scientific reports

OPEN

Spaciotemporal distribution characteristics of glacial lakes and the factors influencing the Southeast Tibetan Plateau from 1993 to 2023

Yu Mingwei[1,2,3], Guo Yonggang[1,2✉], Zhang Jian[1,2], Li Feng[1,3], Su Libin[1,2,3] & Qin Deshun[1]

The southeastern region of Tibet, which serves as the primary concentration area for marine-type glaciers, has fostered a multitude of glacial lakes that are highly sensitive to global climate change. Glacial lakes play a crucial role in regulating the freshwater ecosystems of the region, but they also pose a significant threat to local infrastructure and populations due to flooding caused by glacial lake outbursts. Currently, a limited amount of research has focused on the monitoring and analysis of glacial lakes in southeastern Tibet. Using Google Earth Engine (GEE) data in conjunction with meteorological data, this study examined the variation characteristics of glacial lakes in southeastern Tibet from 1993 to 2023. The region is subjected to segmentation and extraction of glacial lake boundaries via the FCN model. According to research findings, by 2023, southeastern Tibet is projected to contain 3,877 glacial lakes, encompassing an area of approximately 395.74 ± 22.72 km². The distribution of glacial lakes in this region follows a pattern characterized by a relatively high concentration in the southern region and a relatively low concentration in the northern region. The glacial lakes with areas less than 0.1 km² accounted for 94.24%, whereas those exceeding 3.0 km² experienced the least amount of change. The analysis of regional elevation using the natural segmentation method reveals that glacial lakes are predominantly distributed within the altitude range of 4442 ~ 4909 m. The fluctuations in the annual mean precipitation and average annual temperature in the study area have decreased since 2008, while the growth trajectories of both the area and number of glacial lakes have gradually stabilized. However, given the backdrop of a slight increase in precipitation and a gradual increase in temperature, the proliferation of glacial lakes is projected to accelerate predominantly in Nyingchi City's eastern and western regions.

Keywords Southeastern Tibetan Plateau, Glacial lake, GEE, Influencing factors, Object-based image analysis, Spatiotemporal evolution

The Qinghai-Tibet Plateau region has the highest concentration and expansion of glaciers beyond the Arctic and Antarctic regions[1]. Marine glaciers are predominantly influenced by the monsoon climate[2]. Due to the continuous rise in regional temperature, the densely glaciated areas on the Qinghai–Tibet Plateau have experienced different degrees of retreat and material loss[3,4]. Accelerating climate change has fostered conditions conducive to glacier melting, resulting in increases in the formation of glacial lakes in certain regions[5,6]. Many glacial lakes are mostly formed in low-lying regions[7], and the supply of glacial meltwater and rainfall also provides material support for the expansion of glacial lakes.

Glacial lakes are naturally occurring bodies of water formed through glacial activity[8] that serve as natural reservoirs for the storage of glacial meltwater and precipitation. They are intricately connected to the local hydrological cycle and serve as a significant reservoir of freshwater for the surrounding region[9]. However, they also pose a major risk of flooding at relatively high altitudes[10]. Although the frequency of glacial lake breaches has not significantly increased in recent years, the continuous expansion of glacial lake areas has resulted in

[1]College of Water Conservancy and Civil Engineering, Tibet Agriculture and Animal Husbandry University, Nyingchi 860000, China. [2]Research Center of Civil, Hydraulic and Power Engineering of Tibet, Nyingchi 860000, China. [3]Yu Mingwei, Li Feng and Su Libin These authors contributed equally to this work. ✉email: 708942514@qq.com

a heightened probability of glacial lake outburst disasters[11,12]. The potential for glacial lake outburst floods represents a significant threat to local infrastructure and personnel safety, leading to substantial economic losses[13]. The study of glacial lake changes at high altitudes has garnered increasing attention from researchers, as they have explored the positive or negative roles played by the development of these lakes in addressing the aforementioned issues.

In the initial stage, many researchers focused solely on conducting comprehensive investigations of local glacial lakes within the Qinghai-Tibet Plateau, employing diverse research methodologies to accurately delineate the spatial distribution of regional glacial lakes[14–16]. With the continuous increase in computer processing speed, an increasing number of researchers are conducting large-scale analyses of regional geological hazards and environmental changes in high-altitude areas[17–19]. Optical Landsat imagery has been widely used by many researchers because it has provided remote sensing images since 1972. The computing speed of cloud computing has experienced a remarkable surge in recent decades, and Google Earth Engine (GEE) has emerged as an indispensable research tool. The efficiency of regional spatial analysis for extensive coverage across multiple time periods has been significantly enhanced by the expansion of cloud computing[20,21]. The emergence of these new technologies has significantly increased the precision of delineating the vector boundaries of glacial lakes, yet systematic errors still exist in the automated extraction of glacial lake boundaries[22]. After automated processing, manual correction is essential.

The trend of glacial lake change in the Himalayan mountains and Nianqingtanggula Mountains has been subject to relevant research by some researchers in southeast Tibet[23,24]. The overall trend of glacial lake change can be effectively demonstrated through large-scale and long-term regional studies. However, the identification of boundaries for numerous micro and small glacial lakes in complex terrain conditions remains challenging[25,26]. Currently, advancements in machine vision for the extraction of glacial lake boundaries primarily emphasize automated recognition and segmentation. However, traditional machine vision techniques are unable to accurately identify and extract the boundaries of micro-glacial lakes[27]. The current research results are insufficient to accurately predict the timing and dynamics of major glacial lake outburst disasters. A comprehensive understanding of the formation mechanisms and dynamic processes of glacial lakes in the study area is essential. Specifically, it has the capability to fully and accurately identify and extract the outline of glacial lakes, as well as comprehend their change processes. To accurately assess the risks associated with glacial lake disasters and to propose effective scientific prevention and control measures, it is essential to establish a theoretical model, integrate field observation data, and analyze the dynamic processes underlying glacial lake formation. The effects of lake expansion, outbursts, and secondary disasters on surrounding areas were quantitatively analyzed. Modern scientific and technological methods, such as numerical simulation and remote sensing monitoring, are utilized to assess changes in risk levels under future scenarios. Subsequently, tiered and classified monitoring systems, along with early warning and emergency prevention and control measures, are formulated to provide a solid scientific foundation for decision-makers.

The ongoing update of the glacial lake resource dataset in high-altitude regions is essential for studying the spatial distribution of glacial lakes and analyzing the risks associated with geological disasters, including plateau glacier changes, climate change, and glacial lake outburst floods[28–30]. This study analyzes the dynamic changes in glacial lakes in the southeastern Qinghai-Tibet Plateau from 1993 to 2023, utilizing the Google Earth cloud computing platform and Landsat remote sensing data. The spatial distribution of glacial lakes at various elevations in southeast Tibet is investigated based on an analysis of meteorological data. The boundaries of glacial lakes within the study area are delineated and extracted using a complete convolutional segmentation model. Additionally, the variations in the number and area of glacial lakes over the course of three years are analyzed. This model utilizes a convolutional neural network architecture capable of end-to-end pixel-level classification, thereby enabling accurate extraction of target boundaries directly from remote sensing images. By analyzing time series images, dynamic changes in the lakes can be continuously tracked, offering valuable data to inform the development of relevant policies. This study examines the formation mechanisms and dynamic changes of glacial lakes by quantifying the water demand in the study area. The findings presented herein provide significant insights for the development and utilization of water resources, environmental protection, and disaster prevention in southeastern Tibet.

Study area

The average altitude of the study area is 4,100 m, while the maximum elevation reaches 7,782 m. Additionally, the region features rugged terrain in both the western and eastern directions (Fig. 1). The primary research focus of this paper encompasses Nyingchi and Qamdo. The predominant glacier type in the study area is marine glaciers. The glacier encompasses a total area of 3,128.97 km^2 and comprises a total of 3,394 individual glaciers. A study of glacier distribution data from the Global Glacier Monitoring Service (GLMS) revealed that there are 2,925 glaciers in southern Tibet with areas of less than 1 km^2, which constitute 86.18% of the total glaciers in the region. Small glaciers of significant concern are located primarily in the border regions of Tengchen and Bandar, the northern and southern border areas of KampoJiangda, and the eastern border area of Miling. In the study area, numerous mountain ranges exist, including but not limited to the Hengduan Range, Nyantanggula Range, and Himalayas[31].

Data and methods

Most glacial lakes are situated in remote regions, making comprehensive field studies challenging. Consequently, remote sensing data has increasingly emerged as a convenient tool for studying the long-term changes in glacial lakes[32–35]. Landsat optical imagery is now extensively utilized to provide the remote sensing data required for Earth science analyses. The satellites are equipped with a range of sensors, including the Landsat MultiSpectral
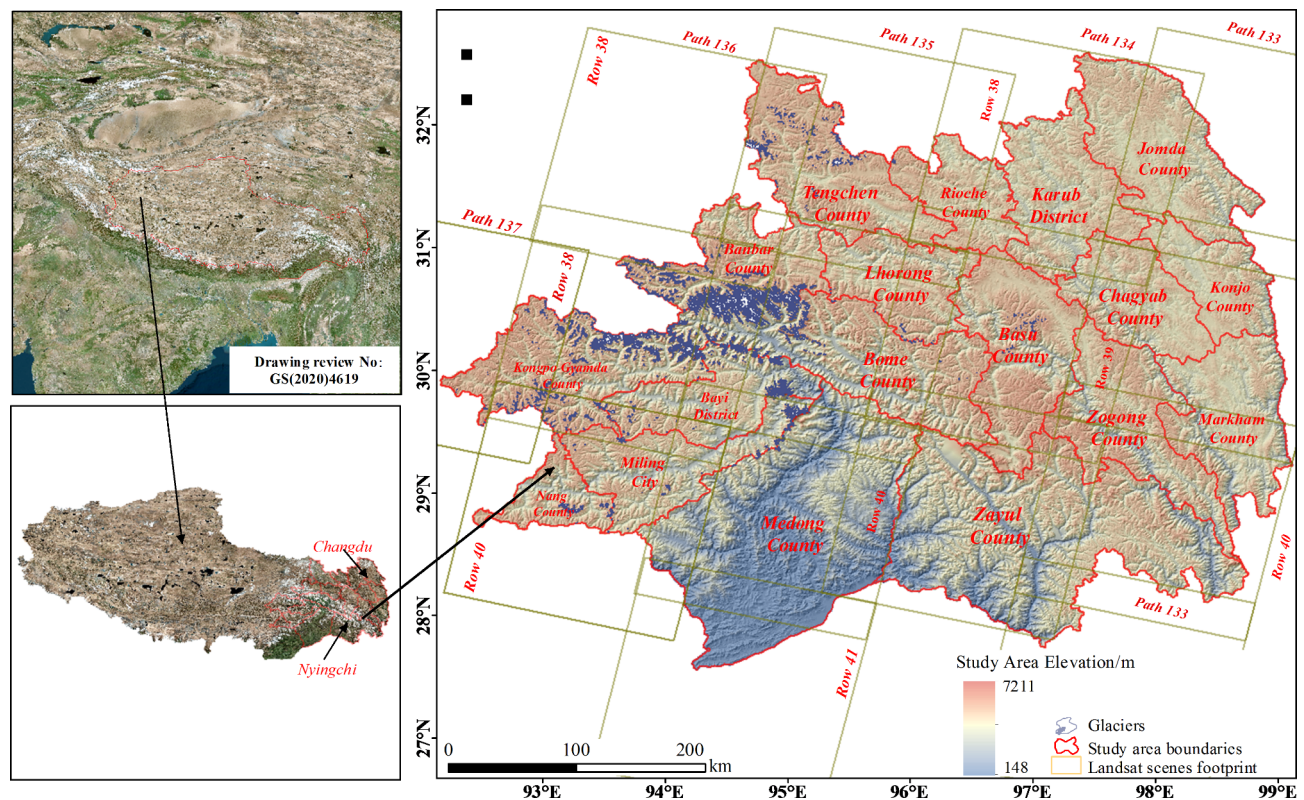
Fig. 1. The administrative boundary maps used in this study are provided by the National Natural Resources Center, and the map number is GS(2020)461. The glacier areas are shown in blue, and the study areas are highlighted in red. Additionally, the dark green outline indicates the footprints of the Landsat scenes. The remote sensing images utilized in this study were obtained from Google Earth and processed using ArcGIS 10.8 software.

Scanner (MSS), Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imagery (OLI)[36–39]. This study employs the GEE platform to acquire satellite images from the years 1993 to 1994, 2007 to 2009, and 2021 to 2023, all at a resolution of 30 m. The program allows for the setting of specific parameters to automatically select remote sensing images that meet the requirements in terms of time and location, and merge them accordingly[40]. The adoption procedure is illustrated in Fig. 2. The subsequent processing involves manual verification and correction conducted by the image interpreter. The final results incorporate 162 remote sensing images to generate an accurate and comprehensive annual spatial distribution map of glacial lakes.

Data

In this study, Landsat Level 1 Terrain (L1T) data were utilized for terrain and radiometric corrections in remote sensing image analysis. The period from June to September is typically the optimal time for monitoring glacial lakes[41]. During this period, the glacial lake attained its maximum size due to the minimal coverage of ice and snow in the area[42]. To minimize the impact of climatic conditions, such as snow cover and cumulus clouds, on interpretability, we selected remote sensing image data characterized by minimal snow and cloud cover (less than 5%) from April to November each year. This approach ensured that the boundaries of glacial lakes in the area were more distinctly differentiated from other features.

This study utilizes the RGI 6.0 glacier dataset, which was re-released by the Global Land Ice Measurements (GLIMS) on February 11, 2022, to examine the spatial distribution characteristics of glacial lakes in the southwestern region[43]. Mapping the spatial distribution of glaciers enables the identification of glacial lakes that exhibit a strong correlation with glacier dynamics[44]. Subsequently, by establishing a buffer zone spanning 10 km, the research area beyond this boundary can be defined as comprising glacial lakes that display minimal association with changes in glacier conditions[45]. Finally, based on the distance between a glacial lake and its glacier, glacial lakes can be classified into two categories: glacial-fed lakes and non-glacial-fed lakes.

During the mapping process, interference from mountain shadows at high altitudes may obscure certain glacial lakes. SRTM DEM possesses high vertical accuracy, enabling it to effectively capture terrain details and accurately eliminate artifacts, such as mountain shadows, present in images[46]. The present study utilizes SETM data to derive slope and shadow topographic maps.

Climate change significantly affects glaciers and high-altitude glacial lakes[47]. This study utilizes fifth-generation atmospheric reanalysis data obtained from the European Centre for Medium-Range Weather
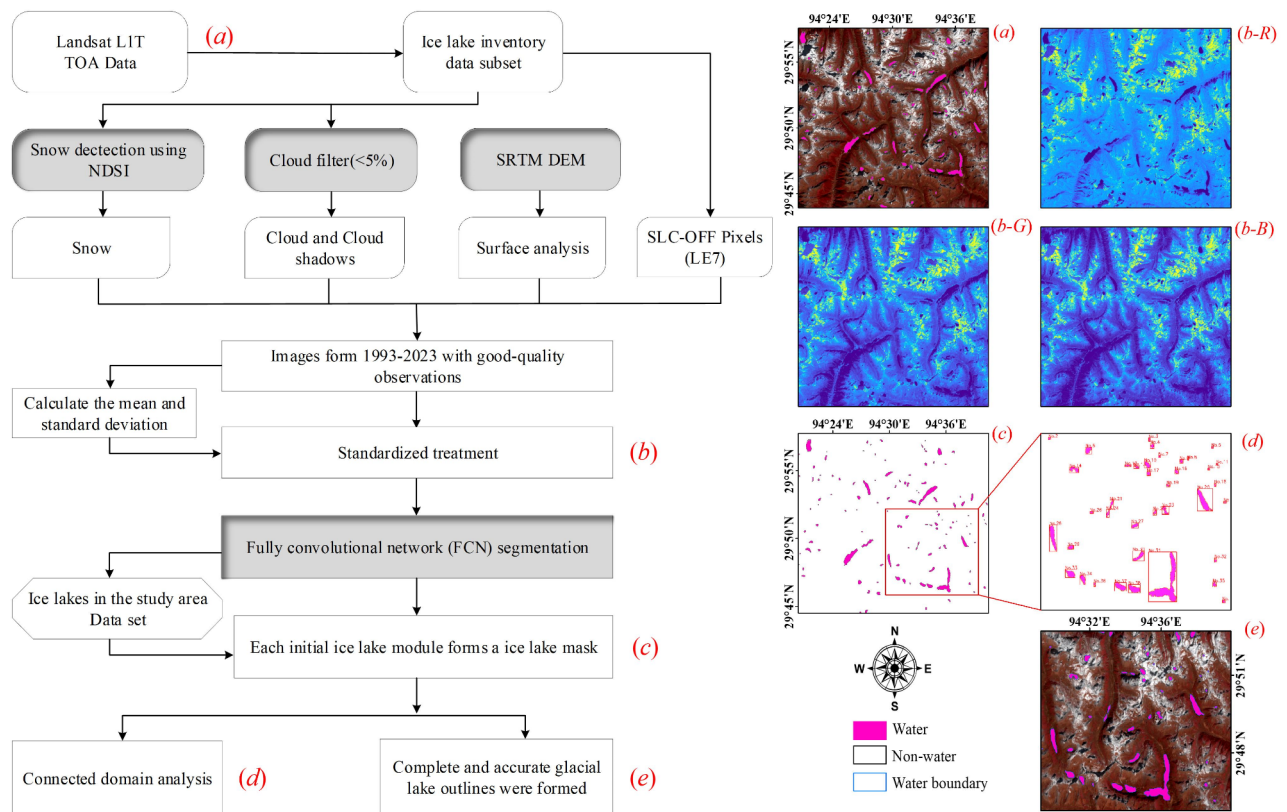
Fig. 2. The automated segmentation process for delineating boundaries of glacial lakes (**left**); Mapping method of glacial lake boundary in southeast central region of Tibet (**right**); (**a**) Pseudo-color composite (R/G/B = Band 5/4/3); (**b**) Enhanced processing of remote sensing imagery using standardized methods; (**c**) The FCN algorithm divides the glacial lake group module into a single module dedicated to glacial lakes; (**d**) The connected domain method is employed to combine individual glacial lake modules; (**e**) The contour of the glacial lake is determined by segmenting the contour of a single module representing a glacial lake.

Forecasts (ECMWF). The grid accuracy of this dataset is 0.1°×0.1°[48]. The Copernicus Climate Data Store provides essential meteorological datasets that facilitate the examination of climate change impacts on regional ice-covered lakes, effective July 18, 2024.

Methods for mapping glacial lakes

Determining the proximity of glacial lakes to the nearest glacial boundary is a key criterion for their identification. Previous studies have typically established maximum thresholds for identifying glacial lakes at equidistant distances of 2, 5, 10, and 20 km[49–51]. To ensure data consistency and comparability, this study selects a buffer zone with a spatial distribution range of 10 km for the classification and segmentation of glacial lakes.

The processing of winter remote sensing images in the study area, which were captured between November and December, necessitates the utilization of the normalized Snow Cover Index (NDSI)[52]. this technique was subsequently employed for the purpose of cartographically delineating regions characterized by persistent snow coverage. The glacial lake undergoes standardized preprocessing before the entire research area is segmented, enhancing the clarity of surface object distinction in the remote sensing image. After preprocessing the remote sensing images for this area, relevant experts compare and evaluate them to ensure the accuracy and reliability of the data.

This study employs the full convolutional network (FCN) algorithm to delineate the boundaries of glacial lakes. In this approach, each nearly complete block of water imagery is constructed for the globally segmented potential glacial lake. Subsequently, the initial glacial lake module is integrated to refine the boundary of the glacial lake. Furthermore, this method effectively segments mini-glacial lakes, and its compact model size eliminates the need for high computational requirements. By establishing a minimum external rectangle for each identified glacial lake, the aspect ratio can be determined. This approach not only fills in gaps regarding small glacial lakes but also accurately delineates their boundaries, thus providing a foundation for further research into the morphological characteristics of these lakes. The glacial lake mask generated by a single glacial lake module is utilized for 240 K iterations. The results from the single glacial lake module, completed through these iterations, are then fused to produce a comprehensive and accurate overall contour of the glacial lake. The results indicate that the Fully Convolutional Network model can effectively adapt to the spectral variations introduced by glacial lakes of varying scales and different types of remote sensing images.

Measurement and error assessment of glacial lake areas

Errors often occur when remote sensing techniques are employed to analyze changes in glacial lakes. Errors typically arise from various factors, including the characteristics of different types of image sensors, the distribution of atmospheric clouds, and variations in research methodologies[53]. This paper employs a specific methodology to compute the area error of glacial lakes[54].

$$u_a = \frac{\lambda^2 \times p}{2\sqrt{\lambda^2 + \lambda^2}} = \frac{\lambda \times p}{2\sqrt{2}} \tag{1}$$

In this context, u_a denotes the area of an individual object(km²), λ represents the image resolution, p signifies the perimeter of the segmented object.

Estimation of glacial lake storage capacity

In estimating glacial lake water storage, Zhang et al.[55] employed a formula to assess the storage capacity of 47 proglacial lakes located near the Himalayas. This assessment was conducted over 16 exploratory surveys in the Himalayan region from 2017 to 2021. This paper employs various methods to estimate the total water storage of glacial lakes across each region[56].

$$V = \begin{cases} 40.67 \times A^{1.184} - 3.218 \times Ratio_{(mxw/mxl)} & A > 0.1 km^2 \\ 557.4 \times A^{2.455} + 0.2005 \times Ratio_{(mxw/mxl)} & A < 0.1 km^2 \end{cases} \tag{2}$$

In this context, V represents the water storage capacity of the assessed target (10^6m³), A denotes the area of the identified target (km²), Ratio$_{(mxw/mxd)}$ indicates the dimensions of the external rectangle surrounding the identified target.

Results

Temporal and spatial distribution of glacial lakes

From the initial stage (1993–1994) to the later stage (2021–2023), the evaluation index of regional glacial lakes exhibited a consistent upward trend. Notably, both microglacial lakes (≤ 0.1 km²) and superlarge glacial lakes (≥ 3.0 km²) significantly contributed to this overall expansion. Between 1993 and 2023, the area increased by 35.90 ± 4.74 km², resulting in an expansion rate of 32.70%. The combined expansion rate accounted for a total of 61.79% (Table 1). Previous studies have indicated that glaciers on the Tibetan Plateau consistently exhibit a significant retreat trend, with an average annual mass loss reaching -0.73 m w.e./a[57]. In the study area, particularly near the Hengduan Mountains, the rapid retreat of marine glaciers further underscores the severity of this issue. The glacier mass loss in this region is quantified as -1.29 ± 0.32 m w.e./a[58], making it one of the most substantial losses observed across the plateau. This rate of retreat and mass loss suggests a dynamic and potentially unstable glacial environment driven by a combination of climatic and possibly geological factors. The expansion of glacial lakes has resulted primarily from the melting of adjacent glaciers within the region. The formation of glacial lakes is influenced by several factors, including changes in glacier morphology, calving events, and the melting process. The extent of glacial lake expansion varies across different regions, highlighting the complex dynamic factors that influence changes in glacial lakes.

We examines the relationship between elevation distribution and the characteristics of glacial lakes, highlighting the similarities in their variation and spatial distribution (Fig. 3a). At the same time, the elevation distribution of glacial lakes at different scales exhibits distinct characteristics, and their quantity and area distribution vary in response to changes in altitude. According to analysis of the three multi-temporal remote sensing images reveals that the predominant elevation range of the glacial lake spans from 2443 to 7201 m. It is essential to highlight that remote sensing images acquired between 2021 and 2023 indicate that over 67.73% of glacial lakes are situated at altitudes exceeding 4,442 m. The main factor behind this phenomenon lies in the heightened intensity of glacier melting at high altitudes, which can be attributed to the escalating temperatures. The prolonged coverage of glaciers in high-altitude regions leads to ongoing weathering and erosion of rock layers, resulting in significant accumulation of meltwater in eroded areas that subsequently forms numerous glacial lakes. The rock erosion associated with glaciation facilitates the accumulation of meltwater in depressions, gradually developing into bodies of water in glacial lakes. This continuous glacial cover allows for persistent erosion of high-altitude rocks, which collect water from melting snow and ice, ultimately giving rise to a multitude of glacial lakes. At this

Size Scale(km²)	1993	2008	2023	1993–2023
≤0.1	1685(76.01±15.63)	2335(91.17±19.06)	2965(100.84±11.09)	1292(25.38±4.54)
0.1–0.2	456(63.73±8.06)	474(66.77±8.20)	501(70.16±4.32)	45(6.74±3.74)
0.2-1.0	350(130.64±10.72)	356(131.38±10.80)	375(138.56±5.66)	27(8.62±5.06)
1.0–3.0	22(33.50±1.60)	25(37.01±1.84)	27(41.90±1.02)	5(8.40±0.58)
≥3.0	7(33.76±0.84)	8(37.58±1.00)	9(44.28±0.64)	2(10.52±0.20)
Total	2520(337.64±36.85)	3198(363.91±40.90)	3877(395.44±22.73)	1371(59.66±14.12)

Table 1. The distributions of glacial lakes in 1993, 2008, and 2023 are categorized according to five scale classes. The values presented in square brackets represent the corresponding areas in km².
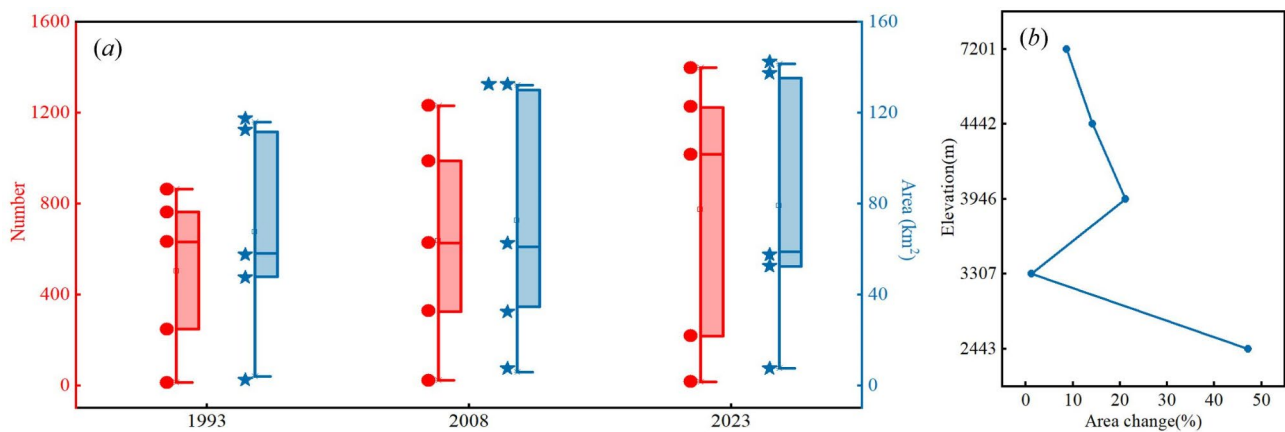
Fig. 3. (a) The spatial distribution of the number and area of glacial lakes within each elevation tier was analyzed; (b) The rate of expansion of glacial lake areas at varying elevations.

Region	Number			Total Area (km²)			Volume(×10⁶m³)		
	1993–2008	2008–2023	Change Rate (%)	1993–2008	2008–2023	Change Rate (%)	1993–2008	2008–2023	Change Rate (%)
Basu	18	272	1411.11	3.47	6.4	84.43	314.94	288.32	-8.45
Banbar	1	2	100	2.94	5.06	72.11	127.80	222.05	73.74
Tengchen	-69	-6	-91.30	-2.44	-1.01	-58.61	-5.1	-13.56	165.88
Lhorong	-22	102	-563.63	-2.06	4.40	-313.59	-41.56	125.71	-402.47
Markham	7	11	57.14	0.50	0.80	60.00	3.38	42.09	1145.27
Zogong	20	91	355.00	3.09	-1.44	-146.60	161.03	-127.21	-179.00
Bayi	129	-36	-127.91	-2.57	4.54	-276.65	-104.07	150.85	-244.95
Bomi	-76	293	-485.53	-3.79	13.37	-452.77	-4.93	116.36	-2460.2
Zayul	371	264	-28.84	17.19	7.03	-59.10	86.08	100.33	16.55
KongpoGyamda	-92	76	182.61	-9.36	14.04	-250.00	-106.47	212.88	-299.94
Nang	28	-34	-221.43	0.50	-0.42	-184.00	41.11	52.41	27.49
Miling	215	-191	-188.84	9.23	-7.31	-179.19	92.88	-74.78	-180.51
Medong	135	-156	-215.56	8.60	-13.05	-251.74	103.11	-134.39	-230.34

Table 2. Regional summary of glacial lake numbers and areas in each period.

altitude, the assessment indicators of glacial lakes are increasing significantly. However, within the altitude range of 2443 ~ 3307 m, the limited presence of glacial lakes contributes to a heightened sensitivity in their expansion, resulting in an anomalous alteration in area (Fig. 3b). The formation and alteration of glacial lakes are typically associated with the erosion of the surrounding rock mass resulting from glacial retreat in the area of elevation.

According to analysis focuses on the variation rate of glacial lake quantity and area in different high sea areas during two periods (Table 2). Over the past 30 years, while the overall assessment indicators of glacial lakes have increased, certain areas analyzed in this study initially exhibited a decrease in these indicators followed by a subsequent increase. This paper posits that the primary reason for this phenomenon is the presence of numerous marine-type glaciers in the study area between 1993 and 2008. Following the retreat of these glaciers, many small and unstable glacial lakes ultimately formed in the affected regions. As the glacier retreats, the unstable glacial lake may breach and merge with an adjacent stable glacial lake, resulting in the formation of a larger glacial lake. This process ultimately leads to a stable equilibrium. Between 2008 and 2023, the notable rise in temperature in the plateau region has resulted in increased evaporation rates, contributing to a slight reduction in the water levels of certain glacial lakes. This phenomenon occurs due to precipitation being insufficient to offset evaporation over specific time intervals. The evaluation indices of the glacial lakes in Basu, Zogong, and the surrounding areas indicate a trend of continuous growth. Evidence suggests that the melting of the Karora Glacier in these regions is primarily attributed to rising temperatures. Additionally, precipitation levels surpass evaporation rates, leading to the accumulation of significant amounts of meltwater in both the valleys and existing glacial lakes. The increased loss of glaciers in the region is closely associated with elevated temperature levels, while the surplus precipitation has facilitated the accumulation of meltwater in the valleys and glacial lakes. Consequently, the evaluation indices of the glacial lakes in these two regions exhibit an upward trend.

This study examines the distribution characteristics of glacial lakes in southeastern Tibet (Fig. 4) reveals that these lakes are predominantly located near glaciers (Fig. 4B-E). The continuous erosion of the ice bed
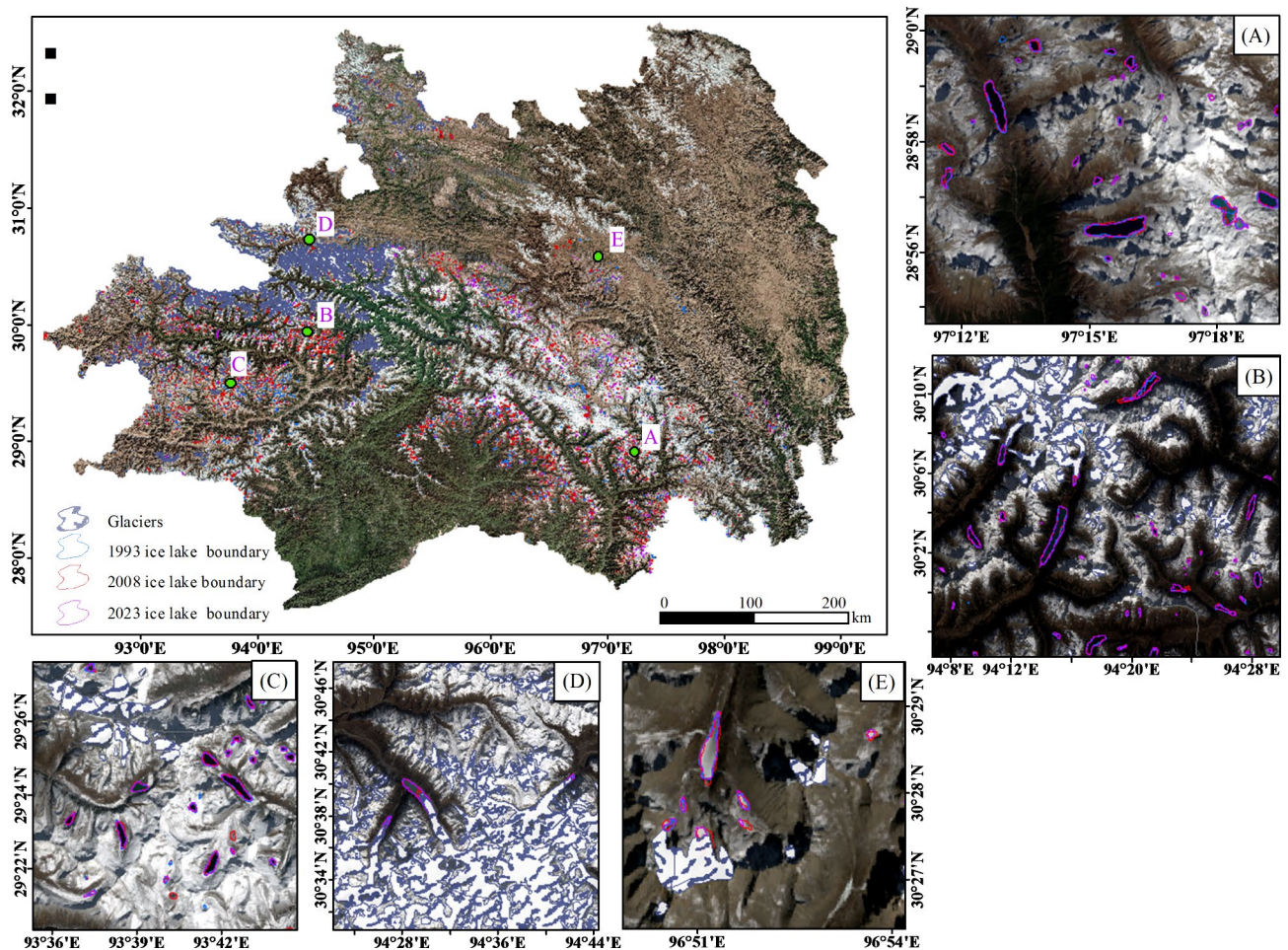
Fig. 4. The map illustrates the distribution of various glacial lakes within the study area. Band combination (R/G/B = Band 4/3/2). The remote sensing image presented in this figure was generated using Landsat 8 data and processed with ArcGIS version 10.8.

by the ancient glacier during its retreat leads to the accumulation of a significant amount of meltwater and precipitation in the trough, ultimately forming a substantial lake in distant areas[59]. The stability of these trough lakes is generally observed after their formation, as depicted in Fig. 4A. These glacial lakes, situated far away from contemporary glaciers, lack the influx of glacial meltwater to replenish their water reserves and solely rely on precipitation for sustenance[60]. Zayul is characterized by numerous micro-glacial lakes, primarily due to the area's abundant precipitation, which supports a rich forest ecosystem. This abundance of water has contributed to a marked increase in the assessment indicators of the region's glacial lakes. It is noteworthy that between 1993 and 2008, the Zayul region experienced an addition of 371 glacial lakes, resulting in an increase of 17.19 km². Statistics indicate that the relevant indicators have increased by 51.60% and 18.78%, respectively. As of 2023, the total count of glacial lakes in the region is expected to reach 1,354, encompassing an area of 115.74 km², water reserves in the region have risen by 186.41×10^6 m³. Although the rate of change of quantity and area in the region is negative, this is mainly because the growth trend of glacial lake during 2008–2023 is smaller than that during 1993–2008(Table 2). The region exhibits a high concentration of both infrastructure and population. Consequently, it is crucial to focus on the evolving dynamics of glacial lakes in this area over the next few years.

Analysis of the factors affecting glacial lake changes

Climate change influences the expansion and contraction of glacial lakes to differing extents. Moreover, variations in precipitation and temperature fluctuations significantly influence the dynamic changes in glacial lakes[61]. Indirect factors, such as climate change, can also profoundly influence the water volume in glacial lakes by affecting glacier ablation, surface runoff, and regional evaporation[62]. Considering that southeastern Tibet serves as the primary convergence zone for marine-type glaciers and microglacial lakes[63], this study primarily examines the variations in annual average temperature and precipitation in southeastern Tibet from 1993 to 2023.

The variation trends of annual average precipitation and temperature in each region of Southeast Tibet from 1993 to 2023 are illustrated in Fig. 5. Overall, there is an observed upward trend in the temperature across all regions. The temperature rise rate in Tengchen was the highest at 0.0409℃/10a, whereas Miling experienced
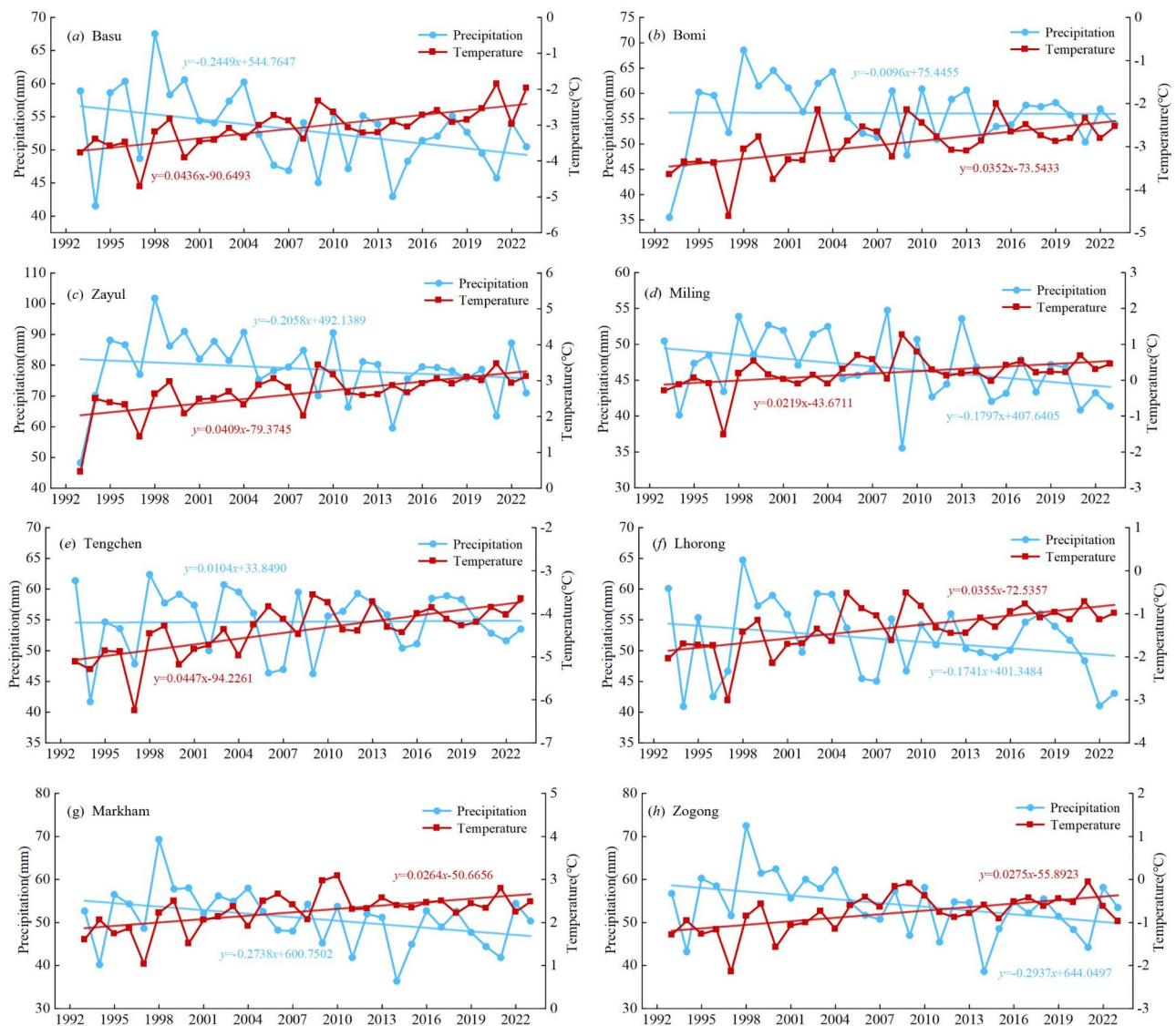
Fig. 5. The variations in average annual temperature and precipitation in southeastern Tibet from 1993 to 2023. The blue line in the figure illustrates the linear regression trend for precipitation, whereas the red line represents the linear regression pattern for temperature.

a comparatively slower temperature rise rate of 0.0219℃/10a. Notably, the marine-type glaciers in this area exhibit heightened sensitivity to variations in climatic conditions. Accelerating temperature increases are likely to significantly enhance the melting rates of these marine-type glaciers, further exacerbating their retreat.

The analysis of ERA-5 meteorological data reveals that the difference between precipitation and evaporation exhibits inconsistent variations over a 30-year period, with an average temperature change rate of 0.42℃/10a (Table 3). A typical illustration can be found in Zar and Metuo counties, where climate change is primarily driven by the southwest monsoon that transports water vapor from the Indian Ocean and is significantly influenced by topographical alterations. The glacial lakes in Zayul exhibit distinct distribution characteristics attributable to abundant precipitation and elevated temperatures. In recent decades, the retreat and thinning rates of marine glaciers in this study area have significantly outpaced those of terrestrial glaciers in other regions[64].

Discussion
Response of glacial lakes to climate change
Previous studies have indicated that climate factors are crucial in the dynamics of high-elevation lakes, particularly glacial lakes at greater elevations, which exhibit heightened sensitivity to temperature fluctuations. Figure 3 reveals that a significant proportion of glacial lakes, specifically those situated between elevations of 2443 and 7201 m above sea level, are concentrated predominantly above the altitude threshold of 4442 m, particularly in 2023. The results of this study align with those of related research, indicating that glacial lakes in this region exhibit an increasing trend across all assessed indicators, accounting for 21.20% of the total. The

Region	Period	Precipitation–Evaporation (mm)		Temperature (°C)	
		Average	Rate (mm/10a)	Average	Rate (°C/10a)
Basu	1993–2023	0.37	3.05	-3.45	0.43
Banbar	1993–2023	8.06	1.82	-4.67	0.47
Tengchen	1993–2023	5.33	1.78	-4.74	0.45
Lhorong	1993–2023	-5.84	2.34	-1.70	0.47
Markham	1993–2023	-21.09	2.58	1.95	0.36
Zogong	1993–2023	-4.28	3.33	-1.09	0.42
Bayi	1993–2023	-9.82	1.94	-0.28	0.41
Bomi	1993–2023	8.07	3.05	-3.35	0.45
Zayul	1993–2023	23.14	4.47	2.38	0.40
KongpoGyamda	1993–2023	-6.80	0.01	-3.96	0.41
Nang	1993–2023	-37.50	-0.76	-0.35	0.39
Miling	1993–2023	-18.86	0.70	-0.13	0.39
Medong	1993–2023	35.06	6.67	12.08	0.36

Table 3. The mean and average 10-year change rates of climate are calculated for each region.

elevations of these lakes range from 3,946 to 4,900 m[65]. The aforementioned observations also demonstrate the significant impact of temperature on the dynamics of high-elevation glacial lakes. Consequently, it is imperative to consider how the elevation distributions of these lakes respond to climate change when their fluctuations are analysed. The data presented in Fig. 6 illustrate a general trend of greater variability in the southern districts and counties than in the northern regions, with higher variation rates observed in the glacial lake area of northern China. Precipitation in Nyingchi is significantly greater than that in Qamdo, primarily because of the influence of the Indian Ocean monsoon. This phenomenon is attributed to the substantial amount of water vapour it transports, along with higher temperatures and increased evaporation rates. The change rate of glacial lake water storage in the northern region is also greater than that in the southern region.

Table 2 reveals that the climate in southeastern Tibet experienced a significant shift around 2008. This phenomenon can be attributed primarily to the increase in the assessment indicators of glacial lakes in the study area from 1993 to 2008, which surpassed those of glacial lakes between 2008 and 2023. We posit that the primary cause is rising temperatures, which led to the accelerated retreat of marine glaciers. During the initial phase, the replenishment of meltwater resulting from glacier retreat mitigated the negative impacts of decreased rainfall. However, from 2008 to 2023, glacial lakes that were once abundant with glacial meltwater sources gradually experienced desiccation due to significant glacier retreat and increased evaporation. Furthermore, the accelerated melting of glaciers in the region has resulted in the formation of numerous microglacial lakes. This phenomenon is also associated with a negative trend in each evaluation index related to the glacial lakes.

Glacial lake change and GLOF risk analysis

This study aims to assess and explore the changes in glacial lakes under varying climatic conditions, as well as to analyze the observed alterations in southeastern Tibet using meteorological data. Over the past 30 years, the majority of glacial lakes in the study area have experienced varying degrees of expansion. However, certain regions have exhibited a declining trend. Notably, regional studies conducted by Lang and Basu indicate that various indicators used to evaluate glacial lakes in 2023 are lower than those recorded in 1993. However, the indicators for assessing glacial lakes reached their peak in 2008. Initially, the glacial lakes in these regions exhibited an increasing trend, followed by a subsequent decline; thus, their changes require more effective characterization. Consequently, this paper selects six glacial lakes with prominent variations as exemplars to illustrate the alterations in their location (Fig. 7) .

Based on the spatial distribution of glacial lakes in the study area, density maps for glacial lake points were created for the years 1993 (Fig. 8a) and 2023 (Fig. 8b). The comparative analysis presented in Fig. 4 illustrates the significant spatial and temporal distribution differences between marine-type glaciers and glacial lakes in this region[66]. This study posits that the observed differences may primarily result from the influence of factors such as environmental topography, climatic conditions, and the composition of detrital material remaining after glacier retreat. Furthermore, the swift proliferation of erosive glacial lakes in the region is attributed to rock erosion. Therefore, in the upcoming decades, with rising temperatures, several glacial lakes will experience an expansion of their water storage capacity, whereas the ice dam body's shrinkage and thinning will gradually lead to instability[67]. Consequently, it is essential to analyse the trends in glacial lake areas and water storage in both the eastern and western regions of Nyingchi City. Future assessments utilizing remote sensing data and advanced boundary extraction methods for glacial lakes can enhance our understanding of the development processes and potential hazard factors associated with glacial lake expansion in these two critical regions. This approach aims to accurately predict the trajectory of changes in glacial lake morphology and the potential occurrence of glacial lake rupture disasters.
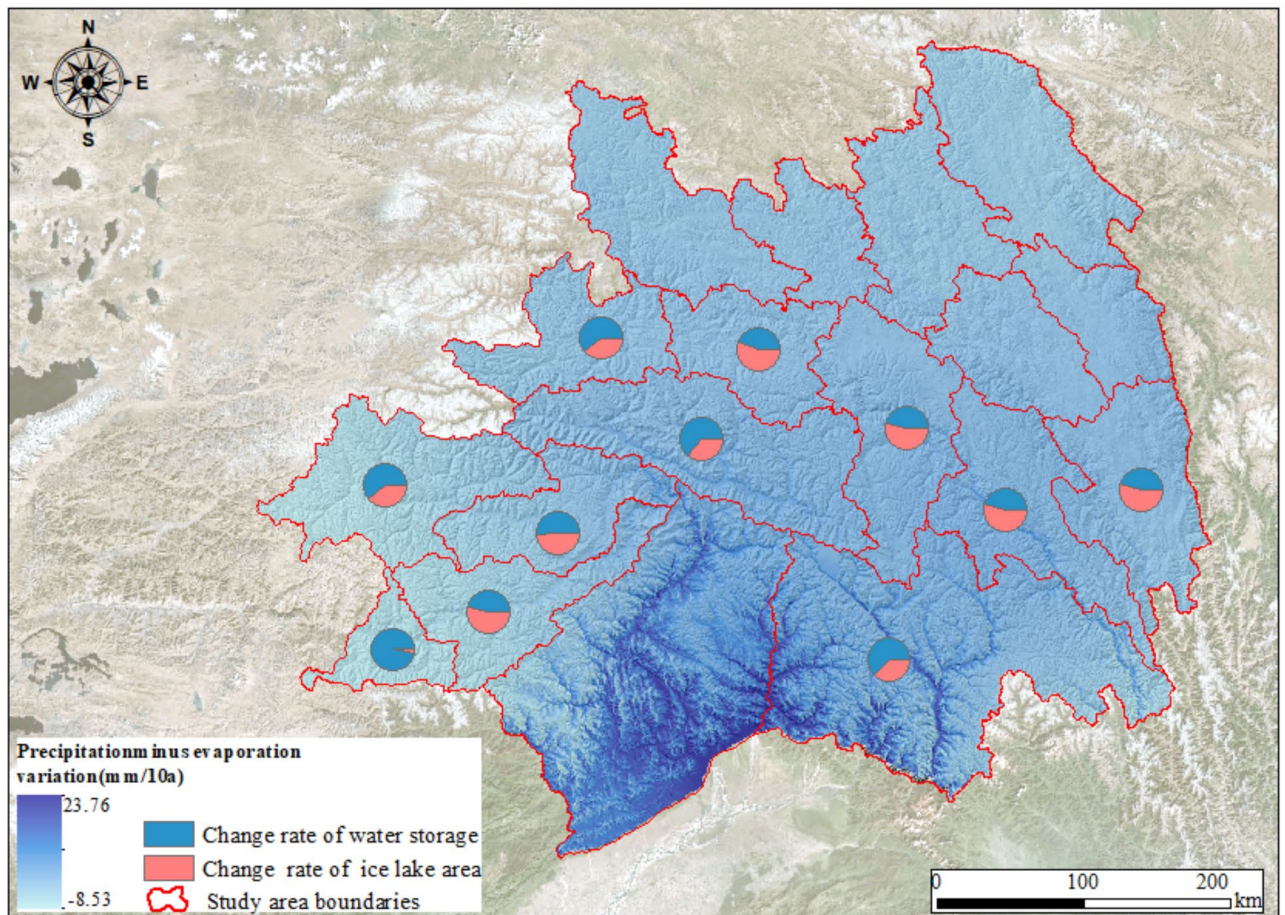
Fig. 6. The average rate of precipitation change over a 10-year period, the rate of glacial lake area change, and the change in glacial lake water storage over a span of 30 years. The remote sensing images used as background in this study are derived from Google Earth, and the mapping software used is ArcGIS version 10.8.

Conclusions

An automatic segmentation algorithm for glacial lake boundaries was employed to delineate a comprehensive and accurate boundary contour of the glacial lakes in southeastern Tibet, utilizing Landsat remote sensing imagery and leveraging the cloud processing capability of the GEE.

According to our research findings, by 2023, southeastern Tibet is expected to have 3,877 glacial lakes, each with an area equal to or greater than 0.0001 km². These lakes are projected to have an average area of 0.10 km^2 and a range of 395.74 ± 22.72 km^2, resulting in a cumulative water storage capacity of approximately 8493.68 × 106 m^3. In the study area, glacial lakes are concentrated in the southern region, whereas their distribution in the northern region is relatively dispersed. Research indicates that increasing temperatures in the region have led to the retreat of several marine glaciers, resulting in the formation of numerous microglacial lakes in Zayul. The glacial lake in Zayul County has undergone expansion, leading to the connection of certain areas with the main body of the lake following a glacial breach. This represents a significant factor influencing the transformation of glacial lakes in the study area.

The results indicate an increase in precipitation and temperature. A comprehensive analysis of climate data suggests that the area of glacial lakes is expected to expand rapidly in both the eastern and western regions of Nyingchi City. The glacial lake near the glacier in southeast Tibet, however, exhibits a higher degree of sensitivity to climate change. As temperatures continue to rise, the combined effects of topographic variations and uneven precipitation distribution in the Nyingchi and Qamdo regions will lead to significant changes in the interaction dynamics of glacial lake research indicators in high-altitude areas. Certain areas of the expanding glacial lakes in Zayul and Bomi are at significant risk of collapse in the coming decades. Currently, most glacial lakes in the Nyingchi region are anticipated to continue their expansion until several lakes reach a critical state.
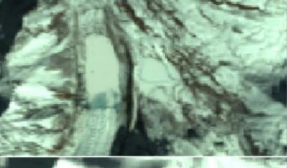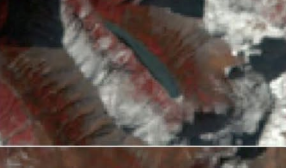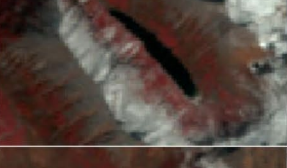
Fig. 7. The latitude, longitude, and elevation of the glacial lake center serve as the geographical coordinates for each example illustrating glacial lake expansion and contraction. The three images in each group were of identical dimensions. The background image is a satellite image captured by Landsat. Band combination (R/G/B = Band 4/3/2). Remote sensing images of the background in the image are derived from Landsat 8. The mapping software is ArcGIS 10.8.
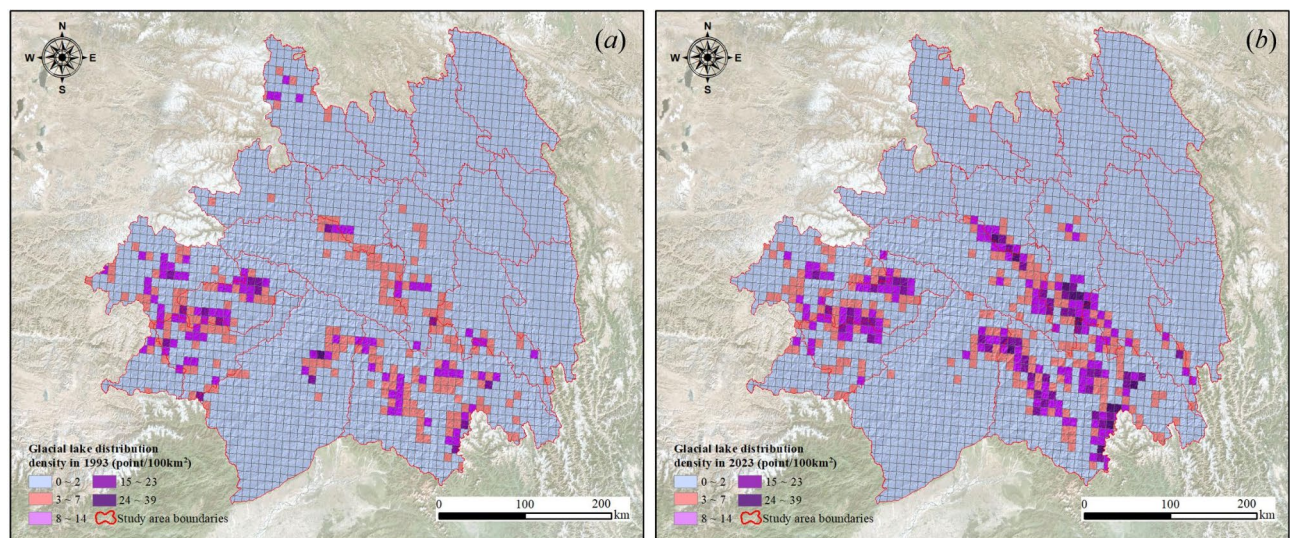
Fig. 8. Spatial point density distribution map of glacial lakes. (**a**) Point density distribution map of glacial lake areas in 1993; (**b**) spatial distribution map of point density in glacial lake regions in 2023. Google Earth image and mountain shadows in the background. ArcGIS version 10.8 was used to create visual representations.

Data availability

The corresponding author can provide the data presented in this study upon request.

References

1. Yang, M., Wang, X., Pang, G., Wan, G. & Liu, Z. The Tibetan Plateau cryosphere: observations and model simulations for current status and recent changes. *Earth Sci. Rev.* **190**, 353–369 (2019).
2. Qi, J. et al. Effect of Indian monsoon on the glacial airborne bacteria over the Tibetan Plateau. *Sci. Total Environ.* **831**, 154980 (2022).
3. Wang, S. et al. Characterizing 4 decades of accelerated glacial mass loss in the West Nyainqentanglha Range of the Tibetan Plateau. *Hydrology Earth Syst. Sci.* **27**, 933–952 (2023).
4. Wei, Y., Lu, H., Wang, J., Wang, X. & Sun, J. Dual influence of climate change and anthropogenic activities on the spatiotemporal vegetation dynamics over the Qinghai-Tibetan plateau from 1981 to 2015. *Earth's Future* **10**, eEF002566 (2022). (2021).
5. Salerno, F. et al. Glacier melting increases the solute concentrations of Himalayan glacial lakes. *Environ. Sci. Technol.* **50**, 9150–9160 (2016).
6. Zhang, G. et al. Response of tibetan Plateau lakes to climate change: Trends, patterns, and mechanisms. *Earth Sci. Rev.* **208**, 103269 (2020).
7. Jones, B. M. et al. Lake and drained lake basin systems in lowland permafrost regions. *Nat. Reviews Earth Environ.* **3**, 85–98 (2022).
8. Zhang, T., Wang, W., An, B. & Wei, L. Enhanced glacial lake activity threatens numerous communities and infrastructure in the third Pole. *Nat. Commun.* **14**, 8250 (2023).
9. Wang, X., Siegert, F., Zhou, A. & Franke, J. Glacier and glacial lake changes and their relationship in the context of climate change, Central Tibetan Plateau 1972–2010. *Global Planet. Change.* **111**, 246–257 (2013).
10. Bazai, N. A. et al. Increasing glacial lake outburst flood hazard in response to surge glaciers in the Karakoram. *Earth Sci. Rev.* **212**, 103432 (2021).
11. Peng, M. et al. Cascading hazards from two recent glacial lake outburst floods in the Nyainqêntanglha range, Tibetan Plateau. *J. Hydrol.* **626**, 130155 (2023).
12. Wang, S., Che, Y. & Xinggang, M. Integrated risk assessment of glacier lake outburst flood (GLOF) disaster over the Qinghai–Tibetan Plateau (QTP). *Landslides* **17**, 2849–2863 (2020).
13. Wang, W., Zhang, T., Yao, T. & An, B. J. I. j. o. d. r. r. monitoring and early warning system of Cirenmaco glacial lake in the central Himalayas. *Int. J. Disaster risk Reduct.* **73**, 102914 (2022).
14. Qu, G. et al. Characterization of long-time series variation of glacial lakes in southwestern tibet: a case study in the nyalam county. *Remote Sens.* **14**, 4688 (2022).
15. Ke, X., Li, Y., Wang, W., Niu, F. & Gao, Z. Hydrochemical characteristics and processes of thermokarst lake and groundwater during the melting of the active layer in a permafrost region of the Qinghai–Tibet Plateau, China. *Sci. Total Environ.* **851**, 158183 (2022).
16. Tian, B. et al. Mapping thermokarst lakes on the Qinghai–Tibet Plateau using nonlocal active contours in Chinese GaoFen-2 multispectral imagery. *IEEE J. Sel. Top. Appl. Earth Observations Remote Sens.* **10**, 1687–1700 (2017).
17. Jiang, L. et al. Combining geophysics, remote sensing and numerical simulation to assess GLOFs: Case study of the Namulacuo Lake in the Southeastern Tibetan Plateau. *Sci. Total Environ.* **880**, 163262 (2023).
18. Mergili, M. & Schneider, J. Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. *Nat. Hazards Earth Syst. Sci.* **11**, 1447–1462 (2011).
19. Tralli, D. M., Blom, R. G., Zlotnicki, V., Donnellan, A. & Evans, D. L. Satellite remote sensing of earthquake, volcano, flood, landslide and coastal inundation hazards. *ISPRS J. Photogrammetry Remote Sens.* **59**, 185–198 (2005).
20. Yang, C., Huang, Q., Li, Z., Liu, K. & Hu, F. Big Data and cloud computing: innovation opportunities and challenges. *Int. J. Digit. Earth.* **10**, 13–53 (2017).

21. Yang, C. et al. Spatial cloud computing: how can the geospatial sciences use and help shape cloud computing? *Int. J. Digit. Earth.* **4**, 305–329 (2011).
22. Kaushik, S., Singh, T., Joshi, P. K. & Dietz, A. J. Automated mapping of glacial lakes using multisource remote sensing data and deep convolutional neural network. *Int. J. Appl. Earth Observation Geoinf.* **115**, 103085 (2022).
23. Sun, F., He, B., Liu, C. & Zeng, Y. Comparison of hydrological patterns between Glacier-Fed and Non-glacier-fed Lakes on the Southeastern Tibetan Plateau. *Remote Sens.* **13**, 4024 (2021).
24. Nie, Y. et al. A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. *Remote Sens. Environ.* **189**, 1–13 (2017).
25. Agarwal, V. et al. Long-term analysis of glaciers and glacier lakes in the Central and Eastern Himalaya. *Sci. Total Environ.* **898**, 165598 (2023).
26. Shugar, D. H. et al. Rapid worldwide growth of glacial lakes since 1990. *Nat. Clim. Change.* **10**, 939–945 (2020).
27. Cao, Y. et al. Refined glacial lake extraction in a high-asia region by deep neural network and superpixel-based conditional random field methods. *Cryosphere* **18**, 153–168 (2024).
28. Singh, H. et al. Assessment of potential present and future glacial lake outburst flood hazard in the Hunza valley: a case study of Shisper and Mochowar glacier. *Sci. Total Environ.* **868**, 161717 (2023).
29. Salerno, F. et al. Glacial lake distribution in the Mount Everest region: uncertainty of measurement and conditions of formation. *Global Planet. Change.* **92**, 30–39 (2012).
30. Wang, X. et al. Glacial lake inventory of high-mountain Asia in 1990 and 2018 derived from landsat images. *Earth Syst. Sci. Data*. **12**, 2169–2182 (2020).
31. Li, J. An Assessment of Ecological Protection Importance Based on Ecosystems Services and vulnerabilities in Tibet, China. *Sustainability* **14**, 12902 (2022).
32. Yao, F., Wang, J., Wang, C. & Crétaux, J. F. Constructing long-term high-frequency time series of global lake and reservoir areas using landsat imagery. *Remote Sens. Environ.* **232**, 111210 (2019).
33. Drenkhan, F., Guardamino, L., Huggel, C. & Frey, H. Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes. *Global Planet. Change.* **169**, 105–118 (2018).
34. Sousa, J. J. et al. Geohazards Monitoring and Assessment using Multi-source Earth Observation techniques. *Remote Sens.* **13**, 4269 (2021).
35. Chen, F., Li, S. & Song, K. Remote sensing of lake chlorophyll-a in Qinghai-Tibet Plateau responding to climate factors: implications for oligotrophic lakes. *Ecol. Ind.* **159**, 111674 (2024).
36. Bhardwaj, A. et al. A lake detection algorithm (LDA) using landsat 8 data: a comparative approach in glacial environment. *Int. J. Appl. Earth Obs. Geoinf.* **38**, 150–163 (2015).
37. Derkacheva, A., Mouginot, J., Millan, R., Maier, N. & Gillet-Chaulet, F. Data reduction using statistical and regression approaches for ice velocity derived by Landsat-8, Sentinel-1 and Sentinel-2. *Remote Sens.* **12**, 1935 (2020).
38. Dyba, K., Ermida, S., Ptak, M., Piekarczyk, J. & Sojka, M. Evaluation of methods for estimating lake surface water temperature using landsat 8. *Remote Sens.* **14**, 3839 (2022).
39. Sojka, M., Ptak, M. & Zhu, S. Use of Landsat Satellite images in the Assessment of the variability in Ice Cover on Polish Lakes. *Remote Sens.* **15**, 3030 (2023).
40. Mingwei, Y., Feng, L., Yonggang, G., Libin, S. & Deshun, Q. Study of the patterns of variations in ice lakes and the factors influencing these changes on the southeastern tibetan Plateau. *Heliyon* **10**, e36406 (2024).
41. Khan, S. et al. Understanding volume estimation uncertainty of lakes and wetlands using satellites and citizen science. *IEEE J. Sel. Top. Appl. Earth Observations Remote Sens.* **16**, 2386–2401 (2023).
42. Zeller, L., McGrath, D., McCoy, S. W. & Jacquet, J. Seasonal to decadal dynamics of supraglacial lakes on debris-covered glaciers in the Khumbu region, Nepal. *Cryosphere* **18**, 525–541 (2024).
43. Li, Y., Li, F., Shangguan, D. & Ding, Y. A new global gridded glacier dataset based on the Randolph Glacier Inventory version 6.0. *J. Glaciol.* **67**, 773–776 (2021).
44. Millan, R., Mouginot, J., Rabatel, A. & Morlighem, M. Ice velocity and thickness of the world's glaciers. *Nat. Geosci.* **15**, 124–129 (2022).
45. Rick, B., McGrath, D., Armstrong, W. & McCoy, S. W. Dam type and lake location characterize ice-marginal lake area change in Alaska and NW Canada between 1984 and 2019. *Cryosphere* **16**, 297–314 (2022).
46. Preety, K., Prasad, A. K., Varma, A. K. & El-Askary, H. Accuracy assessment, comparative performance, and enhancement of public domain digital elevation models (ASTER 30 m, SRTM 30 m, CARTOSAT 30 m, SRTM 90 m, MERIT 90 m, and TanDEM-X 90 m) using DGPS. *Remote Sens.* **14**, 1334 (2022).
47. Zhang, Y. et al. Assessment of lake area in response to climate change at varying elevations: a case study of Mt. Tianshan, Central Asia. *Sci. Total Environ.* **869**, 161665 (2023).
48. Muñoz-Sabater, J. et al. ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth Syst. Sci. data*. **13**, 4349–4383 (2021).
49. Joy, K. et al. Cosmogenic evidence for limited local LGM glacial expansion, Denton Hills, Antarctica. *Q. Sci. Rev.* **178**, 89–101 (2017).
50. Eibl, E. P. et al. Subaerial and subglacial seismic characteristics of the largest measured jökulhlaup from the eastern Skaftá cauldron, Iceland. *Earth Surf. Dyn.* **11**, 933–959 (2023).
51. Bælum, K. & Benn, D. Thermal structure and drainage system of a small valley glacier (Tellbreen, Svalbard), investigated by ground penetrating radar. *Cryosphere* **5**, 139–149 (2011).
52. Wang, X. et al. Snow cover mapping for complex mountainous forested environments based on a multi-index technique. *IEEE J. Sel. Top. Appl. Earth Observations Remote Sens.* **11**, 1433–1441 (2018).
53. Lu, S. et al. An operational approach for large-scale mapping of water clarity levels in inland lakes using landsat images based on optical classification. *Environ. Res.* **237**, 116898 (2023).
54. Xin, W. et al. Using remote sensing data to quantify changes in glacial lakes in the Chinese Himalaya. *Mt. Res. Dev.* **32**, 203–212 (2012).
55. Zhang, G. et al. Underestimated mass loss from lake-terminating glaciers in the greater Himalaya. *Nat. Geosci.* **16**, 333–338 (2023).
56. Qi, M. et al. Improving the accuracy of glacial lake volume estimation: a case study in the Poiqu basin, central Himalayas. *J. Hydrol.* **610**, 127973 (2022).
57. Zhao, H., Yang, W., Yao, T., Tian, L. & Xu, B. Dramatic mass loss in extreme high-elevation areas of a western himalayan glacier: observations and modeling. *Sci. Rep.* **6**, 30706 (2016).
58. Zhao, F., Long, D., Li, X., Huang, Q. & Han, P. Rapid glacier mass loss in the Southeastern Tibetan Plateau since the year 2000 from satellite observations. *Remote Sens. Environ.* **270**, 112853 (2022).
59. Chen, F. et al. Annual 30 m dataset for glacial lakes in High Mountain Asia from 2008 to 2017. *Earth Syst. Sci. Data*. **13**, 741–766 (2021).
60. Li, W. et al. Holocene lake response to glacier and catchment changes on the eastern tibetan Plateau from quantitative conductivity reconstructions based on sedaDNA-derived macrophyte records. *Q. Sci. Rev.* **338**, 108806 (2024).
61. Woolway, R. I. et al. Global lake responses to climate change. *Nat. Reviews Earth Environ.* **1**, 388–403 (2020).
62. Zhang, T., Wang, W. & An, B. Heterogeneous changes in global glacial lakes under coupled climate warming and glacier thinning. *Commun. Earth Environ.* **5**, 374 (2024).

63. Dou, X. et al. The response of glaciers and glacial lakes to climate change in the Southeastern Tibetan Plateau over the past three decades. *Land. Degrad. Dev.* **34**, 5675–5696 (2023).
64. Wang, H. et al. Disaster effects of climate change in high-Mountain Asia: state of art and scientific challenges. *Adv. Clim. Change Res.* **15**, 367–389 (2024).
65. Su, P. et al. Changes in glacial lakes in the Poiqu River basin in the central Himalayas. *Hydrology Earth Syst. Sci.* **25**, 5879–5903 (2021).
66. Li, G. et al. Two periods of geodetic glacier mass balance at Eastern Nyainqentanglha derived from multi-platform bistatic SAR interferometry. *Int. J. Appl. Earth Observation Geoinf.* **104**, 102541 (2021).
67. Dou, X. et al. Spatio-temporal evolution of glacial lakes in the Tibetan Plateau over the past 30 years. *Remote Sens.* **15**, 416 (2023).

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to G.Y.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.