Accelerated changes of glaciers in the Yulong Snow Mountain, Southeast Qinghai-Tibetan Plateau

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Abstract

The Yulong Snow Mountain (YSM) is a region of temperate glaciers in the southeast Qinghai-Tibetan Plateau. The present study systematically assessed the glacier changes during the past several decades using ground-based and remotely sensed observations and referencing topographic maps. The images and maps revealed that the glaciers area in the YSM retreated by 64.02% from 1957 to 2017. The length of Baishui River Glacier No. 1 decreased by 12.5 m/year during this period, whereas the front elevation of this glacier increased by 10.83 m/year. The mean annual mass balance of this glacier was at -0.42 metre water equivalent from 1957 to 2017, and its accumulative mass balance was -27.45 metre water equivalent. The glacier retreats of glacier area, glacier front, and mass balance in the YSM primarily resulted from the increasing air temperature. These glacier retreats not only will have a negative impact on glacier tourism in the future, e.g., the retreat or disappearance of glaciers will reduce the attractiveness of mountainous scenic spots, but also will create new opportunities for the development of local tourism, e.g., “last chance” will simulate tourists’ curiosity. Hence, the findings of our present study help to understand the mechanism between accelerated ablation of temperate glaciers and climate change in southeast regions of Qinghai-Tibetan Plateau and provide references for local tourism administrations.

Keywords Temperate glacier · Accelerating retreat · Yulong Snow Mountain

Introduction

With an average altitude of more than 4000 m above sea level, the Qinghai-Tibetan Plateau (QTP) is considered to be the World’s “Third Pole” and has also been called the “Roof of

the World.”. The QTP is characterized by the presence of numerous glaciers, ice caps, and snow, and the climate is regulated by Westerlies, Indian summer and Southeast Asian Monsoons, as well as by local atmospheric circulation systems (Dong et al. 2016; Neckel et al. 2014; Yao et al. 2012). The diversity of climate factors is the origin of different types of glaciers in the QTP, from marine- or temperature-type glaciers in the southeast to continental- or polar-type glaciers in the northwest (Huang 1990; Shi et al. 1980, 2008; Yao et al. 2012). Temperate and cold glaciers are defined by the temperature of the glacier body, i.e., a temperate glacier is at the melting point in terms of temperature of the glacier body while a cold glacier is below the melting point (Ahlmann 1935; Shi et al. 2008).

Glaciers are affecting human society around the world in ways that exceed their role as a provider of fundamental sources of water (Gagné et al. 2014) and tourism resources (Wang et al. 2010). The relationship between glaciers and societies is bridged by some special ways. For example, the populations living below the glaciers of the Andes from Columbia to Chile and Argentina, who not only rely on the glacier-melt water for consumption, agriculture, and other economic activities but also local social and religious life is

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tightly entwined with the movement of the ice. As a consequence, ice loss not only affects the hydrological cycle in the QTP and its surrounding regions (Farinotti et al. 2015; Huss et al. 2014; Sorg et al. 2012) but also tourism (Gagné et al. 2014; Purdie 2013; Vergara et al. 2007; Wang et al. 2010).

With global warming, a majority of glaciers worldwide have retreated since the end of the Little Ice Age in the mid-nineteenth century. Glaciers in the QTP have exhibited diverse responses to climate change (Che et al. 2017; Kääb et al. 2015; Kraaijenbrink et al. 2017; Neckel et al. 2014; Yao et al. 2012; Zhou et al. 2018; Zhu et al. 2017). On average, glaciers across High Mountain Asia were reduced in area at a rate of 0.04%/year during the period between 1960 and 2010, but this data hides high regional diversity. Glaciers in the Karakoram and West Kunlun Mountains have displayed advances and slight mass gain (also called the “Karakoram Anomaly”; Berthier and Brun 2019; Bhambri et al. 2019; Cogley 2016; Gardner et al. 2013; Kääb et al. 2015; Lin et al. 2017; Mölg et al. 2018; Zhou et al. 2018). In addition, ten glaciers in the Gangrigabu Range have actually advanced from 1980 to 2015 (Wu et al. 2017). Other glaciers in the QTP exhibited extensive retreat or profound mass loss, especially in the southeast QTP (Bhambri et al. 2017; Che et al. 2017; Gardelle et al. 2012; Hewitt 2011; Wiltshire 2014). For example, the area and length of glaciers in the Qilian Mountains declined by 21% from 1956 to 2010 (Sun et al. 2018) and retreated by 5.7 m/year from 1956 to 2008 (Che et al. 2017). Glaciers in Nyainqentanglha had a higher mass loss, with a mass balance of -0.72 ± 0.27 metre water equivalent (m w.e.) (Brun et al. 2017), whereas those of the Parlung Zangbo in the southeast QTP decreased by an area of 23% and a mass balance of -0.19 ± 0.14 m w.e./year from the mid-1970s to 2000 (Zhou et al. 2018). Moreover, glaciers in the Hengduan Mountains exhibited a steady retreat (16.7 m/year) from 1930 to 2005 (Che et al. 2017). In general, temperate glaciers were more sensitive to air temperature than that of cold glaciers (Wang et al. 2014).

For the Yulong Snow Mountain (YSM) located in southeast region of the QTP, a few studies indicate glacier retreat over the past decades. For example, elevation of the Baishui River Glacier No. 1 (BRG1) terminus retreated from 4100 to 4300 m a.s.l. during the period of 1982–2006 (Pang et al. 2007). Ablation of the glacier occurred earlier than for the continental glaciers (i.e., cold glacier), and the accumulation time of the glacier was later than that of the continental glaciers (Du et al. 2013); the mean annual mass balance of this glacier was -1.13 m w.e. between 2008 and 2011 (range, -1.87 to -0.91 m w.e.; Du et al. 2015). Note that the continental glaciers were also divided into two types—that is, subcontinental and extremely continental glaciers (Shi and Liu 2000). The ice temperature of most glaciers in the former ranged from -1 to -10 °C within the upper 20 m ice layer, whereas that of the latter was lower in the same ice layer. For example, the ice temperature at 10 m depth was measured to be -19 °C

in the Guliya Ice Cap of extremely continental glaciers in the western Kunlun Mountains on the QTP.

Retreat and thin down of BRG1 glacier would damage the scenic landscape and even make some glacier tourism resources disappear, which resulted in reducing the attraction of the scenic spot and developing local tourism (Wang et al. 2010). Moreover, the glacier retreat in the region had a significant effect on people's activity because of the more comfortable climate and increased accessibility. Of note, the glacier retreat has been more significant in recent years, but research on glacier change has been more dispersed and discontinuous. Hence, it is imperative to systematically research glacier changes in the YSM to further elucidate the glacier retreat and climate change.

The present study assesses glacier changes in the YSM and their impact on the local glacier tourism. Based on in situ data and remote-sensing images, we first evaluate the glacier changes in the study region, such as changes in the glacier front, glacier area, and glacier mass balance. Then, we analyze the reasons for this glacier change, along with the climate records from a local meteorological station, followed by the major impact factors of the initially rapid glacier retreat. Finally, we discuss the impacts of glacier retreat on local glacier tourism.

Study area

The Yulong Snow Mountain (YSM) ($27^{\circ} 10' - 27^{\circ} 40' \text{ N}$, $100^{\circ} 9' - 100^{\circ} 20' \text{ E}$) located in the southeast region of the QTP, which is the closest temperate glacier area in the Eurasian continent to the Equator (other than Indonesia's Chaya Peak). From north to south, the YSM is 35 km long and 13 km wide from east to west, with the highest peak (Shanzidou) at 5596 m a.s.l. In 2017, there were 13 glaciers with the total area of 4.48 km², and the elevation of the glaciers ranged from 5361 m a.s.l. in the accumulation region to 4395 m a.s.l. at the glacier end (Fig. 1). The region is the intersection point of the Indian monsoon and Southeast Asian monsoon (Yao et al. 2012). During the summer and autumn seasons, the YSM is affected by the southeast and southwest monsoons, whereas the YSM is affected in the winter and spring by the south branch of the westerly belt.

The discrepancy in vertical heights of the YSM is remarkable, and the biodiversity and natural-cultural landscape are rich in diversity and have significant cryosphere service. The existence of the ice-and-snow landscapes is culturally important to the Lijiang ancient town (world cultural heritage and intangible cultural heritage), and ice-and-snow resources are closely associated with the region's economic and social development. Regional warming at the Lijiang Meteorological Station, at the foot of the YSM was 0.3 °C/decade from 1980 to 2013 (Wang and Cao 2015; Wang et al. 2013). With this

Fig. 1 a, b The spatial distribution of glaciers in the Yulong Snow Mountain. In plot (a), the Westerlies, Indian Monsoon, and East Asian Monsoon were redrawn following Yao et al. (2012), and the white line marks the boundary of the Qinghai-Tibetan Plateau

warming, the mass loss of ice and snow resources has continued to intensify and water resources have declined. Thus, it is imperative to strengthen scientific research through positioning observations.

Observations and methods

Glacier area

Two topographic maps from 1968 provided the earliest record of the distribution of glaciers in the YSM, China. The two maps were compiled using aerial images taken in 1957 (Table 1). The distribution of glaciers in the YSM topographic maps was defined according to the referenced year of 1957. In the present study, the topographic maps of Longhua and Daju, with glacier distribution of 1957 and scales 1:50,000, were provided by the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. To assess changes in the glacier area, we also used serial LandSat images (Table 1), including images from LandSat5 TM in 1994, LandSat7 ETM+ in 2008, and LandSat8 OLI in 2013 and 2017 (USGS; <https://earthexplorer.usgs.gov/>). There were

some data gaps in the ETM+ images because of the instrument failure of Landsat 7 Scan Line Corrector (SLC), but these products were still useful and maintained the same radiometric and geometric corrections as data collected prior to the SLC failure. As a consequence, SLC Gap-Fill Methodology of landsat_gapfill.sav (Scaramuzza et al. 2004) widely used to fill the gaps of Landsat7 scenes and was advised by USGS before using the Landsat7 images. Based on the ENVI software, we also used the tool to fill the data gaps in the ETM+ images in order to make the feature of glacier continue in space. Furthermore, we used an image with a spatial resolution of 1.2 m, derived from Google Earth, primarily to modify the glacier boundary in 2013.

Glacier front observations

Changes in the glacier front (e.g., retreat or advance) are crucial to comprehending regional climate change in high latitudes (Oerlemans 2005). Compared with the monitoring work of mass balance, which require field-intensive measurements, measurements of the glacial frontal position are relatively easy to obtain from ground measurements and remotely sensed data (Cook et al. 2005; Schmidt and Nüsser 2009). In the

Table 1 Topographic maps and remote-sensing images used in the present study

Data type	Name or code	Date	Scale/spatial resolution of used bands
Topographic maps	Longhua 7-47-33-C	1957	1:500,000
	Daju 6-47-33-A	1957	1:500,000
LandSat5 TM	LT513104119940905BJC00	1994	30 m
LandSat7 ETM+	LE713104120080311SGS00	2008	30 m
Google Image	11-55-03.tif	22 Nov 2015	1.2 m
LandSat8 OLI	LC813104120170413LGN00	2013	30 m
LandSat8 OLI	LC813104120131011LGN00	2017	30 m

YSM, the glacier front of the BRG1 was first measured in 1999. Changes in the glacier retreat included the horizontal retreat distance and the elevation change of the front. The glacier front position of BRG1 has been measured using the Trimble Global Positioning Satellite (GPS) at the end of the melting season every year since 1999 by researchers at the Yulong Snow Mountain Glacier and Environment Observation Research Station. In the present study, we collected the glacier front observation data (Table 2), including the records of glacier fronts during the periods of 1999–2006 (Pang et al. 2007) and 2006–2017 which was first published. In addition, BRG1 glacier has developed into the largest glacier resort in China, which attracted a lot of tourists and promoted the local economic development (Wang et al. 2010). We also collected the data sets of tourist visitors and tourism income, which were provided by the Lijiang Yulong Snow Mountain Provincial Level Tourist Region Management Committee.

Glacier mass balance estimates

Glacier mass balance is the change in mass during a specific period of time, which is driven by precipitation and temperature and especially by glacier surface ablation resulting from increasing summer temperatures (Cogley et al. 2011). Mass balance of glacier usually is evaluated according to the stratigraphic method using two successive “summer surface” (surface minima) measurements (Østrem and Brugman 1991). For this, measurements of stakes and snow pits on the glacier are essential. We projected the point results on a large-scale topographical map to calculate the mass balance for the entire glacier (Andreassen et al. 2016). In the YSM, the first measurement of glacier mass balance was conducted at BRG1 by the Yulong Snow Mountain Glacier and Environment Observation Research Station in 2007. Here, we also collected and reanalyzed this mass balance data (Table 2). According to the contour line and profile methods (Andreassen et al. 2016), we calculated glacier mass balance during the period from 2008 to 2017 based on these records of stakes and snow pits.

We evaluated the point mass balance by reading the stakes and snow pits, and the one-point mass balance was a sum of balance of snow (or firm) (b_f), spur-ice (b_{sp}), and ice (b_i):

$$b_{(1\sim 2)} = b_{f(1\sim 2)} + b_{sp(1\sim 2)} + b_{i(1\sim 2)}, \quad (1)$$

$$b_{f(1\sim 2)} = \rho_{f(2)} h_{f(2)} - \rho_{f(1)} h_{f(1)}, \quad (2)$$

$$b_{sp(1\sim 2)} = \rho_{sp}(h_{sp(2)} - h_{sp(1)}), \text{ and} \quad (3)$$

$$b_{g(1\sim 2)} = \rho_i [(m_1 + h_{f(1)} + h_{sp(1)}) - (m_2 + h_{f(2)} + h_{sp(2)})], \quad (4)$$

where i , sp , and f denote the glacier ice, super ice, and snow or firm, respectively; 1 represents the records of the former observation, and 2 represents the records of the latter observation. In addition, ρ_i denotes the density of snow/firm in grams per cubic centimeter, ρ_{sp} denotes the density of super ice (0.85 g/cm^3), and ρ_i denotes the density of the glacier ice (0.9 g/cm^3).

Using the contour-line method according to the formation, we projected the point measurements on a large-scale topographical map and interpolated the data to area-averaged values to calculate glacier-wide annual mass balance:

$$b_n = \sum_{i=1}^n S_i b_i / S, \quad (5)$$

where S_i denotes the projected area between the two adjacent contours (e.g., contour of mass balance corresponds to the contour line method of mass balance, and the contour of glacier surface elevation corresponds to the contour line method of elevation); b_i depicts the averaged net annual mass balance of region S_i ; n denotes the number of S_i ; and S denotes the total glacier area. A study reported that the annual mass balance derived from the two different contour methods were extremely close in Urumqi River Glacier No. 1 of east Tien Shan (Yang et al. 1992).

In addition, the equilibrium-line altitude of BRG1 was at 4800 m a.s.l. for 1956/1957 (Pu 1994). On the basis of the meteorological records and observation on the glacier, the following insight could be found (Zhang 2005). First, the

Table 2 Glacier and climate change data observed on the ground, number of tourists, and tourism income

Data type	Images/method	Periods	Reference
Glacier front	Trimble GPS	1999–2006	Pang et al. (2007)
		2006–2017	In the study
Glacier mass balance	Degree-Day model	1952–2007	Zhang (2005)
	Glacial method	2008–2013	Du et al. (2015)
	Glacial method	2014–2017	In the study
	Lijiang meteorological station	1952–2017	In the study
Tourists	Yulong Snow Mountain Glacier Geological Park	1998–2016	In the study
Tourism income	Yulong Snow Mountain Glacier Geological Park	1998–2016	In the study

accumulation of the glacier mass was primarily derived from snow (P_s ; i.e., solid precipitation) on the glacier surface. The annual solid precipitation of 4800 m a.s.l. was a function as follows:

$$P_s = 0.2273P - 172.22 (r = 0.64), \quad (6)$$

where precipitation (P) was the solid precipitation when the air temperature was $< 0^\circ\text{C}$. Second, ablation of the glacier was explained by the following function:

$$f(T) = K \times \text{PDD}, \quad (7)$$

where K denotes the degree factor, and the PDD denotes positive day-degree air temperature $> 0^\circ\text{C}$. Third, the glacier mass balance can be calculated using the Degree-Day model as follows:

$$B = \sum_{i=1}^L P_i T_i - K \times \text{PDD}, \quad (8)$$

where i denotes the Julian day; L denotes the total days of 1 year; T_i equals 1 if the air temperature was $\leq 0^\circ\text{C}$; and T_i was 0 if the air temperature was $> 0^\circ\text{C}$. Here, the serial data of BRG1 mass balance from 1952 to 2007 was reconstructed by the Degree-Day model using data from the nearby Lijiang Meteorological Station (Zhang 2005).

Meteorological observations

Meteorological stations are sparse in most high mountain regions, and multiple meteorological stations have operated next to the BRG1 only since 2005. The Lijiang Meteorological Station was built in 1951 by the China Meteorological Administration to record climate conditions in the Lijiang region. The station is located in the southern region of the YSM with a distance of nearly 26 km to Lijiang city. In the present study, we used the Lijiang Meteorological Station datasets to investigate climate change in the study region (Table 2); the data were derived from the China Meteorological Data Service Center (<http://data.cma.cn/>).

Data processing

In the present study, we used the geographic coordinate systems of the topographic maps for Beijing in 1954, and their projected coordinate systems were Gauss–Krüger projections. These systems differed from the geographic and projected coordinate systems of Landsat and Google images. To spatially match these maps and images, we visually adjusted the maps and images to a common system, and then projected them according to the World Geodetic System (WGS) 1984. On the basis of the adjusted topographical maps, we manually interpreted the 1957 glacier outlines. For the multiband

images taken from Landsat, the spectral-band ratio method has been demonstrated as a simple, highly efficient, and accurate technique to extract the glacier outline (Sidjak 1999; Silverio and Jaquet 2005). This method can reduce problems such as sensor saturation and shadowed areas, and can discriminate debris-mantled ice and ice-marginal water bodies (Paul et al. 2004). We first used spectral red-band and SWIR1-band methods to calculate the band ratio (i.e., TM3/TM5 for TM and ETM+, TM4/TM6 for OLI). Then, we traced the outline of each glacier in the YSM and modified the outline by manual visual interpretation. In addition, we referenced the interpretation of the Dagu Glacier in the north-western region of Sichuan Province, China (Wei et al. 2019). We used the Google Image in 2015 provided by Google Earth as the reference for the glacier outlines of Landsat 8 OLI in 2013 and 2017. Detailed information about the glacier dataset used in this study is given in Tables 1 and 2.

Results

Changes in glacier area

As shown in Fig. 2, the glaciers decreased markedly in terms of their numbers and areas in the YSM. We used the Annual Percentage of Area Change (APAC) to assess the change in the glacier area during the study period (Ding et al. 2006; Nie et al. 2010; Zhang et al. 2011). In addition, the APAC was calculated to assess the glacier area change in the YSM (Table 3). In 1957, there were 22 glaciers, with a total area of 12.45 km² in the YSM based on the topographical maps (Fig. 2; Tables 1 and 3). Until 2017, there were 13 glaciers, with a total area of 4.48 km² distributed in the study region. The glacier retreat in terms of glacier area was the most significant during the period from 1982 to 1994 (APAC, -3.62%), whereas the glacier retreat during the period from 1957 to 1982 was relatively weak (APAC, -0.27%). In addition, the glacier area in the YSM decreased by 7.97 km² (i.e., disappeared glacier area, 64.02%) during the period from 1957 to 2017, and the glacier area decreased by -1.07% /year on average.

Retreats in glacier length and front

We selected the BRG1 glacier as the reference glacier to regularly monitor the YSM to elucidate the relationship between glacier and climate, including measurements of the glacier length and terminus position in the special periods. The BRG1 glacier decreased in length from 2.65 km in 1957 to 1.90 km in 2017 (Table 3), and further decreased by 0.75 km (i.e., decreased by 12.5 m/year between 1957 and 2017). During the period from 2008 to 2013, the length

Fig. 2 Glacier distribution in the Yulong Snow Mountain during different periods

of the glacier decreased by 0.31 km (i.e., decreased by 62 m/year), which was more significant than in other periods. For the elevation of the glacier front, as shown in Fig. 3a, the position of the glacier front has been recorded every year since 1999 using GPS. The BRG1 front retreated from 4200 m a.s.l. in 1999 to 4335 m a.s.l. in 2008, and then continually retreated to 4395 m a.s.l. in 2017. The glacier significantly retreated by 15 m/year

between 1999 and 2008, which was faster than the amount of retreat (i.e., approximately 7 m/year) between 2008 and 2017. During the period from 1999 to 2017, the elevation of the BRG1 terminus averagely retreated by 10.83 m/year. Therefore, we found that the BRG1 retreat was more significant in the horizontal distance than in vertical height after 2008, which resulted from the topography of the glacier front (Fig. 3b).

Table 3 Glacier numbers and areas in the Yulong Snow Mountain in different periods

Year	BRG1			YSM			Topographical map/images
	Length (km)	Area (km ²)	APAC	Number	Area (km ²)	APAC	
1957	2.65	2.07	–	22	12.45	–	Topographical map
1982	2.54	1.86	– 0.41	19	11.61	– 0.27	LandSat MSS
1994	2.44	1.61	– 1.12	19	6.57	– 3.62	LandSat TM
2008	2.36	1.52	– 0.40	19	5.37	– 1.30	LandSat ETM+
2013	2.05	1.44	– 1.05	16	4.76	– 2.27	LandSat OLI
2017	1.90	1.32	– 2.08	13	4.48	– 1.47	LandSat OLI

Changes in the glacier mass balance

Over the past several decades, glacier retreats have been markedly observed in the glacier area and front. The changes, however, essentially have resulted from changes in the glacier mass. As shown in Fig. 4a, the annual mass balance of the BRG1 presented fluctuations that occurred during the time period from 1952 to 2017 (range, -1.94 to 2.26 m w.e). The glacier mass loss was the strongest in 1979, whereas the glacier mass increase was the strongest in 1978. During the period from 1952 to 2017, the cumulative mass balance of the BRG1 was -27.45 m w.e. (Fig. 4b), which indicated that the glacier mass loss was extremely serious over the past several decades. Following Fig. 4b, we observed that the change trend of the cumulative mass balance of the BRG1 altered suddenly in 2002. We divided our study period into two periods using the node of 2002, that is, periods of 1952–2002 and 2002–2017. In the former period, glacier mass loss increased by 0.016 m w.e./year ($p = 0.10$), whereas in the latter, it increased by 0.099 m w.e./year ($p < 0.01$). Notably, the speed of the glacier mass loss after 2002 was more significant than that before 2002, that is, glacier melting accelerated after 2002.

Discussion

Climate change in the Yulong Snow Mountains

Glacier changes in different regions were controlled by local climate change in the QTP, e.g., from glaciers affected by mid-latitude westerlies in the northwest High Asian Mountains to a monsoon-dominated regime in the southeast (Kapnick et al. 2014; Wiltshire 2014; Yang et al. 2016; Yao et al. 2012). During the period from 1951 to 2017 (Fig. 5), a significantly increasing trend was noted in the annual mean temperature, with an increased rate of 0.19 °C/decade ($p < 0.0001$). On the basis of air-temperature variations, a significant change was noted around 1992, such that the entire study period was categorized into two periods: 1951–1992 and 1992–2017. We also found that the mean annual temperature was 12.60 °C during the former period and was 13.33 °C during the latter period. The annual mean temperature increased significantly after the mid-1990s. For the annual precipitation, precipitation in accumulation seasons (i.e., October to April) and precipitation in ablation seasons (i.e., May to September); however, no significant change trend was noted during the period from 1951 to 2017 (Fig. 5). Hence, an increased trend has found in air temperature while no significantly

Fig. 3 Front variation of the Baishui River Glacier No. 1

Fig. 4 **a, b** Changes in the mass balance of BRG1 during the period from 1957 to 2017. In plot (a), the straight lines denote the regressed lines of the annual mass balance before 2002 (pink line) and after 2002 (red line), respectively

increased trend in precipitation. In 1992, the abrupt change of increasing in air temperature was not clearly showed in the change of glacier mass balance until 2002. The increased trend must had an impact on the change of glacier mass balance since 1992, for example, the high air temperature accelerated the

glacier melting and no enough precipitation (solid precipitation) input to glacier surface. It was believed that a complex interaction took place in that period of 1992–2002. The process cannot be fully quantitative description at present, which needs a complicated model of physical process in future, including the processes

Fig. 5 Changes in annual precipitation and annual mean temperature at the Lijiang Meteorological Station. In plot (a), the red and gray straight lines denote the changed trend of the annual temperature and precipitation, respectively, and green lines denote the mean temperature before 1992 and after 1992. In plot (b), the green and red straight lines denote the changed trend of the annual temperature during the periods of

1951–1992 and 1992–2017. In plot (c), gray solid line and short dashed line denote the precipitation and changed trend of precipitation in accumulation seasons, respectively. In plot (d), pink solid line and short dashed line denote the precipitation and changed trend of precipitation in ablation seasons, respectively

of climate change, glacier melting, and glacier accumulation and so on. Nevertheless, we deduced that the glacier retreat and accelerated melt were mainly resulted from increasing in air temperature.

Glacier accelerated retreat in the Yulong Snow Mountains

Glaciers have significantly decreased in the YSM over the past several decades, which have resulted mainly from local climate warming and no significantly increased trend in precipitation. As air temperature has increased, the glacier area in YSM has decreased by 64.02%, at a rate of $-1.07\%/year$ from 1957 to 2017. With respect to terminus variation of BRG1 glacier, the retreat speed in the vertical direction after 2009 was slower than that before 2006 (Pang et al. 2007). On the basis of unmanned aerial vehicle images in 2018 and topographic maps in 1968 (with glacier distribution in 1957), another study indicated that the BRG1 front had retreated by 646.27 ± 12.0 m in the horizontal direction during the period from 1957 to May 2018 (Che et al. 2019). The front retreats observed in this paper were consistent with the results from the previous studies (Che et al. 2019; Pang et al. 2007). Compared with glacier changes in the surrounding mountains, the rate of glacier retreat in YSM was not the strongest. For example, the total glacier area decreased by 41.79% in the Gangrigabu Mountains during the period from 1974 to 2010, with a decrease of $1.13\%/year$. Some of the glaciers decreased by $0.33\%/year$ in the Gongga Mountains during the period from 1974 to 2010 (Li 2015). The strongest areal decrease of glaciers in YSM occurred during the period from 1982 to 1994, whereas the weakest decrease occurred during the period from 1957 to 1982.

A time lag exists in response to variations in glacier shape (e.g., front and area) to climate change; however, glacier mass balance responds instantly to meteorological variations (Zecchetto et al. 2016). During the period from 1952 to 2017, glacier mass of BRG1 showed a net loss, which resulted in glacier retreat as well as in the disappearance of some of the glaciers in the YSM. The net annual mass balance of the glacier was -0.42 m w.e. in the study period, on average, and it ranged from -1.94 m w.e. to 2.26 m w.e. A significant change was revealed in the variation trends of glacier mass balance (i.e., the existing two stages before 2002 and after 2002). Since 2002, in particular, the mass balance of the BRG1 glacier has no longer been positive and has presented a continuous mass deficit. This change has indicated that the increased rate of mass loss (i.e., 0.099 m w.e./year) was larger than that before 2002 (i.e., 0.016 m w.e./year). We also found that the mean annual mass balance of the glacier was -1.67 m w.e. during the period from 2014 to 2017, which was less than that of -1.33 m w.e. during the period from 2008 to 2013 (Du et al. 2015). The annual mass balance was also less than that for the entire study period. In other words, mass loss of the

BRG1 glacier has accelerated in recent years. In terms of annual precipitation in the YSM, there was no significantly increased trend, although we did observe a clearly warming trend in air temperature. Of note, a rapidly increasing trend of 0.54 °C/decade was noted in the region after 1992. That is, air temperature has increased rapidly in the YSM since the 1990s. The abrupt change in air temperature resulted in an increase in glacier ablation, which prompted the glacier mass loss in the YSM.

Compared with those of the adjacent glaciers in the Gongga and eastern Gangrigabu Mountains located in north-eastern and northwestern YSM, respectively, the changing trends of glacier mass loss have been consistent (Fig. 6). In the Gongga Mountains, for example, the annual mass balance of the Hailuoguo Glacier ranged from -1.72 to 0.44 m w.e. between 1959 and 2008, and the mean annual mass balance was -0.44 m w.e. (Liu and Zhang 2017). In the eastern Gangrigabu Mountains (Che et al. 2017; WGMS 2018; Yao et al. 2012), the annual mass balance of Parlung Zangbo Nos. 10 and 12, Parlung Glacier No. 94, and Demula, which showed stronger mass loss, ranged from -2.48 to 0.16 m w.e. during the period from 2005 to 2010 (Fig. 6). In general, the change in glacier mass in the YSM was similar to changes in the surrounding glaciers.

Impact of accelerated glacier retreat on glacier tourism

Since 1996, the YSM has progressively developed into the largest glacier tourist destination in the world. As shown in Fig. 7, the number of tourists increased from 0.10 million in 1995 to 3.84 million in 2016. The direct income from glacier

Fig. 6 Mass balance of Baishui River Glacier No. 1 and surrounding glaciers since 1951

Fig. 7 Trend in tourists and tourism income of the Yulong Snow Mountain Glacier Geological Park

tourism exceeded 500 million RMB in 2016, which increased more than 2000 times compared with that before 2000. In addition, tourism income has improved markedly over the past several years (i.e., since 2014), and the number of tourists has increased continuously since 2007. Thus, glacier tourism in the YSM has been well developed to date.

This glacier retreat was never only a local phenomenon, however, and it has presented new entanglements between nature and society, at both the global and local scale (Gagné et al. 2014). Glacier retreat has had different impacts, including, for example, tourism, natural hazards, increased runoff during specific periods, and threats to building infrastructure. In the present study, we primarily focused on the impact of the glacier retreat on tourism, including opportunities and challenges.

Of note, glaciers are crucial to the livelihood of mountain populations. Among the benefits provided by glacierized mountain landscapes, tourism is crucial to the development of the local economy (Milner et al. 2017; Wang et al. 2010). Some studies, however, have demonstrated that tourism could be decreased or could be redirected to other locations, such as the Andes, the Alps, and China, as iconic features of the YSM landscape slowly vanishes as a result of the glacier retreat (Scott et al. 2007; Smiraglia et al. 2008; Vergara et al. 2007; Wang et al. 2010). For example, the BRG1 in the YSM was the largest glacier resort in China and has been a major contributor to the economic development of Lijiang, accounting for 1.90 million visitors in 2008 (Wang et al. 2010). Pasterze Glacier attracts around 0.80 million people every year in Austria, whereas the Glacier Bay National Park, Alaska, usually attracts in excess of 0.40 million people per year. Compared with other glaciers, with scenic areas at home and abroad, the number of glacier tourists in the YSM has ranked first in the world (Wang et al. 2010).

As noted earlier, the area of the glaciers in the YSM disappeared at a rate of 64.02% during the period from 1957 to 2017 (Table 3). Some surveys have suggested that the number of tourists would be decreased when the glacier disappears (Scott and Lemieux 2010; Yuan et al. 2006). Studies of the Waterton Glacier International Peace Park and Banff National Park have reported that 19 and 31% of visitors, respectively, would not want to visit these parks if climate change affected the scenery (Liu 2016). Mountain tourism possibly could be affected by accelerating the glacier retreat or loss in the long term, although these seem counterintuitive. The number of visitors, however, could increase in some areas if access improved or with an increase in the desire to learn about the effect of climate change on the glacier before it disappears (i.e., “last chance” tourism) (Bury et al. 2011; Purdie 2013). Likewise, the YSM also encounters problems; almost all of the tourist surveys reported a strong perception of the glacier retreat and expressed significant concern and attention. If glacier and snow resources disappeared in the YSM, a minimum of 19.60% and a maximum of 44.20% of tourists would be lost, and the loss of tourism revenue would be enormous (Wang et al. 2010).

Conclusion

As glaciers are retreating in the majority of regions worldwide, glaciers in the YSM have experienced rapid retreat during the period from 1957 to 2017. On the basis of in situ records, remote-sensing images, and topographic maps, the present study found that the glacier area in the YSM decreased from 12.45 km² in 1957 to 4.48 km² in 2017, decreasing by –1.07%/year on average during the study period. For the referenced glacier of BRG1 in this region, the glacier length decreased from 2.65 km in 1957 to 1.90 km in 2017, and further

decreased by 0.75 km, with a decrease of 12.5 m per year. The front elevation of the BRG1 retreated from 4200 m a.s.l. in 1999 to 4335 m a.s.l. in 2008, and then continually retreated to 4395 m a.s.l. in 2017. During the study period, the front elevation of the BRG1 retreated by 10.83 m per year. In addition, the BRG1 experienced a strong mass loss during the period from 1952 to 2017, and its cumulative mass balance was -27.45 m w.e. Meanwhile, glacier melting was stronger during the period from 1952 to 2002 than that during the period from 2002 to 2017. The annual mass balance of BRG1 decreased by 0.016 m w.e./year ($p = 0.10$) during the former period and decreased by 0.099 m w.e./year ($p < 0.01$) during the latter period. In addition, the mean annual mass balance was -0.42 m w.e. throughout the entire study period. Furthermore, we found that the glacier retreats in the YSM resulted primarily from incremental air-temperature changes between 1951 and 2017.

To manage the potential negative impacts from glacier retreat, since 2006, the managements of Gangrigabu, Meili, Gongga, and Daggu snow mountain scenic areas, in collaboration with the Yulong Snow Mountain Glacier and Environment Observation and Research Station, have been conducting a series of glacier and environmental science research studies. In the next step, artificial weather manipulation and artificial snowmaking projects are planned for these scenic areas. The objective is to increase snowfall of glacier accumulation during the winter and spring seasons, which requires the initiative to adapt to the current negative impacts of glacier changes on mountain tourism.

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