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# Divergent glacier area and elevation changes across the Tibetan Plateau in the early 21st century

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**Abstract:** With accelerated warming, mountain glaciers in most parts of the world have been in a state of continuous retreat in recent decades. Assessing glacier change and analyzing its influencing factors are essential for developing climate change mitigation and adaptation measures for a given region. This study provides a spatially explicit assessment and quantification of glacier changes in the early 21st century on the Tibetan Plateau (TP) at individual glacier and basin scales. We established a one-to-one correspondence between the Second Chinese Glacier Inventory (CGI-2, collected from 2004 to 2011) and a dataset of glacier inventory in Western China during 2017–2018 (CGI-2018). The majority of TP's glaciers decreased in size with a mean area retreat rate during the investigated period of 4.1%/decade. In addition, a mean change of the median elevation of the glaciers of 6.7 m/decade was detected. Approximately 2.5% of the total number of glaciers mapped in CGI-2 disappeared, while 681 of them divided to 1758 glaciers as they retreated. The observed variations follow local trends and have different regional characteristics. Generally, the glaciers with the lowest retreat rates are found in the Karakorum and Kunlun Mountains, while those with high retreat rates are concentrated along the Gangdis and Tangula ranges. The observed changes in glaciers are mainly attributed to a significant increase in temperature. Other factors including glacier size, debris cover, orientation and mean elevation also contribute to the heterogeneity of glacier variability. This study provides for the first time a detailed spatially explicit analysis of the glacial changes on the TP in the early 21st century, substantially improving the understanding of glacier response patterns and supporting more sustainable utilization of regional water resources in the TP in the context of climate warming in the 21st century.

**Key words:** Glacier change; Influencing factor; Chinese Glacier Inventories; Tibetan Plateau

## 1 Introduction

Mountain glaciers make up only a minor fraction of all glaciers on earth compared to the Antarctic and Greenland ice sheets, but their retreat has dominated the eustatic sea-level contribution in the past century (Meier et al., 2007; IPCC, 2019). As an important component of the cryosphere, mountain glaciers are the most sensitive indicators of climate change (Solomina et al. 2016; Khromova et al., 2019). With accelerated warming, glaciers in most parts of the world have been in a state of continuous retreat in recent decades (Zemp et al., 2015; Xiao et al., 2023a), which made significant implications for ecology and human activities (Carey et al., 2017; Stuart-Smith et al., 2021). Glaciers are regarded as the "lifeline" of arid zones, and the functions they provide for ecosystems and people are closely linked to sustainable socio-economic development and human well-being (Su et al., 2019). They provide essential water-related ecological services in the context of the severe shortage of freshwater resources in inland dry desert areas (Sun et al., 2018). Therefore, glacier changes can have many negative effects on natural and socio-economic systems, such as water scarcity (McDowell et al., 2013; Byers et al., 2012) and direct glacier-related effects such as ice avalanches, glacial lake outburst floods and glacial mudslides, etc. (Richardson and Reynolds, 2000; Haeberli et al. al., 2014; Kääb et al., 2018).

The Tibetan Plateau (TP) is the most glaciated region at middle and low latitudes providing a significant contribution to the global water cycle (Mölg et al., 2014). The special terrain of the TP and surrounding mountains in the global circulation system makes it the center of core glaciers in China and throughout Asia (Yao et al., 2012). Most major rivers in Asia are recharged by TP's glacial meltwater, which are important for maintaining the region's fragile ecological balance and sustainable socio-economic development, hence glacier research on the TP has been of great interest to scientists worldwide (Immerzeel et al., 2010; Yao et al., 2022; Su et al., 2022a). In recent decades, global warming has accelerated the overall shrinkage of glaciers and perennial snow cover in the TP. Systematic regional differences in glaciers further complicate the understanding of glacier responses to local and regional climate (Li et al., 2019a).

In recent decades, many studies have used in situ observations to investigate changes in glacier mass and length in typical glacier areas (Gardelle et al., 2013; Zemp et al., 2014; Gurung et al., 2023). Field observations are the most direct way to obtain high-accuracy measurement data suitable for long-term monitoring of typical glaciers and accurately reflect the response relationship between glacier ablation and climate change (Guan et al., 2020). However, field observation represents only a small sample size because it is often difficult to conduct comprehensive monitoring on a large scale due to the influence of complex terrain factors and harsh climatic conditions, as well as the significant staff and resources required (Liu, 2012; Pfeffer et al., 2014). With advances in science and technology, remote sensing has become an effective method of glacier monitoring, allowing large-scale monitoring and assessment of glacier distribution and associated changes (Paul et al., 2015; Zhou et al., 2020). Numerous recent studies have used remote sensing to analyze glacier changes at different scales, e.g., in the Qilian Mountains (Sun et al., 2018), the Gangdisê Mountains (Liu et al., 2020a), the Tanggula Mountains (Duan et al., 2019), the Himalayas (Xiang et al., 2018; Zhao et al., 2020), and the Karakorum Mountains (Liu et al., 2022; Li et al., 2019b). large-scale surveys of glacier change are still lacking, especially in the TP. Currently, there are only a few studies that address glacier changes on a large geographical scale. For instance, Yao et al. (2004) and Zhang et al. (2011) used estimation methods to determine the trend of glacier changes in China based on regional glacier monitoring and change data, as well as climate change information. Some studies have provided a broadly consistent description of glacier retreat in China in recent decades, but they mostly combine literature reviews and limited statistical sample analysis with large uncertainties (Xiao et al., 2007; Tian et al., 2016). Glacier inventories are fundamental to quantify glacier change, which also provides a basis for ice volume estimates (Radić and Hock, 2010; Grinsted, 2013; Bahr et al., 2015; Farinotti et al., 2019), hydrological modeling (Radić and Hock, 2011), regional water resource planning, and prediction of global sea level change (Gardner et al., 2013). Su et al. (2022b) connected the glaciers between the first and second Chinese Glacier Inventories (from the 1960 s to the 2010 s) one by one to systematically explore the glacier changes at both the individual glacier and river basin scales for the first time. However, the continuous rise in temperature has led to a substantial retreat of glaciers on the TP, leading to changes in the hydrological cycle and water resources throughout the region (Jiao et al., 2015; Bibi et al., 2018).

Therefore, there is still a lack of comprehensive and systematic investigations of glacier change on a large scale in the whole TP, especially for the last two decades.

To address the existing knowledge gaps on glacial responses to changes in climate at large and regional scales in the TP, we establish a one-to-one correspondence between glaciers based on the glacier inventories since 21st century. Therefore, the second Chinese glacier inventory (CGI-2) and a dataset of the glacier inventory in Western China during 2017–2018 (CGI-2018) compiled by Ran et al. (2021) were selected for this study. Specifically, this paper carries out the following analyses:

(1) Establishing a one-to-one correspondence between glaciers from CGI-2 to CGI-2018 to provide a spatially explicit assessment of glacier changes on the TP at individual glacier and basin scales, and discriminating the disappeared and divided types of glacier evolution.
(2) Analyzing the glacier change under different altitudes, slope, orientation, size and debris cover systematically, and discussing the possible impact of these factors on the glacier changes.
(3) Discussing the reasons related to climate change for glacier changes.

With a detailed spatial explicit analysis of the glacier area and elevation changes across in the TP, this paper provides both information on their responses to climate change in the early 21st century, and for the further analysis of the connected development of glacier-related ecosystem services and disaster as scientific basis for supporting decision-making on sustainable regional development.

## 2 Materials and methods

### 2.1 Study area

The TP is located in the southwest of China, with the terrain extending from high in the northwest to low in the southeast. With an average altitude of 4500 m, it is the largest plateau in China and the highest in the world, and it is known as “the roof of the world” and “the third pole” (Yao et al., 2022). The TP and its surrounding area have the largest ice reserves outside the Antarctic and Arctic (Yao et al., 2012). According to the dataset of CGI-2, there were 40,269 glaciers in the TP, accounting for about 84% of the glacier area in China and half of the glacier area in Asia (Qin, 1998) (**Fig. 1**). TP glaciers are mainly distributed in the peripherical mountain areas of the plateau, such as the Himalayas, the Karakorum Mountains, the Hengduan Mountains, as well as the Kunlun Mountains and the Qilian Mountains, etc. The glaciers here are large in scale and relatively concentrated, and some of the large glaciers in China are more developed in this area. Flat-topped glaciers and small ice caps are mostly developed in the interior mountains of the TP, where glaciers develop on a smaller scale than in the areas because the supply of water vapor is blocked by the conditions in the extremely high mountains.

The glaciers on the TP are an important source of supply for the inland water system in the hinterland of the plateau and the drainage system at the edge of the plateau, as they store large amounts of freshwater that affect the livelihoods of more than 1.4 billion people. Therefore, the TP is also called the "water tower of Asia" (Immerzeel et al., 2010; Pritchard et al., 2019). The glaciers in the TP are highly vulnerable to climate forcing and have important feedbacks to climate change (Yang et al., 2019). From 1960–2010, the rate of temperature increase was 0.20 °C decade$^{-1}$ (Chen et al., 2013). Over the past half century, the TP climate has warmed on a large scale, with significant regional differences and more warming than in the Northern Hemisphere and global average (Liu and Chen, 2000; Yang et al., 2019). Temperature increases occur in all four seasons, and are particularly pronounced in winter (You et al., 2008). There is a general trend of shrinkage of glaciers in the TP and surrounding areas, as evidenced by a reduction in area and an increase in glacier terminal lakes. However, there are significant differences in rate of glacier shrinking in different regions. In the context of global warming, the glaciers of TP have undergone considerable change and received much attention.

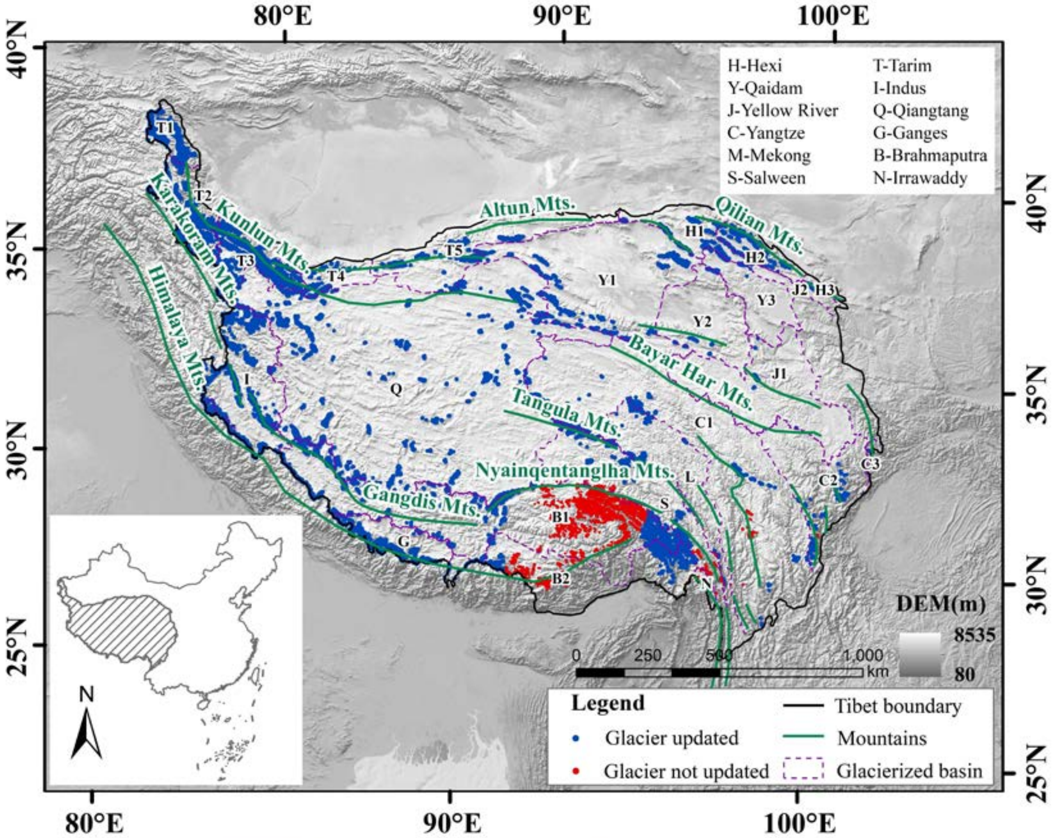


**Fig. 1.** Geographical location and distribution of glaciers of the TP in CGI-2. The blue points indicate the glacier information updated to the 2000s to the 2010s period, while the red points are not updated and follow the information from the CGI-1.

We explore glacier changes and its spatial heterogeneity on the river basin scale, so we divide the TP into 24 glacierized basins and grouped them into 12 glacierized macroscale basins (**Fig. 1**, see right upper corner: H-Hexi, Y-Qaidam, J-Yellow River, etc.). River basin data were obtained from the Data Centre for Resource and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn).

## 2.2 Glacier inventory datasets and processing

The first China Glacier Inventory (CGI-1) was conducted from 1978 to 2002 based on the International Commission on Ice and Snow recommendations for the World Glacier Inventory (WGI). In 2006, the Ministry of Science and Technology of China initiated the project "Investigation of Glacier Resources and their Changes in Western China. From 2006–2012, the second China Glacier Inventory (CGI-2) was carried out (Guo et al., 2015; Liu et al., 2015). In addition, there are a number of glacier catalogues available for the TP, such as Randolph Glacier Inventory (RGI Consortium 2017), the Glacier Inventories for the Western Himalayas (WHGI) (Frey et al., 2012), the Glacier Inventory for the Karakoram and Pamir region (KPGI) (He et al., 2022), and the Glacier Inventory for the Southeastern Tibetan Plateau (SETPGI) (He et al., 2022).

According to He et al., (2022), the comprehensive quality of the small-scale glacier inventories of WHGI, KPGI, and SETPGI is higher than that of the large-scale glacier inventories of RGI, GGI-1, and CGI-2. However, these inventories differ in many ways, including their timing, spatial coverage, sources of remote sensing data, mapping methods, etc. (Racoviteanu et al., 2009; Paul et al., 2017). To ensure consistency of the study, we need to select the same geographic range and data sources. CGI-2018 was on CGI-2 and provides glacier attributes for China for 2017–2018, which are used to determine the spatial attributes of mountain ranges, watersheds and administrative units to which glaciers belong. Therefore, CGI-2 and CGI-2018 are used in this study. The high accuracy of this dataset allows for better observation of the variability of very small glaciers (area <1 $km^2$), which account for 80% of the world's glaciers. CGI-2 and CGI-2018 complied vector maps of glacier distribution and basic parameters (such as longitude and latitude, area, length, elevation and orientation) during two different periods (the 2000 s to the 2010 s and the 2017–2018) (Su et al., 2022b). **Table 1** lists the specific information of these two datasets.

CGI-2 uses Landsat TM/ETM+ and SRTM V4 with 30 m resolution as the data source for glacier boundary and elevation attribute extraction. The SRTM DEM data originally produced by the NASA have the advantage of synchronization (Jarvis et al., 2008). To date, 86% of the glaciers in the western region have been catalogued, with a total of 42,370 glaciers updated, of which 32,889 were contained within the TP. The yet unfinished part is mainly located in the Hengduan Mountains and the middle and eastern part of the Nyenchen thanglha in the southeastern part of the TP (**Fig. 1**). These areas are influenced by the Indian monsoon, have abundant precipitation and are covered by snow and clouds all year round, which caused no clearly visible source of high quality remote sensing data. The current CGI-2 continues to follow the 6201 glaciers from CGI-1, covering an area of 8753.5 $km^2$, which have not been updated. The basic data used for the CGI-2 has a high correction accuracy (Bolch et al., 2010; Guo et al., 2013), therefore the main source of error is caused by using the different method for glacier compilation. Mean glacier positioning errors in CGI-2 were ±10 m for clean ice and ±30 m for debris-covered glaciers (Guo et al, 2015). Therefore, the evaluated area error of all recorded glaciers in western China is about ± 3.2%, which is consistent with the error assessment results of most glacier catalogues and glacier change studies. The smaller the glacier area, the larger the relative error. Moreover, the error for the debris-covered areas are much larger than for the entire glacier areas, reaching ± 17.6% of the debris-covered ice in CGI-2.

**Table 1** Key information about the datasets used in this study

| Dataset | Period | Data description | Spatial/Temporal resolution | Source |
|---|---|---|---|---|
| CGI-2 | 2004-2011 | Using Landsat TM/ETM+ and SRTM V4 as data sources | 30 m | https://data.tpdc.ac.cn/en/ |
| CGI-2018 | 2017-2018 | Using Landsat TM/ETM+; SRTM1 as data sources | 30 m | https://www.csdata.org/en/ |
| CMFD | 2000-2018 | Fusion of remote sensing products, reanalysis datasets and in-situ station data | 0.1°/ 3 hours | https://data.tpdc.ac.cn/en/ |

CGI-2018 is based on CGI-2 and describes the changes in glacier status from 2017–2018 changes in the glacier state in western China. A total of 315 high-quality remote sensing images were selected from the United States Geological Survey (USGS) website and the Geospatial Data

Cloud as the basic data for this dataset. Among them, about 78% of the images were concentrated in 2017 and 2018, and images from the summer and fall seasons (June to November) accounting for 65% of the selected image data (Ran et al., 2021). According to the data quality assessment results, the error value of glacier area caused by the resolution of remote sensing images was ± 19.93 km², accounting for approximately ± 0.04% of the total glacier area in western China. This dataset is another comprehensive and systematic glacier inventory in China since CGI-1 and CGI-2, which can provide key information for this study to quantify glacier distribution and change in China in the last decade. In addition, during our calculation, we also found that some glaciers (n=471) have almost no area change, which may be due to the limitation of optical remote sensing images under cloudy, foggy and rainy weather at the time of cataloging, and a small part of glacier boundaries have no change, which is not as our focus of discussion.

Due to the lack of complete or accurate data, the southeastern TP (SETP) region was not discussed in this study. Therefore, we first removed 6201 glaciers from CGI-2 and CGI-2108 that had not been updated in SETP, and retained 34068 and 34379 glaciers in CGI-2 and CGI-2018, respectively. We then tried to establish a one-to-one correspondence by discerning the evolution of different types of glaciers one by one based on their locations and boundaries in CGI-2 and CGI-2018, referring to the different types of evolutionary trajectories of mountain glaciers proposed by Su et al. (2022b). We found that only 200 glaciers in CGI-2 could not be well matched in terms of position or outline, and these glaciers had more obvious errors in CGI-2 and/or CGI-2018, so we eliminated these glaciers and finally used 33,868 glaciers in CGI-2 as the sample for this study. In CGI-2018, however, due to data errors, the area in and around SETP was omitted from CGI-2, corresponding to 34,103 glaciers in CGI-2018. The number and proportion of glaciers sampled from each basin are described in **Table S1**. Overall, the vast majority of glaciers are considered as samples. After excluding 6201 glaciers, the number of sample glaciers in this study accounts for 99.4% of the total. Among them, the sample number of glaciers in Zangnan basin and Yarlung Zangbo basin is relatively small (proportion = 95.0% and 97.9%, respectively).

### 2.3 Quantification of glacier changes

The response of glaciers to ongoing climate change is manifested in changes in glacier parameters such as length, area, mass balance (MB), surface elevation, median elevation of the glacier (MEG) and equilibrium line altitude (ELA) (Vincent et al., 2013; Garg et al., 2017). Considering the consistency of data acquisition, the most representative factors reflecting the state and extent of glacier changes, i.e. area and MEG were selected for this study.

The area was already documented in the glacier inventory datasets, thus all parameters were taken directly from CGI-2 and CGI-2018 to avoid any digital errors. The glacier area changes are quantified by measuring the annual area change (AAC) and annual percentage of area change (APAC) (Su et al., 2022b). The AAC and APAC can be calculated as follows:

$$AAC = \frac{A_t - A_s}{Y_{t-s}} \quad (1)$$

$$APAC = \frac{A_t - A_s}{A_s \times Y_{t-s}} \quad (2)$$

$$Y_{t-s} = \frac{\sum_{i=1}^{m} A_i \times Y_i}{\sum_{i=1}^{m} A_i} - \frac{\sum_{i=1}^{n} A_j \times Y_j}{\sum_{i=1}^{n} A_j} \quad (3)$$

where $A_s$ and $A_t$ are the glacier area in CGI-2 and CGI-2018, respectively, and $Y_{t-s}$ is the time span between CGI-2 and CGI-2018. where $A_i$ and $Y_i$ are the glacier area and the associated time for the *i*th glacier in a basin during CGI-2018; $A_j$ and $Y_j$ are the glacier area and associated time for the *j*th glacier in the same basin during CGI-2; and *m* and *n* indicate the glacier number for this basin in CGI-2018 and CGI-2, respectively.

The ELA is the elevation of the glacier at the point where the annual material accumulation equals the annual material (Wang et al., 2019). As the ELA increases, glacier will retreat due to the increasing ablation, and as the glacier's ELA increases and exceeds the top of the glacier, the glacier will eventually disappear, On the contrary, if the ELA decreases, then the glacier will advance due to the increase of the material accumulation. The ELA can only be determined by field observation and calculation. Due to the extremely limited number of glaciers monitored in the TP and surrounding areas, it is currently not possible to determine the spatial characteristics of the change in ELA in this area (Pu et al., 2007). Osipov (2004) found that the ELA can be estimated by using the parameter of median elevation of the glacier (MEG). MEG is the contour elevation that divides its area into two equal parts. It is related to the morphological type and recharge method of glaciers, and thus indirectly reflects the hydrothermal conditions of glacier development (Liu et al., 1995). The SRTM GDEM-v3 (vertical accuracy ± 16 m) we used was downloaded from: http://earthexplorer. usgs.gov/. Based on the CGI-2 data description, we calculated the MEG in CGI-2018 by averaging the pixel values of the DEM within the glacier surface boundary. The calculation principle is the histogram elevation value corresponding to the number of DEM pixels in the cumulative histogram obtained from the mask when the number of DEM pixels reaches half the number of all pixels. Similar to the quantification of AAC, annual MEG change (AMC) was also used to estimate glacier MEG change. In addition, an area-weighted period was also used to quantify AMC within the glacier basin.

### 2.4 Climate factors influencing glacier change

Climate conditions are the dominant factors influencing glacier development and change (Scherler et al., 2011). Temperature and precipitation together determine the nature, development and evolution of glaciers (Oerlemans., 1994; Kraaijenbrink et al., 2017). In this study we use temperature and precipitation data from the China meteorological forcing dataset (CMFD) at a spatial resolution of 0.1°, which is the first high spatial-temporal resolution gridded near-surface meteorological dataset developed specifically for studies of land surface processes in China (He et al., 2020) (**Table 1**). The dataset was created by fusion of remote sensing products, reanalysis datasets and in-situ station data. Due to its continuous temporal coverage and consistent quality, CMFD is widely used in China. Compared to other datasets, CMFD showed the best performance in simulating temperature and precipitation on TP, and could simulate the spatial distribution and range of variation of monthly average temperature and precipitation in TP (Yang et al., 2021). Data limitations prevented the calculation of the difference in mean temperature for the five years before and after the two glacial catalogues. To detect multi-year trend of temperature and precipitation, Sen's slope was used to estimate the slope of trends (Sen, 1968), and the nonparametric Mann-Kendall trend test was used to quantify the significance of the trend with a confidence level of 95% ($P<0.05$) (Mann, 1945; Kendall, 1948). As climate change impacts cannot be matched one-to-one with individual glacier responses, we have divided the glacier units at a size of 0.1° × 0.1°.

## 3 Results

### 3.1 Spatial pattern of glacier changes at individual and basin scales

In this study, 34,068 glaciers in CGI-2 were analyzed in detail, accounting 83.3% of the total number of all glaciers in the TP. We established a one-to-one correspondence between CGI-2 and CGI-2018. The results show that during the CGI-2018 period, 842 glaciers (2.5%) disappeared, with a total area of 63.6 $km^2$. In addition, 681 glaciers divided during CGI-2 to 1758 glaciers during CGI-2018, and these glaciers divided into two or more branches as they retreated. In TP, the area of all the glaciers surveyed decreased from 35,102 $km^2$ to 33,890. 7 $km^2$, a decrease of 1,211.3 $km^2$, with AAC of -142.7 $km^2$/a and APAC of −4.1%/decade.

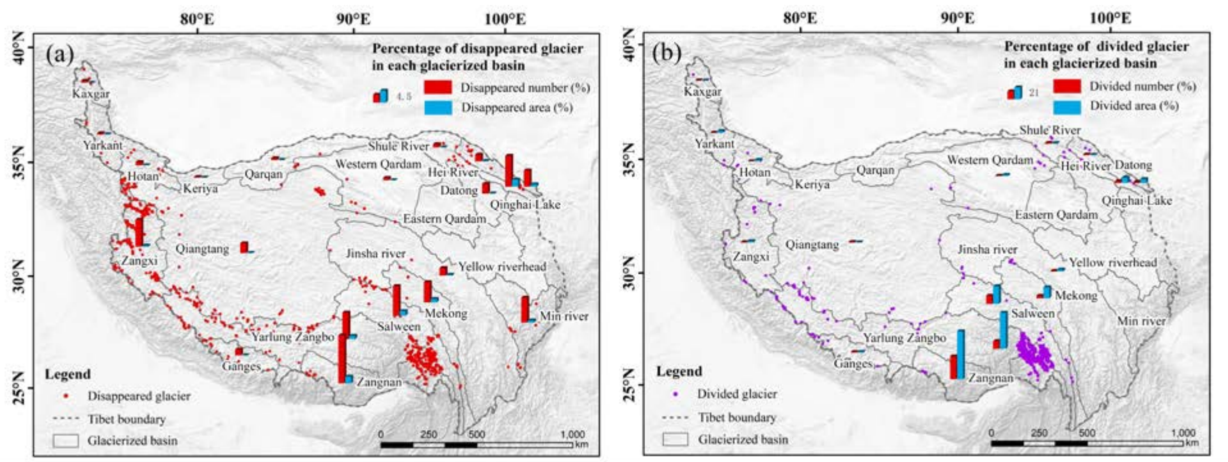


**Fig. 2.** Spatial distribution of disappeared and divided glaciers, and their area proportion in each glacierized basin.

**Fig. 2** shows the spatial distribution of disappeared and divided glaciers in each glacierized basin. The results show that the largest number of disappeared glaciers is in the southern Tibetan basin (n = 9.1%), followed by the Datong (n = 5.9%), Salween (n = 5.6%), Zangxi (n = 5.1%) and Yarlung Zangbo (n = 5.0%), with the Yangtze River and Mekong also being distributed. We found that the proportion of basins with a large proportion of disappearance is not completely proportional to the proportion of disappeared area, suggesting that there is spatial heterogeneity in disappeared glaciers. For example, their number is relatively high in Zangnan and Zangxi basins, but the proportion of disappeared areas is small (n = 1.3% and n = 0.2%, respectively) while the proportion of disappeared glaciers in the Datong basin is relatively high (n = 1.4%). However, overall, most of the disappeared glaciers are small in size. Divided glaciers are mainly located in Zangnan (n = 18.9%, a = 39.8%), Salween (n = 6.7%, a = 14.5%) and Yarlung Zangbo (n = 6.4%, a = 30.0%) basins, but there are six basins that have no divided glaciers. It can be seen that divided glaciers mostly exist in highly glaciated areas. In general, the spatial distribution of divided glaciers and disappeared glaciers is consistent. The absence of disappeared and divided glaciers in the eastern Qaidam Basin and the upper Yellow River suggests that they are relatively stable in these two basins and less influenced by external factors.

**Table S2** and **Fig. 3** show the spatial patterns of area and MEG changes at individual glacier and basin scales for all investigated glaciers in TP from the CGI-2 to CGI-2018 period. These data provide spatially explicit information on glacier changes on TP since the 21st century.

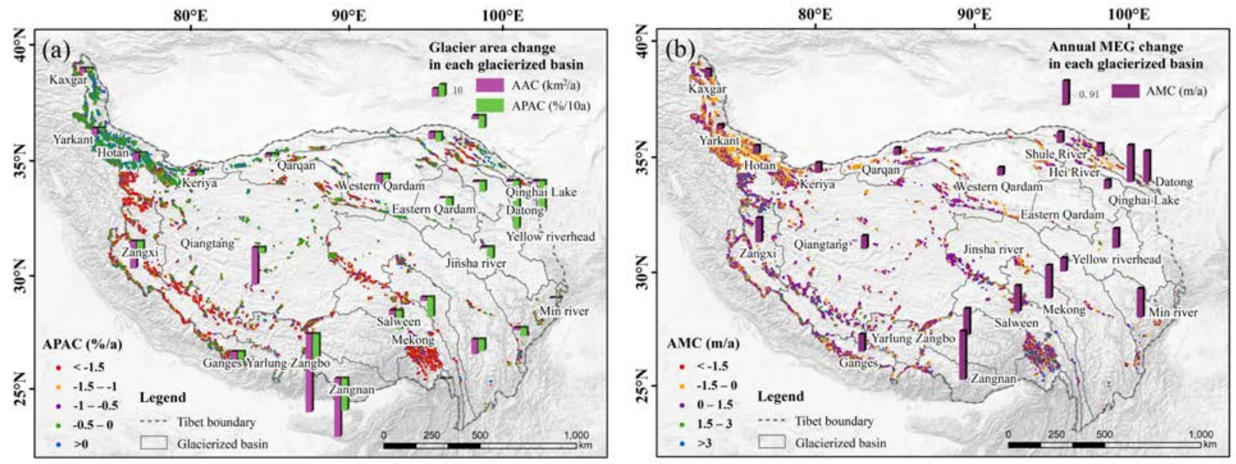


**Fig. 3.** Changes in terms of (a) area, (b) MEG for glaciers at both individual and basin scales.

Spatially, the glaciers with the lowest retreat rates are concentrated in the Karakorum and Kunlun Mountains. From the basin scale, the glaciers in the Tarim Basin have the lowest retreat rates, where a considerable number of glaciers have APAC of more than −0.5%/a or even positive values, and AMC of less than 1.5 m/a or even negative values. These basins specifically include the Kaxgar, Yarkant, Hotan, Keriya, and Qarqan basins. The mean APAC ranged from −1.6%/decade (Keriya) to −0.6%/decade (Yarkant), and the mean AMC ranged from 0.2 m/a (Yarkant) to 0.4 m/a (Keriya). In the meantime, we found some glaciers (n = 4412) with APAC > 0. Here, we cannot judge whether the change is due to advancement by glacier surges, or the abnormal increase in area caused by glacier collapse, so we did not discuss this category of glaciers separately.

The glaciers with high retreat rates are concentrated in the Gangdise and Tanggula Mountains. These ranges extend into the interior of TP, and the shrinkage rate of glaciers in most basins exceeds the average rate of the entire TP, with an average APAC of less than −5%/decade, and even −13.3%/decade (Zangnan) to −7.8%/decade (Salween) in the Mekong, Salween, Yarlung Zangbo, and Zangnan basins. AMC ranged from 9.7 m/decade (Salween) to 18.2 m/decade (Zangnan). For these regions, a larger proportion of glaciers divided, with more than 15−40% divided in the last decade, but not many disappeared.

The MEG increases with glacier retreat according to the decrease in area. The results show that the mean MEG increased for the majority of glaciers during CGI-2 to CGI-2018, and only 14.2% of glaciers had a decrease in AMC, with a mean AMC of 6.6 m/decade for the entire TP. Due to faster retreat rates, the MEG of disappeared glaciers increases much faster than other types of glaciers, even assuming that their extinction time is equal to the area-weighted average period of CGI-2. In terms of area, the retreat of divided glaciers was greater than the overall change rate of all surveyed glaciers in TP during the same period. This conclusion is consistent with Su et al., (2022b). The spatial distribution of AMC change and area change is consistent, that is, the basins with large area retreat has high MEG growth rate.

### 3.2 Glacier changes under different topographic conditions

The formation and development of glaciers is controlled by topographic conditions, which influence the extent and magnitude of their variability (Salerno et al., 2017). In this paper, orientation and slope are used to represent the direction and undulation of the terrain, and mean elevation is used to represent the difference in terrain of the landscape.

Overall, the average elevation of glaciers on the TP decreases from west to north and east. The highest average altitude is located in the Karakorum Mountains, the western part of the Kunlun Mountains, the Gangdis Mountains and the Himalayas (>5500 m). From the perspective of glacier basins, the highest average elevation of glaciers is located in Zangxi (5894.9 m), followed by the Qiangtang (5832.2 m) and the Ganges (5775.1 m); however, the glaciers in the Qilian Mountains have the lowest average elevation (Shiyang River = 4489.9 m, Hei River = 4698.6 m, Shule River = 4926.9 m). The area of TP glaciers at different altitudes has obvious variability and regularity (**Fig. 4**). The variation pattern is as follows: the glacier distribution area increases with the elevation and starts to decrease gradually after reaching a certain altitude. Elevation within glaciated areas affects glacier variability, mainly due to changes in climatic conditions, particularly air temperature. Within the troposphere, air temperature decreases continuously with increasing altitude, while moisture changes differ, according to Li et al., (2019c), the water vapor content in the air increases and then decreases with increasing altitude. In terms of elevation gradient changes, the glacier area decreases in almost all elevation gradients, with the highest retreat rate in the gradient below 4500 m. It is clear that the elevation gradient is negatively correlated with area loss and retreat. Glaciers with lower elevation range are more degenerated than glaciers with higher elevation range.  This could be due to glaciers at higher elevations receiving more snowfall while air temperatures are lower. (Allen, 1998). We found that the glacier area in south of TP has a relatively larger elevation span, and the TP inland extends to Tarim basin, where the glacier has a smaller elevation span. The absolute area change of each basin has a consistent pattern, but the relative rate of change shows irregularities. For example, the relative change rates of Mekong and Salween show an opposite trend to other basins.

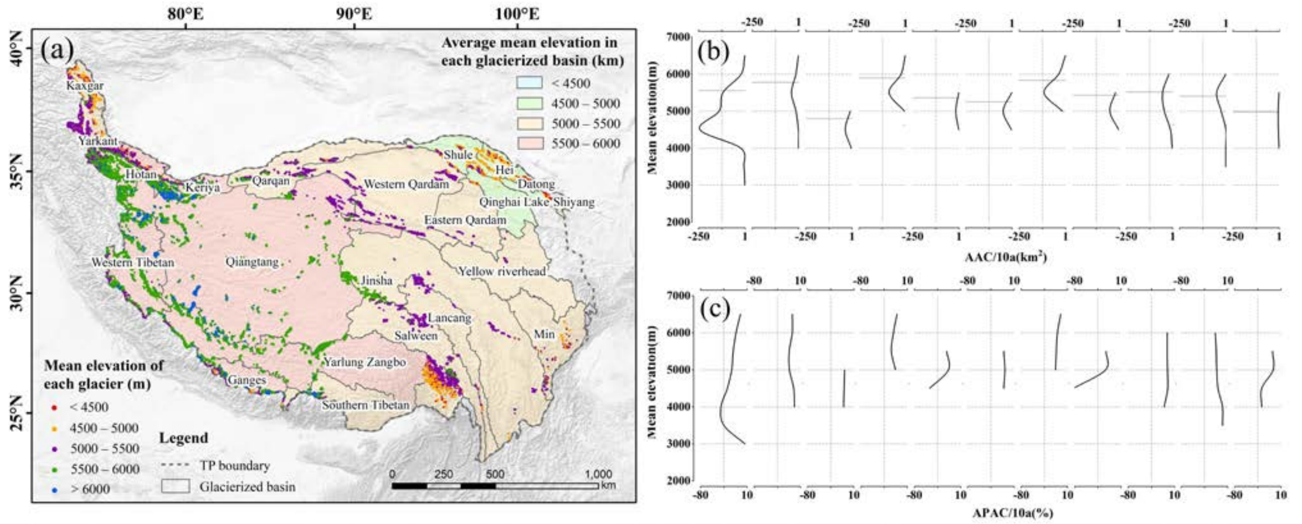


**Fig. 4.** Distribution of glaciers at different altitudes and their area changes (AAC, APAC).

Slope gradient affects ice velocity, mass flux, and snow accumulation rates through its effect on avalanche transport of snow on glacier surfaces (Oerlemans, 1989; Hoelzle et al., 2003). Therefore, slope within the glacial areas has a significant influence on glacier movement and storage (Su et al., 2022b). In general, a large slope is not conducive to glacier storage, but favors glacier movement. **Fig. 5** (a) shows that the distribution of slope is irregular. The basins with the highest average slope are the Hei River (27.80°), Minjiang River (27.59°), and Kaxgar (27.32°). Conversely, the average slope of glacial basins is smallest in Jinsha River (21.97°), followed by Qiangtang

(22.33°) and Salween (22.46°). In this study, the slope of TP glaciers is divided into 6 grades at intervals of 10°. During CGI-2 to CGI-2018, TP glaciers were less distributed in the range of 0– 10° slope, and the range of 20°–30° slope was the largest, followed by 10° ~20° and 30°~40°, and decreasing in order thereafter. In summary, most of the TP glaciers are distributed in gentle areas (20°–30°), while there are fewer glaciers distributed in extremely gentle areas (<10°) and relatively steep areas (>50°). Overall, the retreat rate of glaciers in TP showed a trend of increasing and then decreasing with the increase of slope. At the same time, we note that glaciers on steeper slopes retreat faster than those on relatively gentle slopes. According to **Fig. 5** (b,c), the APAC of glaciers in all basins decreases to different degrees at different slopes. Glaciers at 10°– 40° are distributed in all basins, while glaciers at < 10° and > 40° are not distributed in a small number of basins. We found that the APAC of Brahmaputra, Ganges, Hexi, Tarim, Indus, and Mekong had the largest values in the slope range of 0°–10°, while there was no specific pattern in the slopes of the other basins with the largest relative retreat.

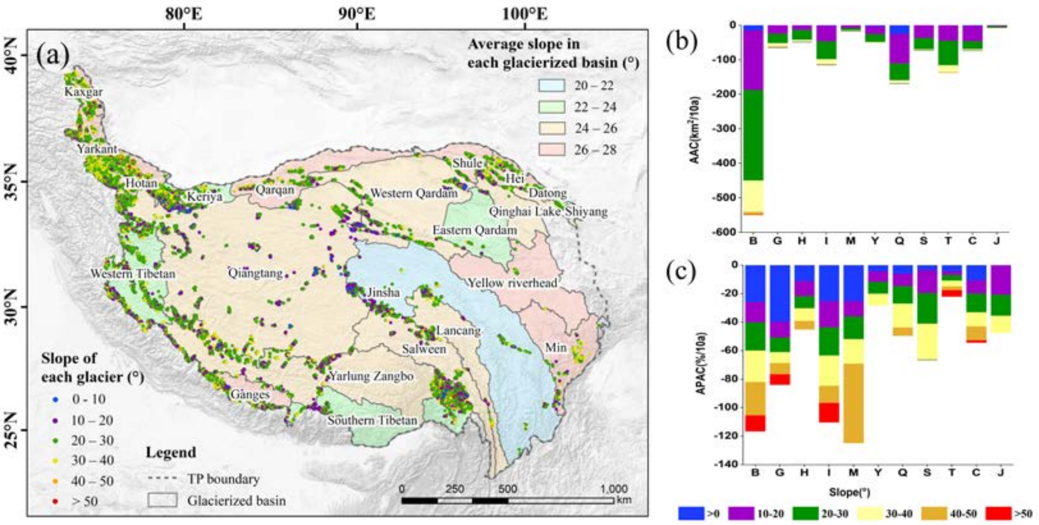

**Fig. 5.** Distribution of glaciers at different slopes and their area changes (AAC, APAC).

Orientation can control the heat balance of glaciers and is an important topographic factor affecting glacier changes (Zhang et al., 2022). The glaciers in TP are largest in the north and northeast directions. The TP consists of numerous northwest-southeast trend mountain ranges and wide valleys, making the north and northeast orientations receive less solar radiation and lower temperatures, which is conducive to glacier development, while the south direction inhibits glacier development by strong solar radiation effects. The glaciers in the west (W) direction are decreasing fastest, the glaciers on the west slope are larger than those on the east slope, and the glaciers on the north slope (including the northwest, north and northeast directions) are larger than those on the south slope. According to DeBeer and Sharp (2009), the sun-facing orientation receives the maximum energy during mid-afternoon, since the sun typically moves westward. This seems to be the most likely reason for the rapid retreat of west-facing glaciers. The aspect within the glacier areas influences the intensity of the glacier retreat mainly by affecting climatic conditions such as solar radiation and air temperature (Su et al., 2022b). **Fig. 6** (a) shows that the spatial distribution of slope direction of glaciers within the TP is also discontinuous. The results show that the association between precipitation and slope orientation is small at individual glacier scale ($R=-0.06$, $P<0.01$). From the basin perspective, except for Mekong, the largest absolute retreat area in all the basins was oriented north. Whereas APAC showed irregularity.

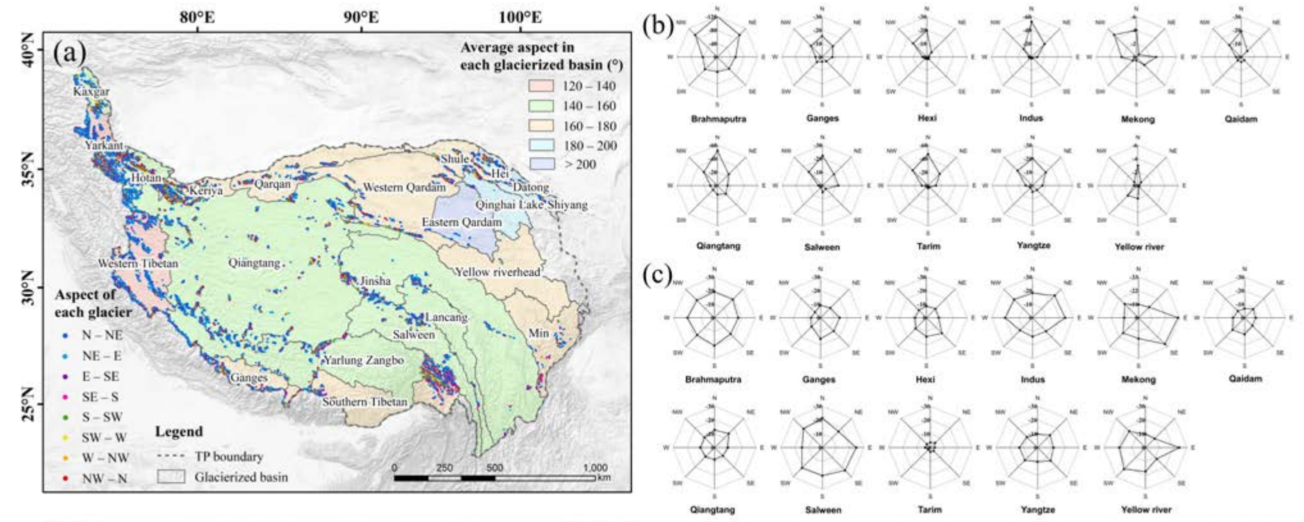


**Fig. 6.** Distribution of glaciers at different aspects and their area changes (AAC, APAC).

### 3.3 Glacier changes across different area sizes

The size of the glacier is a direct factor in the degree of glacier variability. Very small glaciers (with area ≤1 km²) account for 80% of the total number of glaciers in the world.

**Fig. 7** shows that inside TP the majority of glaciers are small ones. Large glaciers are mainly concentrated in Karakoram, western Kunlun and the Himalayas. The average glacier area is the largest in the Kaxgar (1.67 km$^2$), followed by the Keriya (1.56 km$^2$) and the Qiangtang (1.44 km$^2$). The smallest average glacier area is in the eastern Qaidam (0.19 km$^2$), followed by Datong (0.31 km$^2$) and Hei River (0.31 km$^2$). Referring to Su et al. (2022b), we further classified glaciers into seven classes: minimal (<0.2 km$^2$), small (0.2–0.5 km$^2$), medium (0.5–1 km$^2$), comparatively large (1–2 km$^2$), large (2–5 km$^2$), very large (5–10 km$^2$), and super glacier (≥10 km$^2$). Among them, the average area of glaciers in the Altun Mountains, Qilian Mountains, Gangdis Mountains, and Tanggula Mountains are all less than 1 km$^2$. The analysis reveals that the area of glaciers of all scales in TP shows a decreasing trend. Among them, the change rate of glaciers smaller than 0.2 km$^2$ is the largest (–12.22%), and the area change rate of glaciers larger than 10 km$^2$ is the smallest (–1.47%). There is a very high positive correlation between glacier size and AAC. Large glaciers tend to lose a larger absolute area, which has also been mentioned in other studies (Jiskoot et al., 2009; Garg et al, 2017). According to **Fig. 7**, small-scale glaciers in all basins showed high retreat rates; the APAC became smaller as the glacier size increased, and we found that glaciers with smaller size classes had larger fluctuations in glacier area. We explored the relationship between glacier area and glacier size, and found a significant positive correlation between glacier retreat rate and glacier size ($R=0.06$, $P < 0.01$). This suggests that small glaciers are more sensitive to climate change and are causing more dramatic retreat than large-scale glaciers, possibly because large glaciers take longer to respond to climatic perturbations (Li et al., 2011; Mehta et al., 2014).

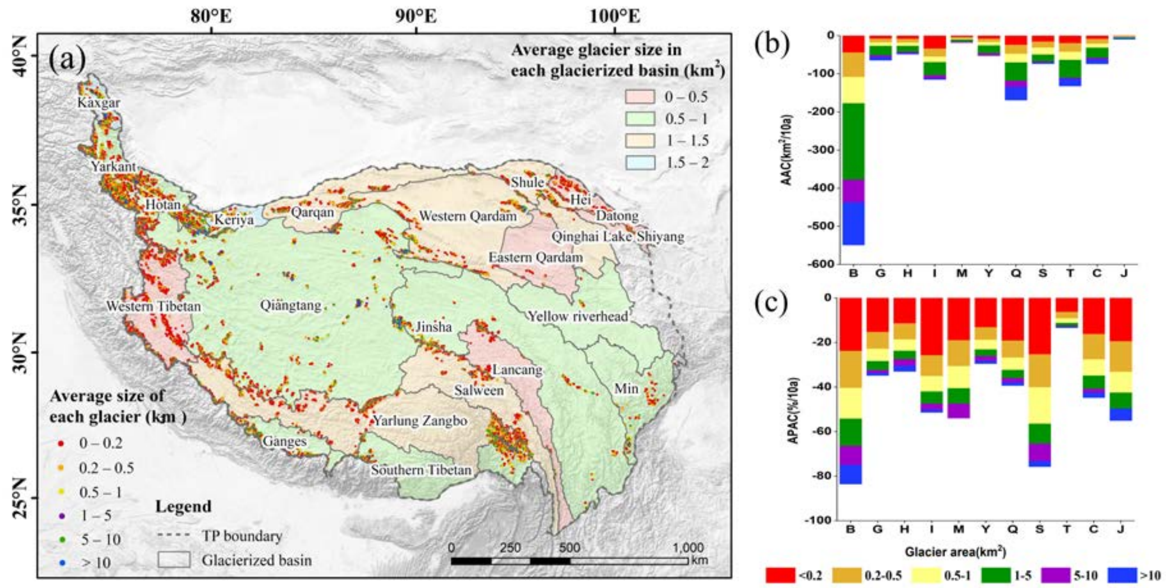


**Fig. 7.** Distribution of glaciers at different sizes and their area changes (AAC, APAC).

### 3.4 Debris-covered glacier changes

Glaciers have an erosive effect on bedrock, making some debris mixed in the glacier and often accumulate on the front surface of the glacier due to glacier movement, reducing the albedo of the ice surface causing the absorption of more solar radiation, which leads to enhance glacier ablation (Shroder et al., 2000). **Fig. 8** (a) shows that most of the glaciers in TP are not covered by debris (n = 32,933, p = 96.67%). The glaciers with high coverage are mainly concentrated in the Karakoram, Kunlun and Himalayas. Within the glacial basin, the debris cover is larger in the south of Tarim Basin (Kaxgar, Yarkant, Keriya, and Qarqan), Min River, Zangnan, and Ganges. Moraines covering glaciers generally affect glacier length, mass balance, and flow (Scherler et al., 2011). The areas with no debris coverage include the eastern Qaida, Datong and Qinghai Lake. Some studies have indicated that although the debris cover originates from rocks formed by weathering and denudation in the surrounding valleys, its distribution may also be largely influenced by the slope characteristics of the glacier (Shukla et al., 2010; Scherler et al., 2011). From **Fig. 8**, it can be seen that clean glaciers retreated and ablate more than glaciers with little debris glaciers covered with debris. When the debris layer on the glacier is very thick, solar radiation on the glacier surface is generally blocked significantly, so that the melting rate of the glacier will slow down exponentially with the increasing thickness (Benn et al., 2013; Juen et al., 2014). This would explain the clear positive correlation between debris cover and glacier size (Su et al., 2022b). We calculated the correlation between glacier area and debris coverage of individual glaciers and found a correlation coefficient of 0.17 ($P < 0.01$) between glacier retreat and debris coverage.

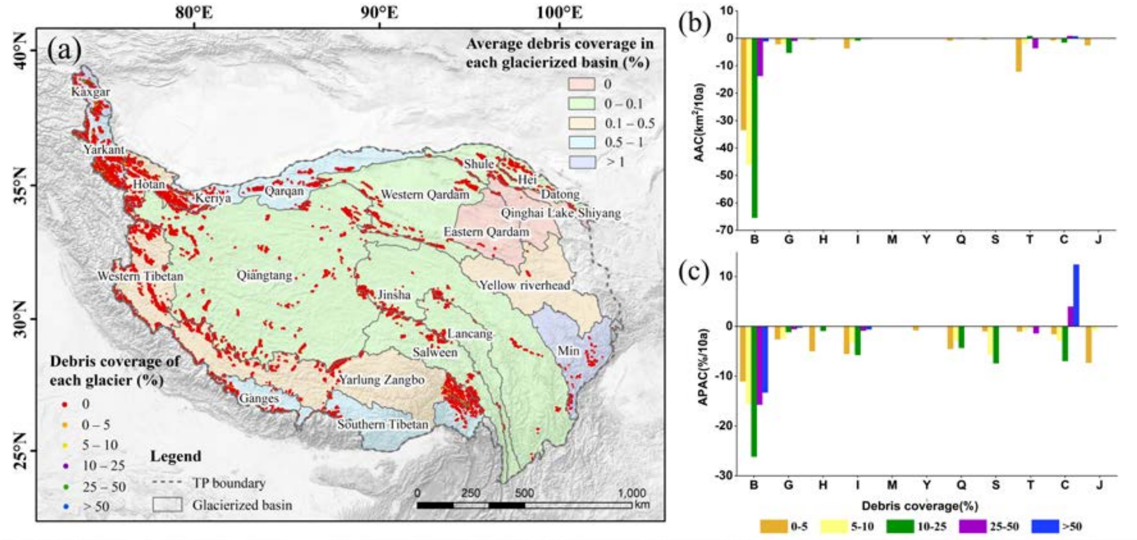


**Fig. 8.** Distribution of glaciers at different debris coverage and their area changes (AAC, APAC).

### 3.5 Climate factors of glacier change

Temporal changes in temperature can be seen in **Fig.9** (a,b). During 2000-2018, the annual average temperature of the TP had an obvious upward trend, with a temperature tendency rate of 0.2 °C/decade, which exceeded the global warming rate of the same period by a factor of two (Chen et al., 2015). The warming rate of the glacier unit is slightly lower than that of the whole TP, at 0.08 °C/decade. **Fig.9** (c,d) shows the interannual evolution of precipitation in glacier basins and glacier units from 2000 to 2018. From the perspective of total annual precipitation, the average annual precipitation in the TP basin shows a downward trend, but the change is not significant. Relatively speaking, the precipitation change rate of the glacier unit is higher than that of the glacier basin, which is –9.9 mm/decade. This result is slightly higher than that mentioned by Yin et al. (2023) in the TP's glacial lake study, where the annual precipitation trend in the TP for the period 2000–2020 was –4.1 mm/decade, but the overall trend is consistent.

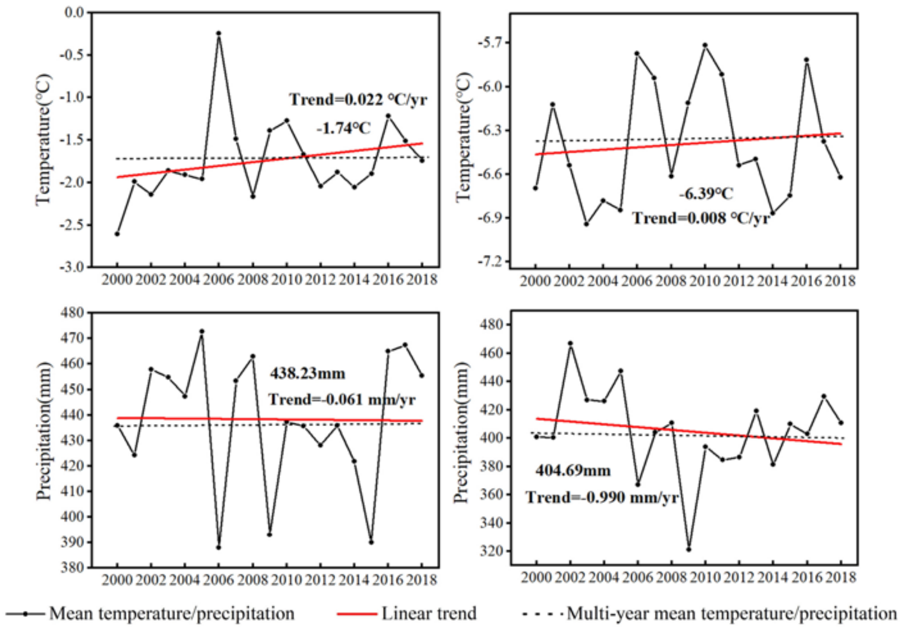


**Fig. 9.** Changes in temperature and precipitation during 2000–2018 on (a) (c) TP; (b) (d) glacierized

areas.

Even within the same climate region, glaciers respond differently to climate change, complicating the generalization of their changes over large regions (Oerlemans, 1989; Salerno et al., 2017), we found a similar pattern in this study. **Fig. 10** (a) shows that the TP has two low-temperature centers (Tarim and Hexi basins), and two high-temperature centers (Zangnan and Qaidam basins). The annual average precipitation on the TP has large spatial differences, and generally shows a gradual decreasing trend from southeast to northwest, which confirms the consistent trend described by Li et al. (2022). The precipitation is mainly concentrated in the lower reaches of the Yarlung Zangbo in the southeast of the plateau and Zangnan region (**Fig. 10** (b)). These areas are affected by the Indian monsoon and East Asian monsoon atmospheric circulation in summer, and the annual average precipitation is more than 1000mm, and the spatial distribution of precipitation is controlled by circulation (Liu et al., 2020b; Wang et al., 2021a). The spatial heterogeneity of climate within the TP has a significant influence on glacier distribution. Large glaciers are mainly found in areas with low mean annual temperatures such as the Karakoram and Kunlun Mountains, the low temperature and precipitation centers of the TP (Tian et al., 2016). On the other hand, small glaciers are concentrated in areas with high values of temperature such as the Qaidam area. The drier the local climate, the earlier a glacier exposes bare ice at a given elevation, and the longer the ablation takes (Abermann et al., 2011). However, there are some special cases: In the Himalayas, there are relatively many large glaciers despite the high temperatures, mainly because of the abundant precipitation in the region. Precipitation determines glacier accumulation, while temperature determines glacier ablation (Salerno et al., 2015). In conjunction with climatic influences, topographic conditions also strongly affect the extent and location of mountain glaciers (Abermann et al., 2011; Garg et al., 2017). Relatively high altitude of glaciers are mainly located in areas with cooler temperatures such as the Karakorum Mountains, the western Kunlun Mountains, and the Himalayas (Forsythe et al., 2017).

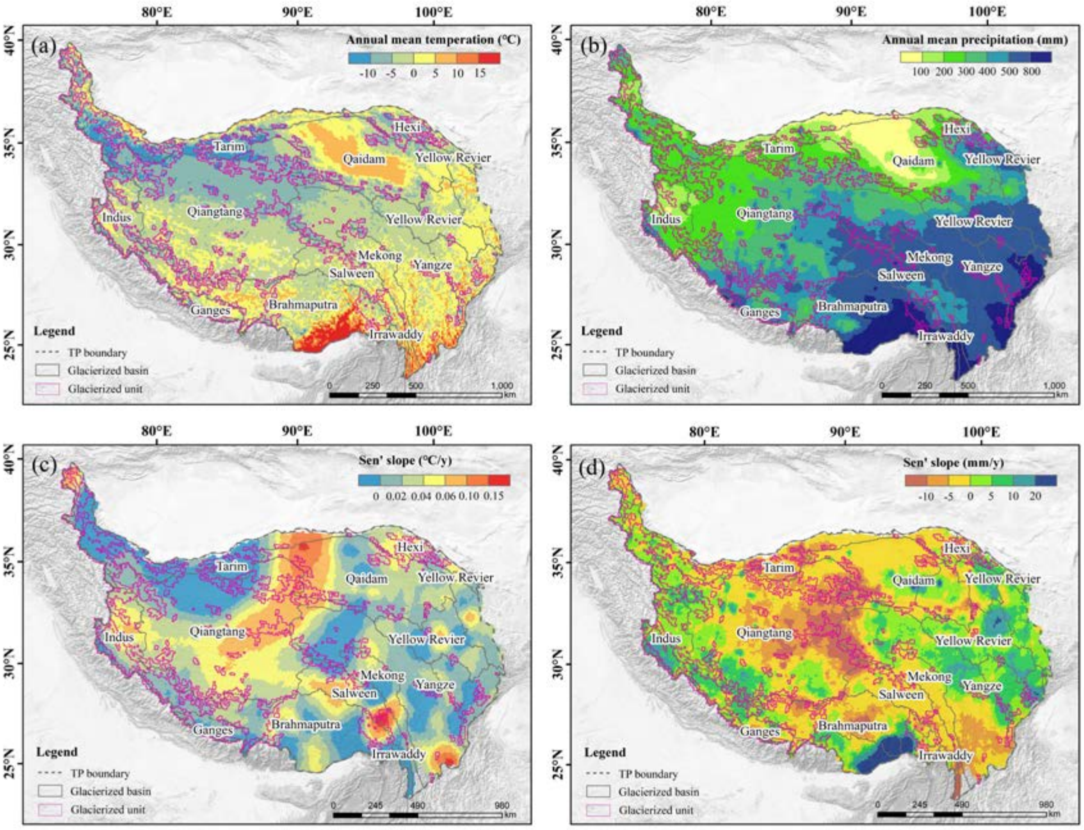


**Fig. 10.** Temperature and precipitation and their changes on the TP during 2000–2018. Spatial distribution of (a) annual mean temperature, (b) annual mean precipitation; Spatial distribution of Sen’s slopes for (c) temperature, (d) precipitation.

As shown in **Fig.10** (c), most areas of TP show a warming trend, with the largest warming trend in the western Hengduan Mountains. The regions with the smallest warming trend are concentrated in the southern part of Tarim. There are significant differences in the change patterns of precipitation in the south and north TP, and even show the opposite trend. From 2000–2018, precipitation patterns have significantly increased in the south and show a decreasing trend in the north, while the annual precipitation in the central TP declining (**Fig.10** (d)). The correspondence between precipitation and temperature on TP is generally characterized by a combination of warm-humid and cold-dry, which was consistent with previous research on TP (Niu et al., 2020; Wu et al., 2021). Clearly, temperature is the dominant factor in glacier retreat and ablation, even in debris-covered areas (Pratap et al., 2019). The glaciers with high coverage are mainly concentrated in the Karakoram, Kunlun and Himalayas. Increasing temperature contributes to the absorption of more thermal radiation at the glacier surface, which decreases the albedo of the glacier and accelerates glacier melting and mass loss (Zhang et al., 2021).

## 4 Discussion

In this first systematic comparison between two recent glacial inventories collected on the TP, we found the majority of TP’s glaciers decreased by an average AAC of 4.1％/decade during the investigated period. The observed variations follow local trends and have different regional characteristics.

**Table 2** lists the statistical results of glacier change rates within the TP from different studies.

Over the past 20 years, the retreat rates of glaciers in each basin within the TP showed the same trend in different studies. Xiao et al. (2023b) found a reduction rate of –0.46%/a for the SETP from 2000 to 2020, which is very close to our overall retreat rate (–0.41%/a). Zhao et al. (2021) investigated the distribution and change of glaciers in China from 2008 to 2018, and pointed out that the area change rate of the entire China was –0.43%/a, which is consistent with the retreat rate of the entire TP of this study. However, the change rate of glacier area shows some differences in different studies, which are mainly caused by different sources of glacier data and research periods, and even differences in the division of basins. For example, Zhao et al. (2021)'s division of basins (Ganges, East Asian endorheic, Qiangtang endorheic) is much larger than the definition of glacierized basins in this study. In addition, our research period is the past two decades, which is later than most previous studies, and it is difficult to compare due to the difference in the scope of the basin and changes of climatic conditions in more recent years.

**Table 2.** Overview of previous basin-scale glacier studies covering the TP after the 21st century.

| Study area | Study period | Rate of change in area | Data used | Source |
|---|---|---|---|---|
| Headwater of the Yellow River | 2000-2018 | –0.8%/a | Landsat TM | Zhang et al. (2022) |
| Tibetan Plateau endorheic basin | | –0.3%/a | | |
| Headwater of the Mekong River | | –2.0%/a | | |
| Pumqu basin | 2010-2020 | -0.7 %/a | Landsat TM | Tang et al. (2022) |
| Nujiang-Salween Basin | 2000-2020 | –1.2%/a | Landsat MSS, TM, ETM+ | Ji et al. (2022) |
| Southeastern Tibetan Plateau | 2000-2020 | -0.5%/a | Landsat TM/ETM+, ERS-2 | Xiao et al., (2023b) |
| Yellow River basin | 2008-2018 | -1.0 %/a | Landsat TM | Zhao et al. (2021) |
| Yangtze River basin | | -0.6 %/a | | |
| Mekong River basin | | -1.5 %/a | | |
| Salween River basin | | -1.2 %/a | | |
| Ganges basin | | -0.8 %/a | | |
| Indus River basin | | -0.8 %/a | | |
| East Asian endorheic basin | | -0.4 %/a | | |
| Qiangtang endorheic basin | | -0.3 %/a | | |

At the same time, we found the evidence for the "Karakoram anomaly". This phenomenon refers to the relatively stable glaciers in the Karakoram region in the past two decades (IPCC, 2019). The occurrence of this anomaly is mainly concentrated in the northwest of TP (Kaxgar, Yarkant and Hotan basins). This shows that due to the influence of decreased temperature, increased snowfall, and the low temperature sensitivity of debris-covered glaciers, glacier retreat is low in this region, and some glaciers even show surges and advanced phenomena (Bonekamp et al., 2019; Farinotti et al., 2020; Shean et al., 2020; Sun et al., 2022). In addition, the absolute glacier shrinkage area in the Ganges basin has a greater tendency to slow down (–25.89 $km^2/a^{-1}$ to –6.41 $km^2/a^{-1}$). This is likely due to the slowdown in the warming rate of the region since 2010 (Wang et al., 2021b). We found that the precipitation in TP decreased to a certain extent from 2000 to 2008, but showed an insignificant increasing trend after 2008. The AAC and APAC of Qiangtang also have a downward trend, which is similar to the reason for the slowdown of the retreat of the glacier in the Ganges basin. The arid precipitation distribution characteristics within the Qiangtang lead to a reduced degree of glacier retreat within the TP. We also found that the absolute retreat of the glaciers in Qaidam increased. The greater decline of this glacier may be mainly due to the temperature rise in the central and eastern Qilian Mountains and the surrounding areas of the Altun Mountains, and the increase in mass brought about by the increase in precipitation cannot fully balance the mass loss caused by the rise in temperature, which eventually leads to the degree of glacier recession in this area intensification. Previous studies (Brun et al., 2017; Shean et al., 2020) have shown that the SETP is one of the regions with the most significant glacier retreat across the TP and globally, which is consistent with our study. In this study, the relative shrinkage rate and median height of glaciers in the Yarlung Zangbo and Zangnan regions increased to varying degrees, and the shrinkage was the highest in the entire TP. The glaciers in this area are marine glaciers, and their changes are more closely related to precipitation. Wu et al. (2020) pointed out that the precipitation in the upper and lower reaches of the Yarlung Zangbo River has shown a decreasing trend in the past ten years, which is consistent with our results. The average annual shrinkage of glaciers in the Himalayas is the largest in the eastern section, followed by the western section, and the smallest in the middle section, which is consistent with the results of Shi et al., (2022). Here we also find that the shrinkage of glaciers is correlated with the rising temperature and the spatial patterns of the shrinkage were influenced by other factors superimposed on the rising temperature such as glacier size, type, elevation, debris cover (as also found by Tian et al., 2016). The amount of precipitation and its intra-year distribution and interannual variations affect glacier recharge and activity (Barnett et al., 2005; Yao et al., 2012). In our study, we found that the temperature in glacial areas in TP all show upward trends, while precipitation trend shows weakly positive (negative) characteristics of regional differences. This is largely consistent with Sun et al., (2022).

To further investigate glacier changes in TP after 21st century, we carried out a comparison with the results of Su et al. (2022b) who systematically investigated glacier changes in China (including TP) from 1960 s to 2000 s using the similar method (**Table S3**). We found that the overall retreat rate in our study was lower. Compared with the pre-21st century, the retreat rate in some basins has shown a trend of slowing down, which is mainly in Tarim, Qiangtang, ganges and Zangxi. However, some studies also suggest that there is a retreating trend in glaciers within China. Xiao et al., (2023b) revealed that glaciers in the SETP retreated faster in the period of 1970 s to 2000 than in the period of 2000–2020. Wang et al. (2020) used remote sensing in their study in the Tianshan Mountains of Xinjiang, China. Their results show that in most regions the rate of glacier mass loss has slowed down in the last decade (2010 s). We assume that in our study the result is mainly due to the use of different data sources for the three glacier inventories, which may lead to uncertainties and a loss of data precision. Second, our sample size (34068 glaciers) is larger than in the study of Su et al., (2022b) that used 26924 glaciers. In addition, there only a few studies on glacial changes in TP have been carried out during the past two decades, and most studies focused on long time series, mostly from 1960 s to 2010 s (Yang et al., 2019; Bhattacharya et al., 2021). Since the period of this study is nearly 15 years after 2000, and which cover only a relatively short period, the glacier change detected may have occurred in a relatively gentle period of fluctuating retreat. Therefore, further investigation on whether the slowing retreat is a general pattern and continuing requires further research. However, in terms of the trend of spatial change, this study is consistent with the trend of Su et al., (2022b).

Glaciers on the SETP have experienced significant mass loss in recent decades, about three times that of glaciers on the entire TP (Hugonnet et al., 2021; Brun et al., 2017). According to Xiao et al. (2023b), the retreat rate in the SETP from 2000–2020 is −53.97 $km^2$/a (0.46%/a). Compared to the retreat rate before 2000 (0.48%/a), the glacier retreated faster than in the last period. In this regard, the Nyainqentanglha region has the highest retreat rate, which is even much higher than that of the entire SETP; while Hengduan Shan and Eastern Himalayau are below the whole SETP retreat rate (0.43%/a and 0.36%/a, respectively). In this study, the number of glaciers in the SETP that we did not include in the sample size is much smaller than that of Xiao et al (2023b), and because of the inconsistent classification of basin, we can only make a local comparative assessment in a small area. Our results show that the shrinkage in Nyainqentanglh region is the highest in the whole SETP (e.g. Zangnan and part of Yarlung Zangbo watershed); Hengduan Shan (e.g. part of Jinsha River, Min River, Mekong, and Salween) has an average shrinkage rate of 0.56%/a, which is lower than the average for the entire SETP. The shrinkage rate of SETP in this study is slightly higher than that of the above studies, but this is mainly due to the imprecision of the data accuracy and the geographical division.

## 5 Conclusion

In this study, the detailed characteristics and spatial and temporal patterns of TP glacier development at the beginning of 21st century bare quantitatively assessed based on the second China Glacier Inventory and the 2017–2018 Western China Glacier Inventory datasets. We connected the glaciers between the two inventories one by one to explore the area and elevation changes. It provides the first comprehensive examination of glacier change on TP in the early 21st century at both individual and basin scale, and discusses the possible causes of the glacier changes. This study maps and quantifies the spatial patterns of glacier change on TP over the last 20 years in unprecedented detail and discusses the factors influencing glacial change in that period. This provides a scientific basis for a more comprehensive understanding of glacier response patterns and rational utilization of regional water resources in the TP in the context of climate warming in the 21st century. In addition, it serves as an important reference for the survival and development patterns of people in the TP and its surroundings, and even the entire arid region of Asia. We found that:

(1) 842 out of 33,904 glaciers have disappeared in the last two decades. 681 glaciers split into 1758 by 2018.

(2) we estimate that all surveyed glaciers in TP have an AAC of –142.7 $km^2$/a, an AMC of 9.1 m/decade, and their APAC is –4.1%/decade. The Karakorum and Kunlun Mountains regions exhibit the lowest retreat rates, while high retreat rates are found in the Yarlung Zangbo, Zangnan and Mekong River regions.

(3) Increasing temperature has the greatest influence on glacier retreat. TP glaciers are likely to continue to retreat in the coming decades. Small glaciers are most vulnerable to the influence of climate.

(4) While there is significant geographical heterogeneity in TP glacier change, climate is the main cause of glacier retreat.

Glacier retreat is a complex process, and its interactions with various factors are multifaceted, sometimes indirect, and vary widely in different parts of the world (Six and Vincent, 2023). To further understand the correlation between glacier retreat and its drivers across regions, in-depth research is needed to quantitatively evaluate glacier change mechanism and influencing factors. In addition, there is a need for more field work and improved modelling of physical glacier processes. Data quality has a major impact on the accuracy of glacier change assessment. There is still a lack of high-precision remote sensing assessment of the whole TP, which may have led to data uncertainty so far. Because the extent of mountain glaciers monitored in the field is too small and remote sensing images are subject to weather-related inaccuracies, it is currently difficult to make an accurate assessment of spatial and temporal changes of large-scale glaciers on an individual scale. Therefore, we need to further consider how to compare the results to clarify the trend of glacier changes when the temporal and spatial coverage of the study is different. In addition, the relationship between glaciers and the atmosphere is two-way, and the high albedo properties of glaciers also feedback on local atmospheric cooling. How to quantify the bidirectional feedbacks between glacier change and atmosphere to better understand the intrinsic driving mechanisms of glacier change still deserves further exploration.

Glacial change has a profound impact on the natural and human ecosystems of the surrounding areas (Qin et al., 2018). How to deal with the negative impact of glacier changes on human society, especially human life in arid areas, is a topic that requires more research. The study may add to an increased understanding of glacier changes on TP under climate warming in the 21st century and contribute towards regional socio-ecological sustainability research that identifies pathways to mitigate the negative consequences for ecology and society caused by glacial retreats.

## CRediT authorship contribution statement

**Can Zhang:** Conceptualization, Methodology, Visualization, Writing − original draft, Writing − review & editing. **Weijie Ran:** Methodology, Software, Writing -review − review & editing. **Shiming Fang:** Writing − review & editing. **Shougeng Hu:** Funding, Writing − review & editing. **Michael Beckmann:** Writing − review & editing. **Martin Volk:** Methodology, Writing − review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ancene.2023.100419.

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