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Research article

Study of the patterns of variations in ice lakes and the factors influencing these changes on the southeastern Tibetan plateau

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ABSTRACT

The ice lakes in the southeastern Qinghai–Tibet Plateau have exhibited a pronounced expansion against the backdrop of global warming, consequently amplifying the local risk of ice lake outburst disasters. However, surveys of ice lake changes in the entire region have consistently been incomplete due to the prevalent high cloud density. On the basis of Landsat remote sensing images and the Google Earth Engine (GEE) cloud computing platform, in this study, the full convolution segmentation algorithm is utilized to accurately and comprehensively map the regional distribution of ice lakes in southeastern Tibet at consistent time intervals in 1993, 2008, and 2023. Furthermore, the formation, distribution, and dynamic changes in these ice lakes are investigated. The numbers of ice lakes discovered in 1993, 2008, and 2023 were 2520, 3198, and 3877, respectively. These lakes covered areas of approximately 337.64 ± 36.86 km^2, 363.92 ± 40.90 km^2, and 395.74 ± 22.72 km^2, respectively. These ice lakes are located primarily between altitudes of 4442 m and 4909 m. The total area experienced an annual growth rate of approximately 0.57 % from 1993 to 2023. In the present study, the long-term variations in ice lakes in each district and county are examined. These findings indicate that between 1993 and 2023, the expansion of ice lakes was more pronounced in regions with a large number of marine glaciers. Notably, Basu County presented the highest annual growth rate of the ice lake population, at 6.23 %, followed by Bomi County, at 4.28 %, and finally, Zayul County, at 2.94 %. The accelerated shrinkage of marine glaciers induced by global warming is the primary driver behind the expansion of ice lakes. The results obtained from this research will enhance our overall understanding of the complex dynamics and mechanisms that govern the formation of ice lakes while also offering valuable perspectives on the potential risks linked to their expansion in this particular area.

1. Introduction

The southeastern part of Tibet is situated in the eastern section of the Himalayas, where the Nyainqentanglha range converges with

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the Hengduan Mountains. The predominant topographical characteristic of this region is its dense distribution of towering mountains and deep valleys [1]. This region of southeastern Tibet experiences the highest amount of precipitation in the entire Asian alpine region, primarily due to the influence of the Indian Ocean summer monsoon [2]. The region boasts the most concentrated oceanic glacier cluster on the Tibetan Plateau because of the copious rainfall caused by the monsoon climate [3]. The sensitivity of marine-type glaciers to increasing temperatures has significantly increased due to the ongoing phenomenon of global warming [4]. In recent years, a noticeable decrease in the rate of glacial mass depletion has been observed in southeastern Tibet. Consequently, there has been an increase in the population residing in alpine areas; nevertheless, the significant recession of glaciers has led to the emergence of multiple ice lakes in the area that could pose potential danger [5]. If geological activity in the region leads to continuous snow and ice disasters, such as avalanches and rock falls, it can further result in damage to natural moraines and unstable ice lake ice dams, ultimately leading to catastrophic ice lake outburst floods (GLOFs) [6]. The retreat of Beimu Glacier in Nyingchi city, Bayi District, in 1994 resulted in flood disasters; the collapse of Zhuomulari Glacier in Milin city and Nyingchi city in 2002 led to ice lake outbursts and subsequent flooding; and the collapse of Basongcuo Glacier in Qamdo city in 2006 also caused an ice lake outburst; these events occurred in high-altitude regions. The resulting floods from catastrophic events such as these can continue downstream, posing threats to human lives and causing damage to infrastructure.

The inaccessibility of ice lakes, owing to their predominantly remote locations, poses challenges for field research. However, satellite remote sensing has emerged as a widely applicable and efficient means to monitor and study long-term changes in these lakes [7–11]. Landsat data have been extensively utilized to provide comprehensive information on the extent of glaciers and ice lakes since 1972. The Landsat Multispectral Scanner (MSS), Landsat Thematic Mapper (TM), Land Enhanced Thematic Mapper Plus (ETM+), and Land Operational Land Imager (OLI), which are Landsat sensors, are composed of multiple data sources [12–15]. The changes in ice lakes within the Qomolangma region [16], the Nyainqentanglha range [17], the central part of the Tibetan Plateau, and the northern part of the Tibetan Plateau [18] were investigated via Landsat remote sensing data. On the basis of Landsat satellite data, a study conducted in the Rongxer Basin of the central Himalayas revealed that summer warming from 1975 to 2005, coupled with anomalous changes in annual precipitation patterns, exacerbated glacier retreat and ice lake expansion within the basin [19]. Research on ice lake evolution in the southeastern Qinghai–Tibet Plateau reveals that the thinning and retreat of glaciers have emerged as primary factors driving the recent expansion of these lakes [20]. Research on the trends of glacier shrinkage and ice lake expansion in the Sino-Nepal transboundary basin of the Himalayas reveals that geomorphologic characteristics of glaciers play pivotal roles in facilitating the rapid expansion of ice lakes [21]. Research on the temporal and spatial distribution of ice lakes in the Altai Mountains on the Qinghai–Tibet Plateau reveals that, amidst increasing precipitation and rising temperatures, future expansion of ice lakes will occur predominantly in the southern region of the Altai Mountains [22]. Owing to global warming and the rapid large-scale retreat of marine glaciers in southeastern Tibet, the region is facing a severe threat of ice lake outburst disasters. Therefore, conducting research on the dynamics and assessing the damage of ice lake outbursts and of ice lakes in this area is highly important [23]. The Himalayan ice lake library was recently established by employing automated ice lake mapping methods and artificial interpretation techniques to quantitatively assess the extensive changes occurring within ice lakes. This goal is achieved primarily through meticulous investigations of key representative ice lake regions [24]. Combined with geomorphic data, a data reservoir of ice lakes on the Qinghai–Tibet Plateau was also established, revealing a significant number of previously unreported ice lake outburst events. Researchers subsequently conducted comprehensive modelling and analysis of these occurrences [25,26]. The production of ice lake datasets has recently been extended to cover the entire Tibetan Plateau [27,28]. In addition to conventional optical remote sensing imagery, there is widespread utilization of high-resolution synthetic aperture radar (SAR) satellite data, such as those from TerraSAR-X, Radarsat-2, Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR), and data from similar sources. Furthermore, Sentinel-1 SAR imagery [29] has been extensively employed in glacier and ice lake analysis.

Although the temporal variations in ice lakes in the Himalayan region, southeastern Tibetan Plateau, Nyainqentanglha range region, and even the entire Tibetan Plateau have been investigated and studied extensively within a specific timeframe, comprehensive regional studies are still needed to fully identify the contours of numerous marginal small ice lakes. Furthermore, there is a need for further improvement in the available datasets pertaining to changes in ice lake dynamics. The primary method for mapping ice lakes in high-elevation areas is still artificial visual identification. However, this method is subject to limitations imposed by meteorological factors, such as image quality related to cloud cover, resulting in variable accuracy and level of detail obtained for ice lakes. The commonly employed large-scale mapping methods require the establishment of a robust distribution map under uniform spectral conditions. However, when confronted with complex terrain, these methods are inevitably constrained to varying degrees in terms of accuracy and other visual effects. Consequently, the monitoring of high-altitude ice lakes has reached a critical juncture, where improvements in accuracy seem unattainable. Machine vision-based automatic recognition methods have been extensively employed for ice lake identification and boundary extraction, with empirical evidence demonstrating their efficacy in effectively addressing diverse spatial configurations of various ice lake types [30,31]. The utilization of machine vision-based models in ice lake recognition is still in its early stages, resulting in incomplete identification and depiction of certain small ice lake edges. Currently, there is limited research on the processes involved in ice lake formation, hindering the ability to predict major ice lake outburst disasters. The formation and expansion of ice lakes necessitate a comprehensive understanding of their mechanisms and processes, particularly for accurately identifying and delineating changes in ice lakes and their directions of movement. This is crucial for precisely predicting potential risks associated with ice lakes and timely implementation of mitigation measures.

Continuously updating ice lake datasets in high-elevation areas is crucial for investigating the latest distribution and spatiotemporal specificity of ice lakes. Additionally, continuous updating plays a vital role in assessing the risk of new geological disasters, such as those induced by glacial changes and climate change, as well as ice lake dam breaks, on the plateau. The primary research area of this study is the southeastern Tibetan Plateau. The main research objectives of this study are to (1) generate a precise and comprehensive map of ice lakes via high-resolution Landsat remote sensing images (30 m) acquired continuously in 1993, 2008, and 2023; (2) monitor changes in the number and size of ice lakes, as well as quantify variations in the boundaries of these features across different regions over time; and (3) investigate the distribution, formation, and dynamic changes in ice lakes in southeastern Tibet, while exploring their relationships with climate change.

2. Study area

The southeastern Tibetan Plateau region encompasses two prefecture-level cities, namely, Nyingchi city and Qamdo city, which are located in the southeastern part of the Tibet Autonomous Region (Fig. 1). The study area is characterized by the presence of Namjbarwa Peak, which is the highest peak, with an elevation of 7782 m and an average altitude of 4100 m. Additionally, this region boasts a multitude of mountains and rivers, intricate fault systems, and renowned mountain ranges, such as the Himalayas, the eastern section of the Nyainqentanglha range, and the Hengduan Mountain range [32].

The study area predominantly features glaciers and snow cover at altitudes exceeding 4000 m. Analysis of the Asian glacier dataset provided by the GLMS reveals that the southeastern region of Tibet encompasses a total glacier area of 3128.97 km^2, comprising 3394 individual glaciers. Within this region, there are 2925 glaciers with areas smaller than 1 km^2, accounting for approximately 86.18 % of the overall number of glaciers in the area. These smaller glaciers are primarily distributed across Tengchen County, along the border of Bandar County, on both the northern and southern borders of Kongpo Gyamda County, and along the eastern border of Miling city. Additionally, 426 glaciers ranging from sizes between 1 and 10 km^2 exist, which constitute approximately 12.55 % of all the observed glaciers; these larger glaciers are mainly found surrounding prominent glaciers in Kongpo Gyamda County, in the western part of Bandar County, within central Bomi County and towards the eastern part of Bayi District. The number of glaciers with areas exceeding 10 km^2 is 43, constituting a mere 1.26 % of the total glacier count, and these glaciers are concentrated primarily in the northeastern region of Kongpo Gyamda County and at the junction of Bandar County and Bomi County [33]. The majority of glaciers consist of nonsurface moraine-covered glaciers and surface moraine-covered marine glaciers [34]. Compared with continental glaciers, the distinguishing features of marine glaciers include high rates of accumulation and ablation, elevated ice temperatures, rapid movement, and heightened susceptibility to climate change [35,36]. The representative glaciers include Ruoguo Glacier, Aza Glacier, Zepu Glacier, Lagu Glacier, and others.

Southeast Tibet features a pleasant climate characterized by predominantly subtropical and tropical mountainous humid

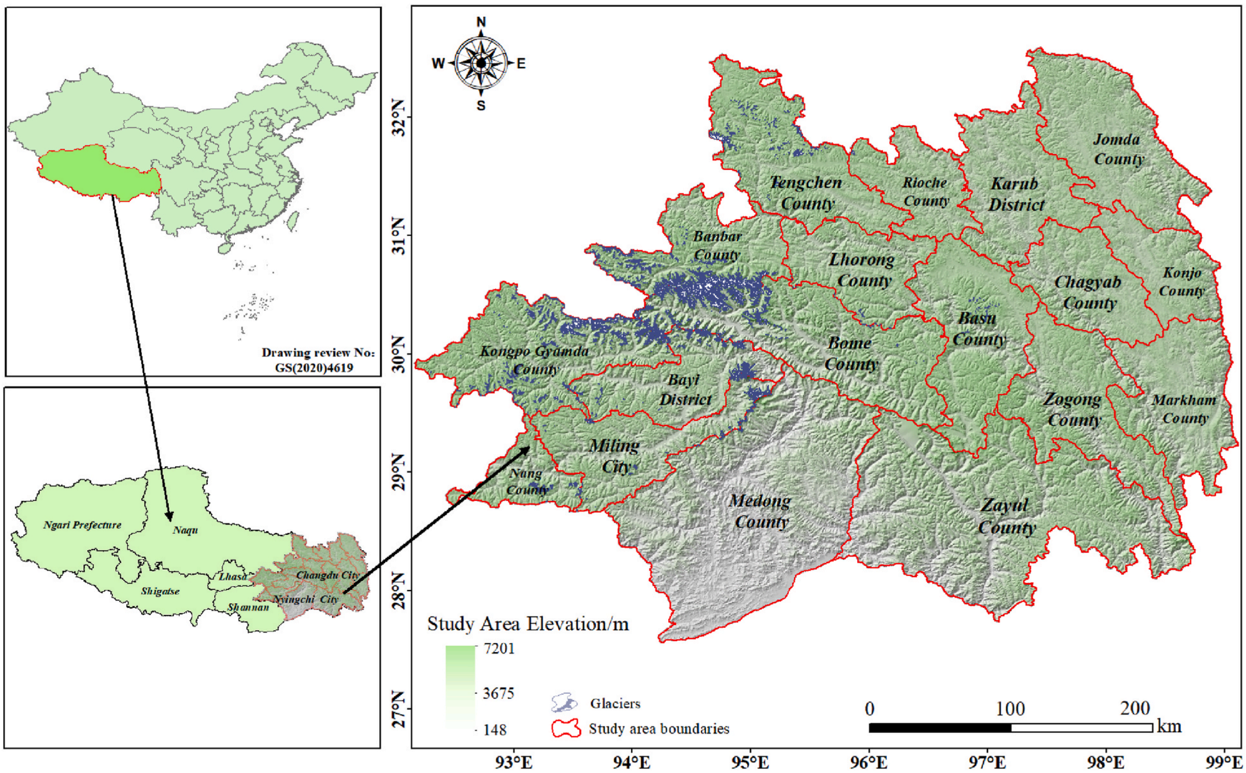

Fig. 1. The geographical location of southeastern Tibet is determined on the basis of the standard map system established by the Map Technical Review Center of the Ministry of Natural Resources, PRC. The corresponding review number for these maps is GS (2020)4619. The glacier outline is derived from the Randolph Glacier Survey (RGL v6.0), depicted by the glacial blue colour, with purple outlines delineating the study area and grey outlines representing the surrounding administrative region.

conditions. The mean yearly temperature fluctuates between 12 and 18 °C, with approximately 180 days annually experiencing temperatures exceeding 10 °C. The warmest month experiences average temperatures of 18–24 °C, whereas the lowest extreme temperature recorded annually is approximately −10 °C [37]. Affected by monsoons in the Bay of Bengal, the region has abundant water resources and possesses a multitude of rivers, predominantly seasonal ones, with significant variations in water quantity across different seasons. Notable rivers include the Brahmaputra River, Nujiang River, Niyangqu River, and Yigong Zangbo River; together, they form an intricate hydrological network within the study area [38,39]. The period of highest rainfall occurs mainly from June to September, with the annual precipitation amount surpassing 600 mm [40].

3. Data and methods

3.1. Study materials

3.1.1. Landsat imagery

The Landsat TM and OLI images, with spatial resolutions of 30 m and 15 m, respectively, cover three periods (in 1993, 2008, and 2023). These remote sensing images were acquired from the Google Earth Engine (GEE) cloud-based computing platform on January 15th, 2024. The Landsat remote sensing image data utilized in this research are L1T data that have undergone radiometric correction and have been projected onto the WGS84 and UTM Zone 46 coordinate systems [41]. To address the potential impact of climate factors, such as snow and clouds, Landsat remote sensing data indicate a consistent reduction in snow coverage within the research region from April through November each year. Furthermore, cloud cover is limited to less than 5 % during certain months, which significantly improves the accuracy of identifying lake boundaries in the study area [42]. An average of 54 remote sensing images were utilized for each year, resulting in a cumulative total of 162 remote sensing images encompassing the entire study area for the production of a precise and comprehensive annual map depicting the distribution of ice lakes within the study region.

3.1.2. Glacier data inventory

The Randolph Glacier Inventory (RGI) is a comprehensive global dataset that provides detailed outlines of glaciers [33]. The dataset of glaciers used in this research is sourced from the Global Land Ice Measurements from Space (GLIMS) database, which was published again on February 11, 2022. Glacier outlines were specifically selected for extraction from Central Asia on the basis of the study area. The Randolph Glacier Inventory (RGI) 6.0 dataset includes glacier outlines extracted from glaciers in southeastern Tibet, and these outlines were originally obtained from the Second Chinese Glacier Inventory (CGI2) [43]. The present study utilizes extracted glacier outline data from southeastern Tibet to establish a 10 km buffer, enabling the ice lake extent to be determined; this extent is highly correlated with glacial changes [44,45]. The primary objective of this paper is to investigate the variations in ice lakes within southeastern Tibet, encompassing those that exhibit minimal correlation with glacial changes. Consequently, once the extent of ice lakes closely associated with glacial changes has been determined, the research scope will extend beyond a 10 km buffer zone for ice lakes that display no significant relationship with glaciers. Therefore, the ice lakes in the study area can be classified into two categories: those that exhibit a high correlation with glacial changes and those that do not. By utilizing data from the High Asia Ice Lake Catalogue [46], we can identify the locations and numbers of ice lakes that do not closely correspond to glacial fluctuations within our study area during the three distinct periods. Ultimately, this allows for comprehensive coverage of all ice lakes throughout our research region.

3.1.3. Digital elevation model (DEM) data

The Shuttle Radar Topography Mission (SRTM) is an international collaborative project that is jointly organized by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) [47]. The project employs an enhanced imaging radar system with the objective of globally mapping elevation data. In January 2015, NASA's Land Processes Distributed Active Archive Center (LPDAAC) released the SRTM Version 3 dataset, which provides elevation data with a precision of 30 m and covers Asia and Australia. The SRTM DEM boasts high vertical accuracy and is capable of accurately representing topographic features [48]. The dataset includes disturbances, such as mountain shadows in the high mountain canyon region, whereas minimal effects of such disturbances are observed on flat terrain, particularly near glacier tongues and ice lakes [49]. In the process of mapping, due to their similar spectral characteristics, some ice lakes can be easily confused with mountain shadows. To mitigate this issue and remove unwanted images, SRTM data are utilized to generate topographic maps on the basis of slopes and shadows.

3.1.4. Meteorological observations

In this study, the ERA5 Land dataset, which is derived from the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis data, is utilized. This dataset covers atmospheric reanalysis data from 1950 to present and focuses exclusively on land areas while excluding oceanic regions. The utilization of only land-based data enhances the update frequency of the dataset. Moreover, note that this dataset has a horizontal resolution of 9 km, is vertically divided into 137 layers, and a temporal resolution of 1 h [50]. The ERA5 monthly land data used in this study have a global grid accuracy of $0.1^\circ \times 0.1^\circ$ and can be accessed online from the Copernicus Climate Data Store as of July 18, 2024. These meteorological datasets are crucial for investigating the impact of climate change on regional ice lakes.

3.2. Methods

3.2.1. Ice lake mapping

The primary procedural approaches that are employed for automatic ice lake mapping in this study are illustrated in Fig. 2. The original Landsat top-of-atmosphere (TOA) images were initially classified and segmented on the basis of the 10 km range of the glacier. These data were subsequently integrated into a time series dataset with consistent temporal intervals. The analysis utilized remote sensing images with cloud coverages less than 5 %, followed by the application of various techniques to detect mountain shadows, identify mountain snow, and address scan line corrector-off (SLC-OFF) issues. Mountain shadows vary in intensity due to differences in the shooting angles of remote sensing images. Surface slopes in the shadow areas are significant, whereas topographic relief is minimal. Hence, in this study, a slope threshold of greater than 10° and a shadow threshold of less than 0.25 derived from SRTM data are used to detect the presence of topographic shadows [51].

A significant number of remote sensing images captured during the winter months, specifically from November to December, exist for the study area. These winter remote sensing images were processed via the normalized difference snow index (NDSI) to account for terrain shadow effects and were subsequently used to map areas with permanent snow cover. After preprocessing the ice lake data, manual proofreading and editing were employed to obtain high-quality regional images. Prior to segmenting the entire research area, standardization was applied to calculate the mean value and standard deviation, enabling clearer discrimination of surface objects in remote sensing imagery [52]. Fully convolutional network (FCN)-based regional segmentation was employed to improve precision by minimizing the possibility of overlooking ice lakes in the overall filtration process for global segmentation. To optimize the ice lake boundary, an almost complete image block of water bodies was constructed for potential ice lakes identified globally through this method. The connected domain analysis method was then employed to integrate various initial ice lake modules. Moreover, this approach was used to effectively identify and incorporate numerous previously unrecognized very small ice lake regions, thereby enhancing the level of detail in the ice lake boundaries. Finally, the smallest limited rectangle enclosing each recognized ice lake was formed, and its width-to-length ratio was determined. An ice lake mask generated by each initial ice lake module was utilized as the basis for iterative local segmentation, and it was then combined with the original remote sensing image to achieve comprehensive and

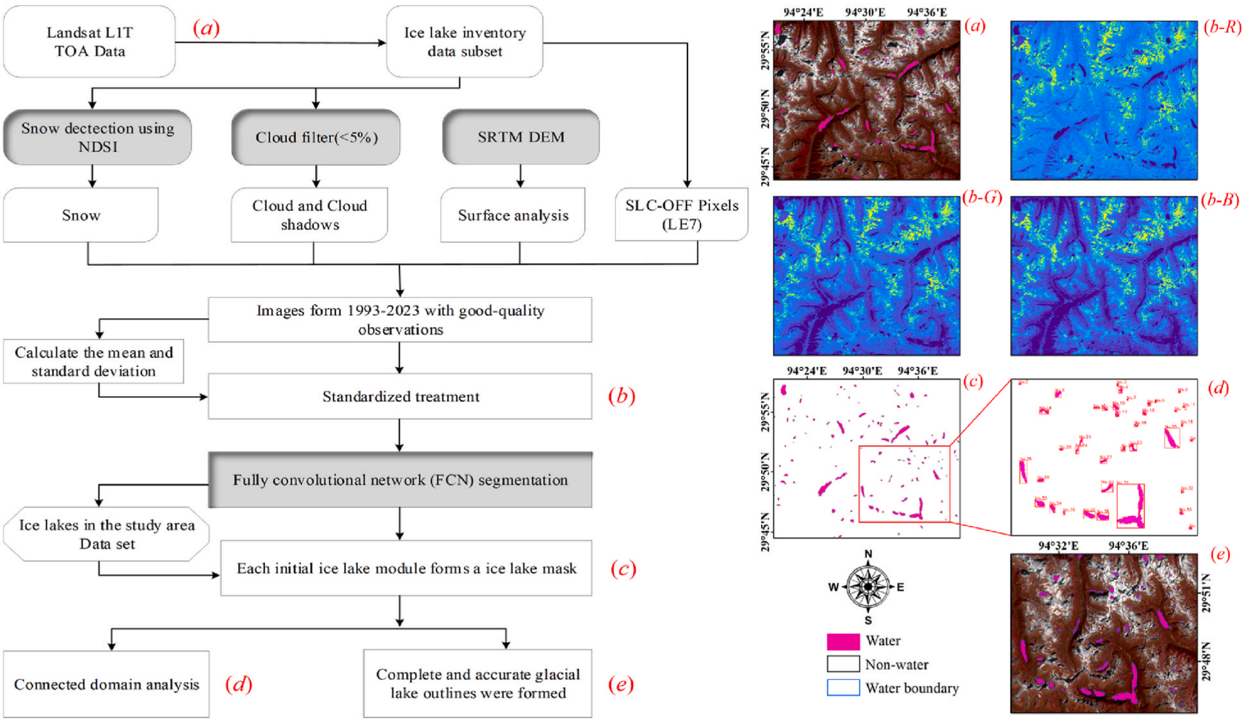

Fig. 2. The automated process for lake segmentation (**left**) involves preprocessing of remote sensing images and global fully convolutional segmentation. An ice lake mask is generated via the ice lake dataset in the study area along with the initial segmentation results. Subsequently, connected domain analysis is performed on the final results, which are then integrated with the initial ice lake module to form complete and accurate outlines of ice lakes. A cartographic methodology for delineation of ice lakes in a central region of southeastern Tibet (**right**); (**a**) false colour composite (R/G/B=Band 5/4/3); (**b**) standardized image; (**c**) fully convolutional (FCN) segmentation utilized to generate individual initial modules, resulting in the formation of an ice lake mask; (**d**) connected domain analysis utilized to integrate the initial ice lake module, and the minimum limited rectangle width−to-length ratio of each ice lake is computed; (**e**) complete delineation of the ice lake is based on figure panel c in conjunction with the original image. The effects applied in this case were derived from Landsat-8 OLI data acquired on October 28, 2022. The corresponding counterparts in the right diagram are represented by the alphanumeric labels (a–e) in the left diagram.

accurate delineation of ice lake boundaries.

The FCN semantic segmentation model with different Backbone as Encoder is employed in this study to train a dataset of 8000 remote sensing images of ice lakes. The training set and test set are divided in an 8:2 ratio. After 240K iterations, satisfactory segmentation results were achieved. In the final verification, the image segmentation mIoU exceeded 87.66 %, as shown in Fig. 3a, while the mAcc performance surpassed 93.87 %,as shown in Fig. 3b. These findings demonstrate that the FCN model effectively adapts to local spectral variations caused by different types of ice lakes and sensor image acquisition dates, thereby enhancing the accuracy of ice lake segmentation.

3.2.2. Assessing the margin of error in measuring the ice lake surface area

The measurement error for lake areas is influenced by various factors, including disparate image data sources, the spatial resolution of satellite images, and the research methodologies employed in lake mapping. The most commonly utilized research approach for quantifying the lake area is that defined by the Landsat Data Continuity Mission, which ensures consistent image quality. The application of remote sensing image data in the fields of environmental change and resource investigation necessitates continuous updates to Landsat series database sensors, resulting in constant improvements in the quality of remote sensing images. Consequently, varying degrees of improvement have been observed for radiation resolution, geometric precision, and signal-to-noise ratios. In this study, the World Geodetic System 1984 (WGS84) coordinate system was used as a reference to extract multitemporal ice lake contours from Landsat remote sensing images. After being converted to the Asia North Albers Equal Area Conic Projection system, no positional deviation was observed between them. The Landsat TM/OLI images employed in this investigation had a spatial resolution of 30 m. Within the images with the same resolution, the estimation of the uncertainty in ice lakes ensured that both internal and external errors of the extracted lake contours were within a range of ±1 pixel. To mitigate discrepancies in the quality of maps showing the distribution of ice lakes resulting from different mapping methods, in this study, a consistent automated segmentation and extraction approach for extracting and classifying ice lakes across various years was employed. Additionally, visual assessment was incorporated to differentiate ice lakes from other water bodies while considering the accuracy of ice lake classification. Finally, high-resolution images were utilized to rectify any remaining mapping errors. The research method proposed by Wang et al. [53] was additionally employed to compute the error in the ice lake area.

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

where u_a is the error of the ice lake area (km^2), λ is the spatial resolution of satellite images (Landsat TM is 30 m and Landsat OLI is 15 m), and p is the perimeter (m) of the ice lake.

3.2.3. Ice lake water storage Calculation

The ice lakes in the study area are located at high elevations, predominantly within uninhabited regions, thereby posing challenges and hazards for conducting field research on the lakes in the region. In the present study, remote sensing image analysis was employed, and the area–volume formula for ice lakes proposed by Qin et al. was utilized [54]. The purpose of this method was to determine the water storage capacity of ice lakes in different regions. The formula proposed by Zhang et al. [55] was employed to estimate the storage capacity of 47 ice lakes in the Greater Himalaya region during 16 exploration surveys conducted from 2017 to 2021, and its reliability was further validated. Hence, this approach was also adopted in this study to calculate the water storage of ice lakes in the region.

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

where V is the water storage area (10^6 m^3) of the ice lake, A is the area (km^2) of the ice lake, and $Ratio_{(mxw/mxd)}$ is the ratio between the width and length of the smallest circumscribed rectangle of the ice lake.

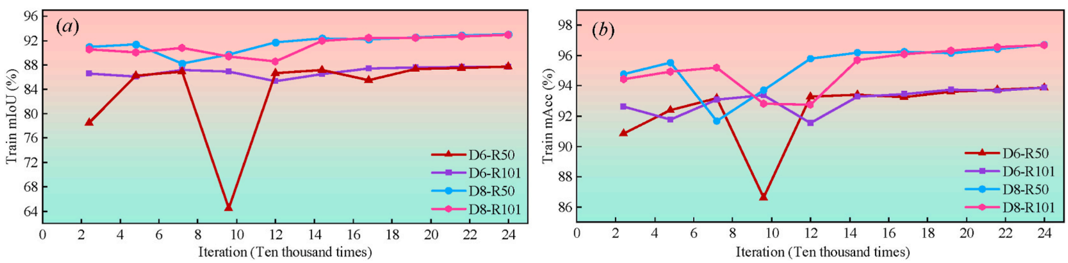

Fig. 3. (**a**) The validity of the results is confirmed by calculating the average intersection ratio between the model and the ice lake; (**b**) The model has been used to validate the mean accuracy of semantic segmentation for ice lakes.

4. Results

4.1. Temporal evolution and spatial distribution of ice lakes between 1993 and 2023

Using the object segmentation technique employed in this study, totals of 2527, 3134, and 3844 ice lakes with areas larger than 0.0081 km^2 were identified in southeastern Tibet in 1993, 2008, and 2023, respectively (Fig. 4). The cumulative areas of these lakes were found to be approximately 337.64 km^2, 363.92 km^2, and 395.74 km^2 (Table 1). The ice lakes were situated at the intersection of Zayul County and Bomi County in the northeast, as well as at the junction of Bayi District, Kongpo Gyamda County, and Milin city. The

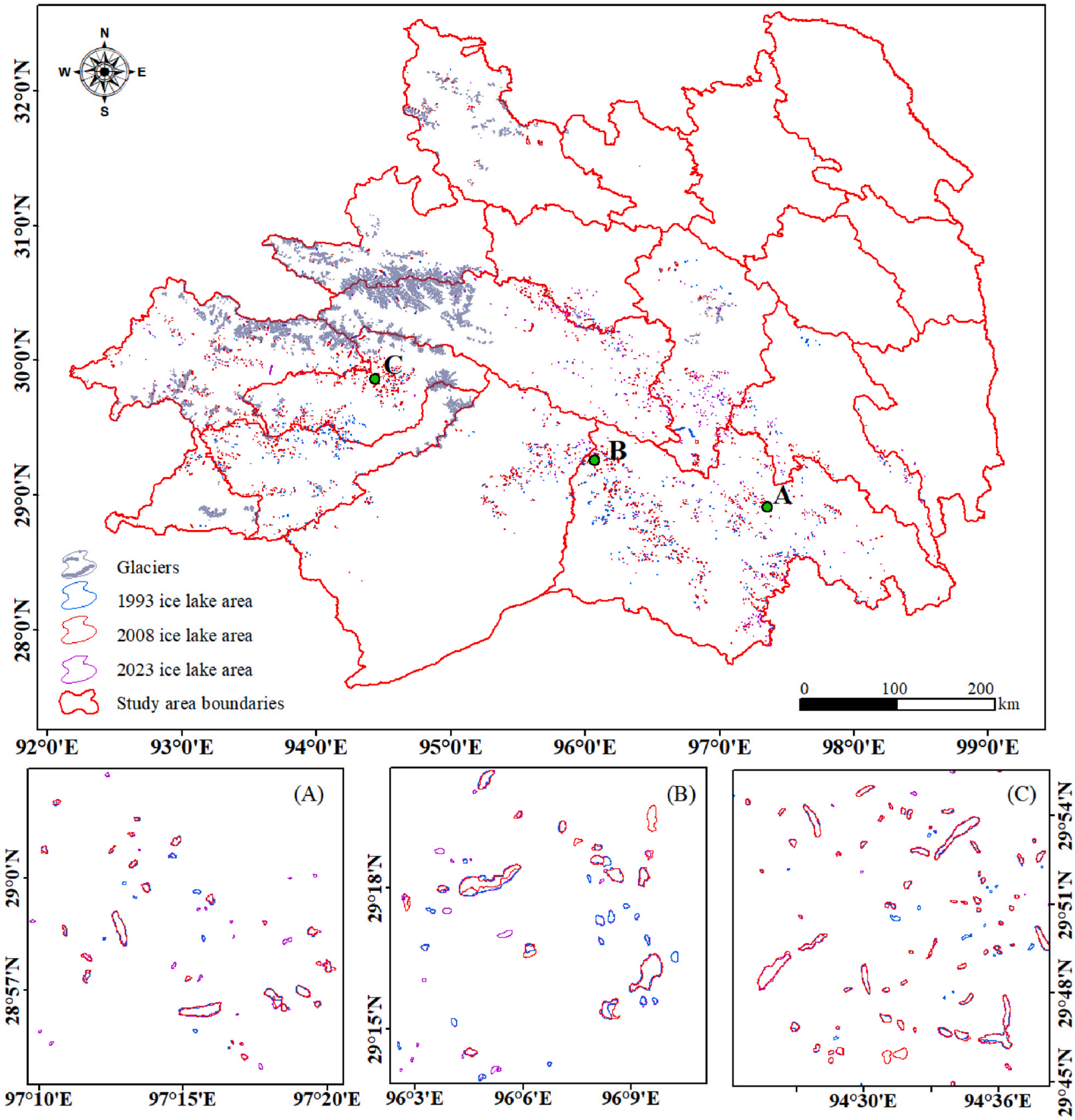

Fig. 4. The distributions of ice lakes in southeastern Tibet in 1993, 2008, and 2023 are depicted on this map. This cartographic representation was generated via automated mapping techniques and Landsat imagery acquired throughout the entire year. The three enlarged maps (A–C) depict specific local details of various districts, encompassing the northern region of Char County (A), the intersection between Metok and Char Counties (B), and the central area of Bayi District (C).

Table 1
The number of ice lakes at the five scales in 1993, 2008 and 2023; the change in the area and the annual average rate of change in the area are represented as the corresponding area (km^2) and the corresponding area error (km^2), respectively.

Size Scale (km^2)	1993	2008	2023	1993–2023	Rate of change in the area (%/a)
≤0.1	1685 (76.01 ± 15.63)	2335 (91.17 ± 19.06)	2965 (100.84 ± 11.09)	1292 (25.38 ± 4.54)	1.11
0.1–0.2	456 (63.73 ± 8.06)	474 (66.77 ± 8.20)	501 (70.16 ± 4.32)	45 (6.74 ± 3.74)	0.35
0.2–1.0	350 (130.64 ± 10.72)	356 (131.38 ± 10.80)	375 (138.56 ± 5.66)	27 (8.62 ± 5.06)	0.22
1.0–3.0	22 (33.50 ± 1.60)	25 (37.01 ± 1.84)	27 (41.90 ± 1.02)	5 (8.40 ± 0.58)	0.84
≥3.0	7 (33.76 ± 0.84)	8 (37.58 ± 1.00)	9 (44.28 ± 0.64)	2 (10.52 ± 0.20)	1.04
Total	2520 (337.64 ± 36.85)	3198 (363.91 ± 40.90)	3877 (395.44 ± 22.73)	1371 (59.66 ± 14.12)	0.59

ice lakes were primarily concentrated in the southern part of Basu County, while their distribution throughout the Chamdo region and Medong County in the Nyingchi Region was relatively sparse (Fig. 4(A–C)). In 2023, the majority of ice lakes had areas smaller than 0.1 km^2 (2965), while larger ice lakes with areas exceeding 0.1 km^2 constituted 74.52 % of the total area (Table 1).

In general, this study reveals a significant increase in both the extent and quantity of ice lakes from 1993 to 2023. However, importantly, the expansion rate varies among different sizes of ice lakes. Throughout the study period, there was a total increase of 1371 ice lakes, with a corresponding expansion in the total area of 58.10 ± 14.13 km^2 (17.21 %, Table 1). On the interannual time scale, the ice lake area exhibited a growth rate of 0.57 %/a during the period from 1993 to 2023. When variations among different sizes of ice lakes were compared, it is evident that micro-ice lakes (≤0.1 km^2) and super large ice lakes (≥3.0 km^2) made the most significant contributions to the overall expansion of ice lakes. From 1993 to 2023, there was an expansion of approximately 35.90 ± 4.74 km^2 in the ice lake area, with an annual growth rate of 1.09 %, accounting for a total expansion rate of 61.79 % (Table 1). Small ice lakes (0.1–0.2 km^2) and large ice lakes (1.0–3.0 km^2) experienced increases of 6.74 ± 3.74 km^2 and 8.40 ± 0.58 km^2, respectively, from 1993 to 2023, with growth rates of 0.35 %/a and 0.84 %/a, respectively. However, the degree of expansion in the medium-sized ice lakes (0.2–1.0 km^2) was relatively modest, with an increase of 8.62 ± 5.06 km^2 (0.22 %/a). Previous studies have predominantly reported a continuous and substantial trend of retreat among glaciers in high-altitude regions, with an average mass loss as high as −0.73 m w.e./a [56]. The rate of glacier retreat in the southeastern region of the Qinghai−Tibet Plateau was characterized by a rapid and uneven distribution, with the Hengduan Mountains experiencing the most significant decline in glacier mass (−1.29 ± 0.32 m w. e./a) [3]. The expansion of the ice lake area is attributed primarily to the melting and rapid retreat of glaciers. Alterations in glacier morphology, collapse events, and glacial melting are among the factors contributing to the formation of ice lakes.

In the present study, the relationships between altitude distribution and the size and quantity of ice lakes was examined, revealing a striking similarity in their respective patterns (Fig. 5a). The variations in the ice lakes constantly changed in accordance with altitude fluctuations. The elevation of the ice lake, as measured by three multitemporal remote sensing images, ranged from 2443 m to 7201 m. Notably, in 2023, more than 67.73 % of the ice lakes were concentrated at altitudes exceeding 4442 m. In the elevation range of 3946∼4909 m, there was a significant increase in both the number and area of ice lakes (accounting for approximately 21.20 % of the total expansion). The primary factor is the increasing temperature, which intensifies the glacial melting process in high-altitude regions. Within these areas, continuous erosion of rock layers occurs due to prolonged glacier coverage, resulting in substantial accumulation of melted snow at erosion sites and the subsequent formation of numerous ice lakes. Consequently, there has been a rapid increase in both the quantity and size of ice lakes within this altitude range. The sensitivity of ice lake expansion in the altitude range of 2443∼3307 m is pronounced due to the limited number of ice lakes within this range, leading to an anomalous change in the area (Fig. 5b). The formation of ice lakes is closely linked to the extent of erosion caused by glacier retreat at various elevations.

4.2. *Distinctive evolutionary Trajectories of ice lakes*

In southeastern Tibet, three distinct categories of ice lakes exist: (1) Proglacial lakes, which receive direct nourishment from

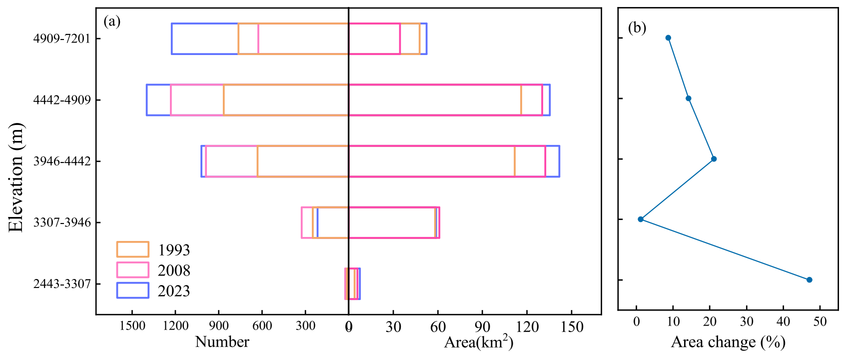

Fig. 5. (**a**) Distribution of ice lakes by elevation class in terms of the number and area; (**b**) rate of expansion in the ice lake area at various elevations from 1993 to 2023.

meltwater near the glacier terminus, are usually linked to the end of the glacier and confined by loose moraines [41]. (2) Ice valley lakes, characterized by their large scale and distance from modern glaciers, are typically found in "U" shaped valleys with steep sides and wide flat bottoms. These valleys are formed through the erosion of ice beds and the lateral erosion of branch trenches by large valley glaciers. The lakes themselves are created by the accumulation of glacial meltwater and atmospheric precipitation within these trough valleys [57]. (3) The typical form of a cirque lake is primarily steep rock walls on three sides and high reverse sills on the remaining side. These lakes usually exhibit a small scale of development and relatively dispersed spatial distribution and are predominantly replenished by atmospheric precipitation [58].

The development of different types of ice lakes varied significantly. Most ice lakes continued to expand within the area of the receding glacier front, resulting in a larger size in 2023 than in 1993, as depicted in Fig. 6a–c. The primary factor was the progressive increase in temperature within the plateau region, resulting in glacier retreat and melting. Consequently, there was a continuous increase in meltwater accumulation within the area. Furthermore, the retreat and thinning of the glacier tongue also facilitated the expansion of ice lake formation at the forefront of the glacier. The existence of ice-capped bodies of water contributes to the

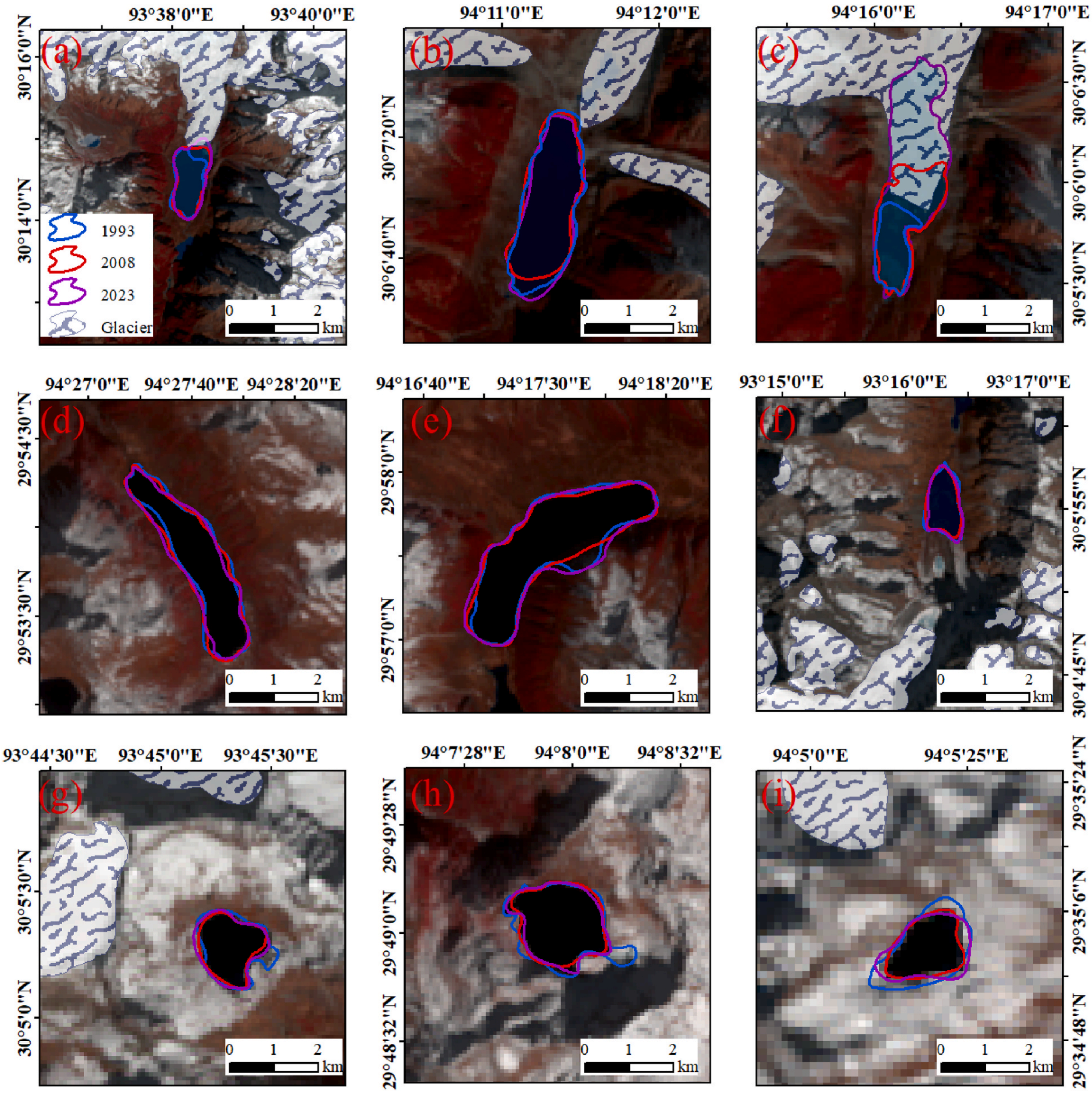

Fig. 6. The evolution of various categories of ice lakes: (a–c) ice lake; (d–f) ice valley lakes; (g–i) cirque lakes. The background remote sensing image is derived from Landsat 8 satellite data acquired in 2023.

acceleration of a glacier's retreat from its contact with the lake, as both subterranean and above-ground water sources gradually erode the underlying rock strata. The integration of ice lakes into a multitude of external water sources further amplifies their vulnerability to ice lake outburst disasters.

The stability of ice valley lakes are higher than that of ice lakes [59]. The images in Fig. 6d–f depict three typical ice valley lakes that are situated at considerable distances from contemporary glaciers. The favourable conditions for the formation of ice valley lakes are facilitated by the steep and straight slopes of the glacier, as well as its wide and flat base, which enables glacial meltwater to collect and atmospheric precipitation to occur within the trough valleys. The rapid melting of ice and snow caused by marine glaciers, combined with seasonal variations and the highly uneven distribution of precipitation and evaporation in the study area, are the primary factors contributing to the relatively stable changes observed in ice valley lakes. The stability of cirque lakes in southeastern Tibet changed from 1993 to 2023 (Fig. 6g–i). The distribution of cirque lakes is primarily concentrated in areas characterized by significant glacier mass loss and rapid glacier retreat. The majority of ice valley lakes and cirque lakes formed through the erosive action of Quaternary glaciers. Because there are few large glaciers nearby, these independent ice lakes depend mainly on the water supply from seasonal snowfall and precipitation. The most apparent distinction among these three types of ice lakes lies in the fact that the first type exhibits conspicuous changes and displays a high sensitivity to climate variations, whereas the latter two types demonstrate relatively stable alterations. The increasing water volume leads to the rise of ice lakes, thereby greatly facilitating the occurrence of outburst disasters.

4.3. Alterations in the geographical distribution of ice lakes

Both the total area and the number of ice lakes in southeast Tibet are experiencing an upward trend (Table 1), yet notable regional disparities exist. In 1993, the count of ice lakes in Banbar County, Tengchen County, Lhorong County, Markham County, Zogong County, and Nang County of Nyingchi City was below 100 (Table 2), In the last 30 years, there has been a noticeable rise in the abundance and dimensions of ice lakes. However, Tengchen County experienced a substantial decline in both the quantity and extent of its ice lakes. From 1993 to 2023, the count of ice lakes decreased to 12, while the total area reduced to 18.73 km^2, and the water storage declined to 948.55 × 106 m^3. The number and extent of ice lakes in Lhorong County exhibited a declining trend followed by an increase. Between 1993 and 2008, there was a reduction of 22 ice lakes, accompanied by a decrease in area and water storage by 2.06 km^2 and 41.56 × 106 m^3 respectively. The number is projected to increase to 130 by 2023, while the area will expand to 10.68 km^2 and the water storage capacity will reach 460.83 × 106 m^3. However, there was an initial increase in both the quantity and size of Nang County, which was later followed by a decrease. The number of additions increased by 28 from 1993 to 2008, resulting in an expansion of the area by 0.5 km^2 and an increase in water storage capacity by 41.11 × 106 m^3. Between 2008 and 2023, there was a decline in the quantity of ice lakes to 41, accompanied by a reduction in their total area to 2.93 km^2. However, it is noteworthy that water storage experienced a substantial rise to reach an impressive volume of 179.84 × 106 m^3.

The Zayul County is situated in the southeastern part of the study area, characterized by its elevated altitude, abundant precipitation, extensive distribution of marine-type glaciers, and a noticeable increase in both the quantity and size of ice lakes. From 1993 to 2008, the number and area of ice lakes in Zayul County experienced a significant increase, with an expansion of 371 km^2 and 17.19 km^2 respectively. The growth rates were recorded at 51.60 % and 18.78 % correspondingly. The number of ice lakes is projected to reach 1354 by 2023, covering a total area of 115.74 km^2. Over the past three decades, there has been an increase in water storage within this region amounting to 186.41 × 106 m^3. The predominant form of ice lake expansion in this region is characterized by the presence of micro-sized lakes, while the infrastructure and population distribution exhibit a relatively high degree of concentration. The monitoring of ice lake development in the region should be given priority in the upcoming years. In 1993, there were a total of 155 ice lakes in Basu County, covering an area of 31.13 km^2. From 1993 to 2008, the number and extent of ice lakes witnessed an increase by 15 (11.61 %) and 3.47 km^2 (11.15 %), respectively. By the year 2023, it is projected that the number of ice lakes will rise to 445 with an expanded area reaching up to 41.00 km^2, representing a significant growth compared to the figures recorded in 1993-specifically, an increment of approximately 290 lakes and an expansion by 9.87 km^2 in terms of area; consequently leading to a substantial increase

Table 2
The variations of ice lakes in various districts and counties in southeastern Tibet.

Region	1993			2008			2023		
	Area /km^2	Number /n	Volume / × $10^6 m^3$	Area /km^2	Number /n	Volume / × $10^6 m^3$	Area /km^2	Number /n	Volume / × $10^6 m^3$
Basu	31.13	155	2180.61	34.60	173	2495.55	41.00	445	2783.87
Banbar	4.70	19	132.31	7.64	20	260.11	12.70	22	482.16
Tengchen	22.18	87	967.21	19.74	18	962.11	18.73	12	948.55
Lhorong	8.34	50	376.68	6.28	28	335.12	10.68	130	460.83
Markham	0.50	6	21.26	1.00	13	24.64	1.80	24	66.73
Zogong	7.40	89	178.59	10.49	109	339.62	9.05	200	212.41
Bayi	51.46	310	1182.30	48.89	439	1078.23	53.43	403	1229.08
Bomi	20.63	169	131.50	16.84	93	126.57	30.21	386	242.93
Zayul	91.52	719	421.72	108.71	1090	507.80	115.74	1354	608.13
KongpoGyamda	43.20	365	616.52	33.84	273	510.05	47.88	349	722.93
Nang	2.85	47	86.32	3.35	75	127.43	2.93	41	179.84
Miling	27.01	272	290.08	36.24	487	382.96	28.93	296	308.18
Medong	26.44	227	279.32	35.04	362	382.43	21.99	206	248.04

in water storage capacity amounting to 603.26 × 106 m^3. The number of ice lakes in other districts and counties also experienced an initial increase followed by a subsequent decrease over the past 30 years, resulting in a reduction to levels comparable to those observed in 1993. According to the analysis presented in this paper, the aforementioned situation observed in certain districts and counties can be attributed to the substantial presence of marine-type glaciers within the region from 1993 to 2008. This resulted in the formation of numerous micro-small unstable ice lakes across these areas. Subsequent glacier retreat led to localized outbursts of these unstable ice lakes, causing them to merge with adjacent ice lakes and ultimately culminating in the development of large-scale stable ice lakes. The water storage capacity of ice lakes in certain regions has experienced a slight decline due to the rapid increase in temperature and the resulting imbalance between rainfall and evaporation from 2008 to 2023.

4.4. Climate data analysis

Although increasing temperatures and alterations in precipitation patterns result in the reduction and thinning of glaciers across numerous high-altitude regions, few studies have specifically demonstrated the correlations between the evolutionary processes of ice lakes and variations in temperature, precipitation, and evaporation. This is particularly true for complex terrains such as that in southeastern Tibet. Obtaining large-scale areas for onsite measurements poses significant challenges.

The characteristics and temporal trends of temperature changes (Fig. 7b), as well as the differences in values between precipitation and evaporation, are analysed for the period spanning from 1993 to 2023. The meteorological data provided by ERA-5 indicate a significant acceleration of warming in the counties in the study area over the past 30 years, accompanied by inconsistent changes in the precipitation–evaporation difference (Fig. 7). The average rate of temperature change was 0.42 °C/10a (Table 3). The analysis of weather data during this period revealed an observable trend of increasing temperatures and precipitation in certain regions across the research area. Southwest monsoons, which carry a substantial amount of water vapour from the Indian Ocean, primarily drive climate change in Zayul County and Medong County. Moreover, these regions are highly susceptible to topographic alterations. The presence of vast oceanic glaciers in Zayul County can be attributed to the copious amounts of precipitation and elevated temperatures that promote ice formation. Recently, there has been a noticeable increase in the withdrawal and thinning of marine-type glaciers on the Tibetan Plateau compared with continental glaciers. These findings indicate that these marine-type glaciers are particularly sensitive to climate change and its rate of advancement. The swift retreat of marine-type glaciers in southeastern Tibet is likely the primary factor contributing to the enlargement of ice lakes in this specific region.

However, the chart for analysing the large-scale difference between the rainfall and evaporation of the ERA-5 grid data from 1993 to 2023 (Fig. 7a) indicates an overall increasing trend in the difference between the rainfall and evaporation across various districts and counties. The potential cause of the observed phenomenon may be linked to the increasing influence of the monsoon from the Indian Ocean on climate patterns in southeastern Tibet. The glaciers in the Gangrigabu region of southeastern Tibet are located south of Bomi County, adjacent to Medong County, Zayul County, and Basu County. The area occupied by marine-type glaciers in this region has experienced a significant reduction, with a year-to-year decrease in negative mass balance. The main contributors to the replenishment of water in ice lakes are typically precipitation runoff and glacial melt, while evaporation plays a major role in reducing water storage. Therefore, the existence of ice lakes in the research area can be strongly influenced by the influx of glacial meltwater caused by arid climatic conditions.

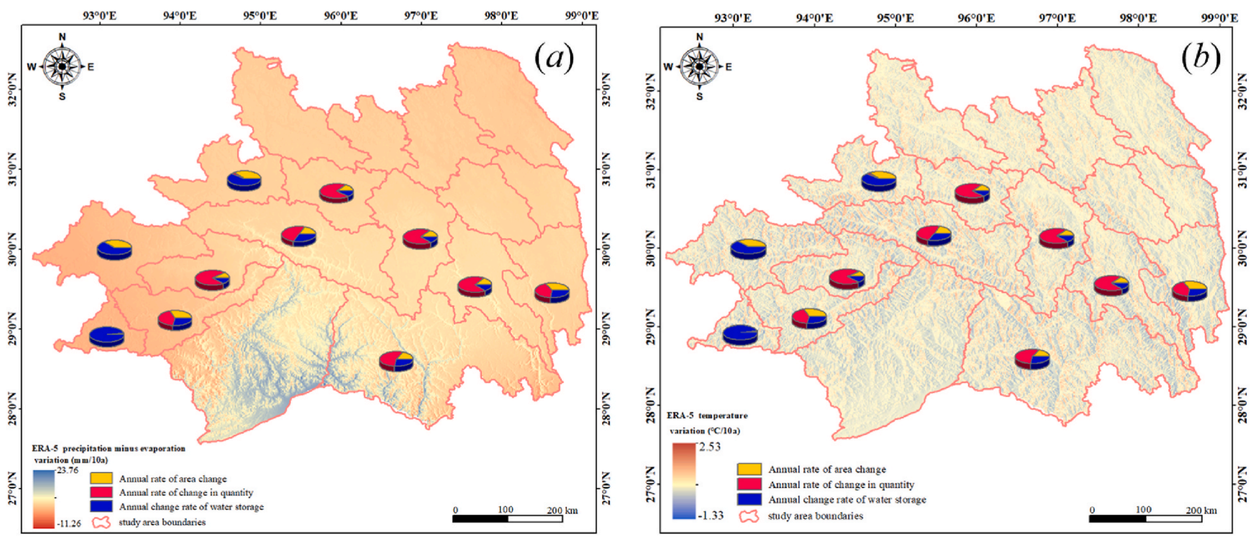

Fig. 7. Correlation between climate change and ice lake variations in southeastern Tibet from 1993 to 2023. (a) Spatial variability of the precipitation–evaporation difference per decade derived from ERA-5 data; (b) trend of temperature change per decade.

Table 3
Temporal variation in temperature and difference between precipitation and evaporation in the region where the ice lake is situated from 1993 to 2023.

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

5. Discussion

5.1. *Causes of ice lake change in the Southeast Tibetan plateau*

The variation in Ice lake area serves as a crucial indicator that reflects climate change. Alterations in precipitation, evaporation, and temperature can potentially contribute to the transformation of ice lakes. The annual mean temperature (0.36 °C/10a) and the annual rainfall (10.4 mm/10a) on the Qinghai-Tibet Plateau both exhibited an increasing trend. In southeast Tibet, the "spring accumulation type" glacier snow cover reached its peak in May, while precipitation peaked in August. The glaciers' mass balance has consistently shown a downward trend of -6.5 ± 0.8 Gt yr^{-1} over an extended period of time. Moreover, with each degree rise in summer temperatures, there is an additional-10.7 ± 4.2 Gt of meltwater generated [60]. The lakes within the research region have the capacity to accumulate a significant amount of water, which is consistent with the outcomes of this investigation suggesting a gradual expansion in the ice lake coverage in southeastern Tibet.The increasing temperature will lead to gradual melting of the ice in the moraine ridge, resulting in a tunnel effect. This occurrence will undermine the stability of the ice lake dam structure and increase the likelihood of an ice lake outburst.

The reasons for the transformation of ice lakes vary across different districts and counties. From 2008 to 2023, following the retreat of the glacier to a certain extent, numerous micro-small ice lakes were formed during the period from 1993 to 2008 (Table 1). However, these lakes lacked stability and experienced dam breaks. Consequently, some water sources merged into larger and more stable ice lakes, resulting in a reduction in the number of ice lakes in certain regions. However, there was an increase in both the area and water capacity (Table 2), particularly in Nang County and Basu County. In specific geographical areas, the count, expanse, and water holding capacity of ice lakes witnessed a decrease in 2023 compared to the observations made in 1993. Nevertheless, by 2008, these ice lakes reached their maximum point in terms of number, size, and water storage before experiencing a subsequent decline. The regions experienced a consistent trend of initial expansion followed by a subsequent decline. Based on the findings presented in this research paper, there was a notable withdrawal of marine glaciers from 1993 to 2008 within these areas. This retreat led to the emergence of numerous micro-sized ice lakes and facilitated abundant water supply for medium and large ice lakes, resulting in their expansion within the region. However, as marine glaciers gradually disappeared from the area, a considerable number of micro-sized ice lakes experienced dam failures. Consequently, this has contributed to an increase in the overall number of ice lakes within these areas. The area and water capacity experience significant reduction, ultimately leading to a balanced number, area, and water capacity

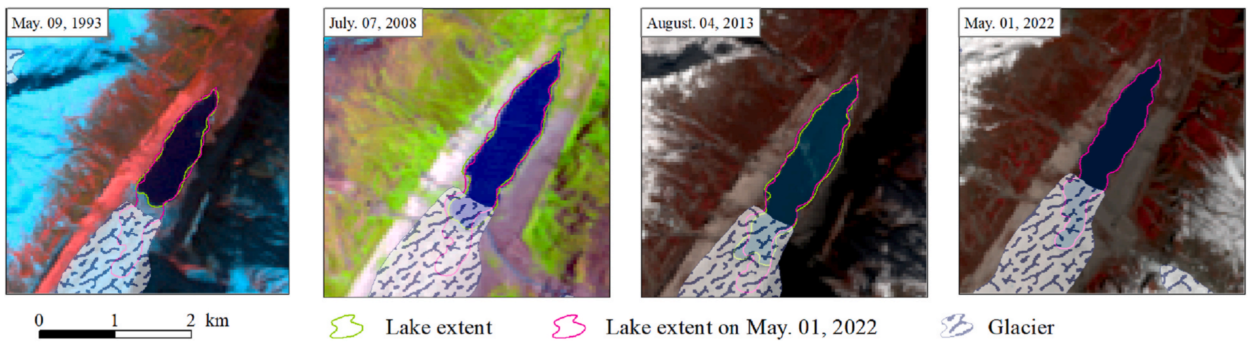

Fig. 8. The study focuses on the temporal development and spatial expansion trend of a ice lake in this region(26. 94°E, 37.30°N).

of ice lakes in the region, such as Medong County. As depicted in Fig. 8, certain regions consistently witness expansion of ice lakes due to their location at the mountain base and proximity to the ice tongue's terminus. Consequently, these types of ice lakes easily acquire ample water sources without being prone to outbursts.

5.2. Factors influencing the morphological features of ice lakes

The morphological changes of ice lakes in high altitude areas are influenced by various factors, including the orientation of the mother glacier, relief degree, surface ice content, monsoon patterns, and other environmental conditions in low temperature environments. The distribution of ice lakes is closely associated with the extent of glacial activity. Ice lakes tend to form in valleys that have been eroded by glaciers year-round, aligning their development trajectory with the direction of glacial movement. The expansion of ice lakes is particularly prevalent in regions characterized by minimal topographical variation and more stable terrain. The southeast Tibet region is influenced by the Indian Ocean monsoon, which brings ample precipitation. This leads to a synchronization between the melting degree of marine-type glaciers in different altitude gradients within the region and the expansion pattern observed in ice lakes. The impact of Marine glacier melting on the formation of numerous micro-small ice lakes is particularly pronounced. After analyzing the development trend of ice lakes, it can be concluded that ice lakes located near the mother glacier and in the valley exhibit a more continuous and stable growth pattern, gradually evolving into larger ice lakes (Fig. 8). However, the formation of cirque lakes resulting from glacial erosion limits the potential for further expansion of this type of ice lake (Fig. 6g–i). Therefore, the combination of all factors can exert a significant influence on the development and morphological alterations of ice lakes, thereby resulting in the occurrence of large-scale ice lake outburst disasters.

5.3. Cause analysis of ice lake expansion and disaster treatment suggestions

The distribution of marine glaciers and ice lakes in southeast Tibet exhibits distinct spatial and temporal variations. Factors such as the predominant surrounding topography, primary extent of marine-type glaciers, and the composition of detritus left behind by glacier retreat are likely to be the key determinants contributing to these disparities. However, through an analysis of the relationship between regional climate fluctuations and changes in ice lakes, this paper posits that the alternating accumulation and retreat of marine-type glaciers are primarily driven by the pronounced disparity between summer and winter climates in the plateau region. This discrepancy leads to perennial rock layer erosion within the region, consequently facilitating rapid growth of eroded ice lakes. Furthermore, against the backdrop of global warming, climate change serves as a significant contributing factor to the expansion of other types of ice lakes in this area. Due to the superposition of the topography and geomorphology of Nyingchi City and Qamdo City, coupled with the highly uneven distribution of precipitation, ice is present in the region. The number and size of lakes are undergoing rapid changes; however, it is likely that most ice lakes in Nyingchi will continue to expand until some reach their breaking point. Consequently, there exists a significant risk of ice lake outburst in certain growing individual ice lakes within Zayul and Bomi counties in the forthcoming decades. The effectiveness of identifying potentially hazardous ice lakes can be enhanced by focusing on the area and water storage changes of individual ice lakes that exhibit continuous growth, as demonstrated by numerous studies. However, conducting a large-scale assessment of GLOF risk incurs significant costs. Therefore, in the risk assessment process, it is crucial to make timely adjustments based on the intensity of local human activities, infrastructure distribution density, and post-disaster economic losses. Particular attention should be given to ice lakes that pose a high risk of outburst but do not cause severe economic losses or casualties. The utmost focus should be placed on those ice lake areas that have the potential for substantial economic losses and numerous casualties. Additionally, disposal plans should be developed in response to changes in local precipitation intensity and ice lake water storage. The boundary ice lake segmentation method is employed to determine changes in the area and water storage of ice lakes based on a multi-temporal inventory in southeast Tibet. This approach will facilitate a more comprehensive investigation into the dynamic processes and driving factors behind ice lake expansion in the region, as well as enable predictions regarding trends in ice lake morphological changes or potential outburst disaster events.

6. Conclusions

In the current study, an innovative and inclusive approach to map ice lake profiles by employing an automated method for segmenting ice lakes was introduced. This study involved the examination of ice lake data from different periods. In this work, the specificity and differences in the changes in the ice lake range and ice lake water capacity in southeastern China and Tibet from 1993 to 2023 were quantitatively studied to better understand the complex characteristics of ice lake changes in the region.

(1) In 2023, 3877 ice lakes were present in the southeastern Tibetan Plateau, with an average area of 0.10 km^2 and a total area of 395.44 ± 22.73 km^2. These lakes collectively possessed a remarkable water storage capacity of 8493.68×10^6 m^3. In the study area, there were a total of 1354 micro to small ice lakes in Zayul County, accounting for 34.93 % of the total number of lakes, with a water storage capacity of 608.13×10^6 m^3, which represents 7.16 % of the total water storage capacity. However, the ice lake water storage in Basu County accounts for 32.77 %, representing a significant portion of the total area. The total number of ice lakes is 1399 (36.08 %), covering an area of approximately 135.25 ± 8.11 km^2 (34.18 %).

(2) The number, area, and water storage of ice lakes on the southeastern Tibetan Plateau consistently increased from 1993 to 2023. Specifically, the number of ice lakes increased from 2520 to 3844, with an annual growth rate of 1.75 %/a. Specifically, there were 1468 newly formed ice lakes and 102 previously existing lakes that disappeared. The total ice lake area increased from

337.64 ± 36.85 km^2 to 395.74 ± 22.72 km^2, representing a growth rate of 17.21 %. Climate warming has resulted in the significant retreat of marine glaciers in the region and the formation of numerous micro to small ice lakes, leading to the expansion of ice lakes. Additionally, this phenomenon has caused ice lakes in some districts and counties to connect with other bodies of water after outbursts, ultimately increasing the overall lake water capacity. This is also the primary reason for the changes observed in the ice lakes on the southeastern Tibetan Plateau.

(3) Through an analysis of research findings and climate data, it can be inferred that the regional specificity and variation in climate change inevitably lead to disparities in ice lake transformations across the entire study area. The variations are a result of disparate local rates of temperature, precipitation, and evaporation. The main factors influencing the changes in ice lakes and ice lake outburst events are fluctuations in temperature and increases in precipitation. Therefore, the ongoing retreat of marine-type glaciers may further accelerate the expansion of ice lakes in southeastern Tibet due to the continuous temperature increase in this high-elevation region.

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Not applicable.

Informed consent statement

Not applicable.

Data availability statement

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

Declaration of interest's statement

The authors declare no conflict interest.

CRediT authorship contribution statement

Y.U. Mingwei: Writing – original draft. **L.I. Feng:** Methodology. **G.U.O. Yonggang:** Writing – review & editing. **S.U. Libin:** Formal analysis. **Q.I.N. Deshun:** Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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