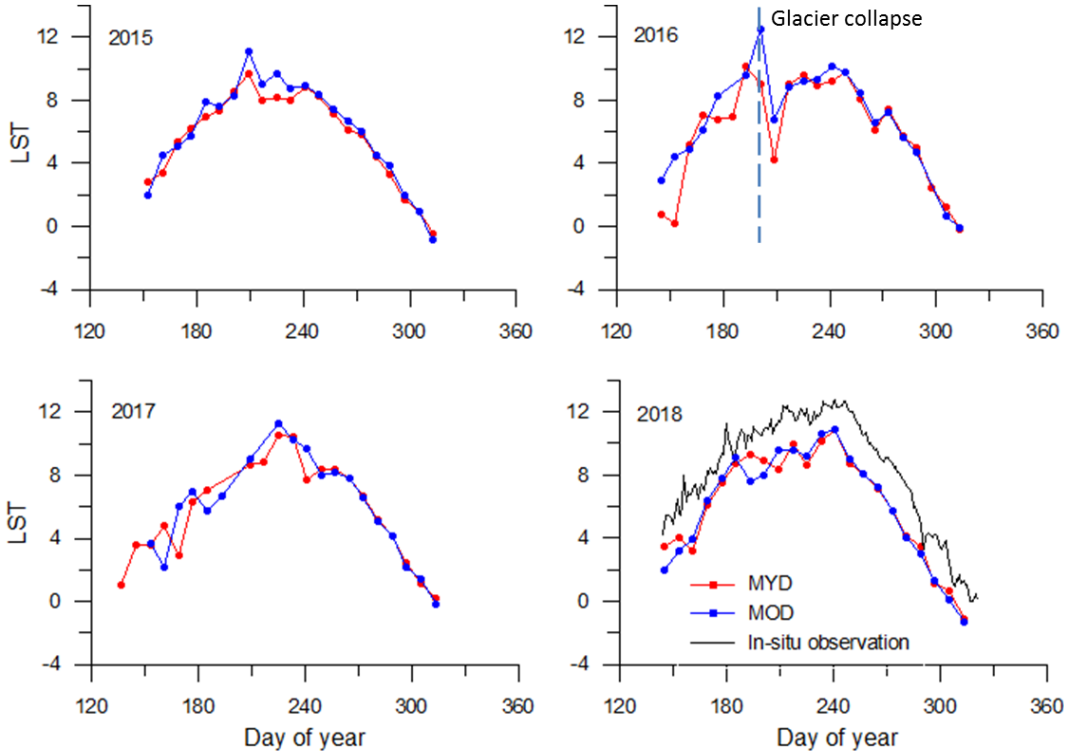

580 **Figure 8: Time series of lake surface temperature (LST) derived from MYD11A2 (red cycles) and MOD11A2 (blue cycles) at Memar Co between 2015 and 2018. The thin line represents in-situ lake water temperature at the shoreline. The dashed line in 2016 is the time of the first glacier collapse.**