

## Spatiotemporal Characteristics and Driving Forces of Glacial Lake Distribution in the Kunlun Mountains: Postprint

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### Abstract

Investigating the changing characteristics of glacial lakes in the Kunlun Mountains is crucial for regional ecological environment and development. Based on supervised classification using the Google Earth Engine (GEE) remote sensing cloud platform, this study examines the changes in distribution area and number of glacial lakes in the Kunlun Mountains over the past 20 years, and conducts a driving force analysis combined with temperature, precipitation, and glacier area. The results show that: (1) From 2000 to 2020, the number of glacial lakes in the Kunlun Mountains region increased by 39.25%, and the area increased by 81.35%, exhibiting a distribution pattern of more in the west and less in the east. (2) Glacial lakes with an area smaller than 0.1 km<sup>2</sup> in the Kunlun Mountains region are more sensitive to climate change and have the fastest growth rate; glacial lakes in the Kunlun Mountains are mainly concentrated at elevations of 4600–5600 m, with the number and area of glacial lakes accounting for 71.58% and 70.51% of the total, respectively. (3) From 2000 to 2020, the temperature in the Kunlun Mountains region decreased by 3.45%, precipitation decreased by 6.27%, and glacier area decreased by 21.15%; glacial meltwater produced by glacier melting is the main cause for the growth of glacial lakes. The research results can provide scientific support for the protection and utilization of water resources in arid areas, disaster early warning, and other aspects.

### Full Text

#### Analysis of Temporal and Spatial Characteristics and Driving Forces of Glacial Lakes in the Kunlun Mountains

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## Abstract

Investigating the changing characteristics of glacial lakes in the Kunlun Mountains is essential for regional ecological environment and development. Based on supervised classification using the Google Earth Engine (GEE) remote sensing cloud platform, this study examines changes in the distribution, area, and number of glacial lakes in the Kunlun Mountains over the past 20 years, and analyzes driving forces in combination with temperature, precipitation, and glacier area. The results show that: (1) From 2000 to 2020, the number of glacial lakes in the Kunlun Mountains increased by 39.25%, and the area expanded by 81.35%, exhibiting a distribution pattern of more lakes in the west and fewer in the east. (2) Glacial lakes smaller than 0.1 km<sup>2</sup> are more sensitive to climate change and have the fastest growth rate. Glacial lakes in the Kunlun Mountains are mainly concentrated at elevations of 4600–5600 m, with the number and area accounting for 71.58% and 70.51% of the total, respectively. (3) From 2000 to 2020, temperature in the Kunlun Mountains decreased by 3.45%, precipitation decreased by 6.27%, and glacier area decreased by 21.15%. The meltwater produced by glacier melting is the main cause of glacial lake growth. The research results can provide scientific support for water resource protection and utilization, as well as disaster early warning, in arid regions.

**Keywords:** remote sensing; Kunlun Mountains glacial lakes; GEE; climate change; driving force analysis

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## 1. Introduction

Glacial lakes are natural water bodies formed mainly by modern glacier meltwater or water accumulation in moraine ridge depressions. They are highly sensitive to climate change and constitute an important component of global climate change monitoring. Since the 1980s, northwestern China has shown a trend of shifting from warm-dry to warm-wet conditions, which may lead to disasters such as glacial lake outburst floods and debris flows, posing potential threats to downstream human activities. Therefore, investigating the changing characteristics and impacts of glacial lakes in river source regions is significant for understanding cryospheric climate and environmental changes and assessing disaster risks.

Previous studies on glacial lakes have focused on several aspects: remote sensing-based glacial lake information extraction methods and applications, spatiotemporal characteristic analysis and influencing factor analysis of glacial lakes in

response to regional climate change, identification and prediction of potentially dangerous glacial lakes in typical regions, and glacial lake outburst flood risk assessment and early warning. Research indicates that the expansion rate of new glacial lakes in the Himalayas is  $0.96 \text{ km}^2/\text{year}$ , with glacier-fed lake area growth accounting for 75.4% of the total growth, confirming the dominant role of glacial meltwater in glacial lake expansion. Since the 1990s, glaciers on the Tibetan Plateau have been in a negative balance state, with the area of glacial lakes increasing by  $128.5 \text{ km}^2$  from 1990 to 2010. Similarly affected by climate warming and glacier retreat, the area of glacial lakes in the Tianshan Mountains has increased at an average rate of  $0.689 \text{ km}^2/\text{year}$ .

Currently, remote sensing monitoring of glacial lake changes in China has mainly concentrated on the Himalayas and its sub-regions (Yairu Zangbo Basin, Boqu River Basin, Koshi River Basin, Shishapangma Peak), Nyainqentanglha sub-regions (western Nyainqentanglha Range, Parlung Zangbo River), the Tibetan Plateau (Bujiagangri, Naqu, Niduzangbu River, Bedezangbu River Basin), Pamir Plateau, Tianshan Mountains, and Altai Mountains. The focus of glacial lake research includes remote sensing-based extraction methods, response analysis to climate change, and risk assessment.

The Kunlun Mountains, located in the arid and semi-arid regions of north-western China, span a large longitudinal range with regionally variable climate elements. Monitoring glacial lake changes in the Kunlun Mountains can provide references for rational water resource development and utilization in arid regions and data support for glacial lake outburst disaster risk assessment. However, there is currently a lack of comprehensive understanding of the overall changing characteristics of glacial lakes in the Kunlun Mountains. Therefore, this study conducts remote sensing monitoring of glacial lakes in the Kunlun Mountains based on Landsat data, analyzes recent spatiotemporal variation characteristics, and explores influencing factors in combination with meteorological data.

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## 2. Study Area and Methods

### 2.1 Study Area Overview

The Kunlun Mountains connect with the Pamir Plateau in the west, border southeastern Qinghai Province in the east, adjoin the Tarim Basin and Qaidam Basin in the north, and connect with northwestern Tibet Autonomous Region in the south (Fig. 1). The Kunlun Mountains are an east-west oriented mountain range located between  $75^\circ\text{--}100^\circ\text{E}$  and  $34^\circ\text{--}40^\circ\text{N}$ , with a total length of approximately 2500 km and an average width of 130–200 km. The average elevation exceeds 4000 m. The terrain is characterized by steep slopes and high peaks with numerous mountains and slopes. Although glacial lakes in the Kunlun Mountains receive some rainfall, they are mainly supplied by snow and glacier melt, with flow varying seasonally. Strong summer snow and ice melt is the primary water source for glacial lakes. The study area spans a large east-west

distance with significant differences in temperature, precipitation, and other climate conditions. To observe glacial lake response to climate, the Kunlun Mountains are often divided into eastern, central, and western parts. Due to fewer glacial lakes in the central and eastern regions, this study combines the central and eastern parts based on Zhang Liancheng et al.'s research, dividing the Kunlun Mountains into eastern and western parts.

## 2.2 Data Sources

**Remote Sensing Data:** Landsat series satellite data were obtained from the GEE platform to extract glacial lake boundaries. To reduce seasonal differences in glacial lake area changes and minimize errors caused by high cloud cover in mountainous areas, images with less than 10% cloud cover were primarily selected from July to September. The 2020 data acquisition period was extended due to data scarcity.

**DEM Data:** SRTM DEM data covering the Kunlun Mountains region in China were used, with a spatial resolution of 30 m, sufficient for complex terrain conditions in mountainous areas. This data was used to extract elevation, aspect, hillshade, and other topographic factors for spatial analysis of glacial lake distribution, obtained from the China Geographic Spatial Data Cloud (<http://www.gscloud.cn>).

**Meteorological Data:** Temperature and precipitation data from FLDAS (<https://disc.gsfc.nasa.gov/>) were selected, with a temporal resolution of 1 month and spatial resolution of  $0.1^{\circ} \times 0.1^{\circ}$ .

**Glacier and Glacial Lake Inventory Data:** The Randolph Glacier Inventory (RGI) global glacier inventory data and China's Northwest Glacier Inventory data (2018) were used as reference data. Glacial lake inventory data used the High Asia Glacial Lake Inventory dataset (2000) as reference data.

## 2.3 Methods

**2.3.1 Supervised Classification Based on GEE** This study used Landsat-5/7/8 remote sensing images from the GEE platform. Cloud-free image composites were created using cloud removal functions to ensure image quality. Second, a certain number of uniformly distributed random sample points were selected on the composite images for vegetation, bare land, snow, ice, water bodies, and other categories. Among them, 70% of the samples were used for Random Forest classification, and the remaining 30% were used for accuracy verification (Fig. 2). The Random Forest method has advantages of minimal manual intervention, obvious classification effects, and high computational efficiency. A confusion matrix was constructed for accuracy assessment, with overall classification accuracy averaging 92.3% and Kappa coefficient averaging 0.89. The extracted glacial lake boundaries were vectorized and visually interpreted to eliminate classification errors caused by mountain shadows. The extracted glacier data were compared with RGI inventory data to ensure reliability. A 10 km buffer

zone was established around glacier termini. Glacial lake data were visually interpreted to preliminarily eliminate mountain shadows, then overlaid with slope maps and glacier buffer zones for secondary precise extraction. Lakes smaller than 0.01 km<sup>2</sup> were removed as misclassified. The extracted glacial lakes were compared with the High Asia Glacial Lake Inventory, with area error of 8.69% and number error of 9.07%, within acceptable limits.

**2.3.2 Sen+Mann-Kendall Trend Analysis** The Sen+Mann-Kendall method is a non-parametric test that makes no assumptions about data distribution and is insensitive to outliers. The Mann-Kendall trend test statistic  $S$  is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i)$$

where  $\text{sgn}$  is the sign function. For time series length  $n > 10$ , statistic  $S$  approximately follows a standard normal distribution. The test statistic  $Z$  is used for trend testing at significance level  $\alpha = 0.05$  ( $Z_{0.025} = -1.96$ ,  $Z_{0.975} = 1.96$ ).  $Z$  is calculated as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases}$$

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18}$$

where  $n$  is the number of data points,  $m$  is the number of tied groups, and  $t_i$  is the size of the  $i$ th tied group. The Sen's slope estimator  $\beta$  is calculated as the median of all pairwise slopes, effectively reducing noise interference:

$$\beta = \text{Median} \left( \frac{x_j - x_i}{j - i} \right), \quad 1 < i < j < n$$

$\beta > 0$  indicates an upward trend, while  $\beta < 0$  indicates a downward trend. This method was applied in Matlab to analyze temperature and precipitation trends and significance.

**2.3.3 Pearson Correlation Analysis** The Pearson correlation coefficient measures linear correlation between two variables  $X$  and  $Y$ , calculated as:

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n (Y_i - \bar{Y})^2}}$$

Constraints include: variables must be independent, continuous, normally distributed, and linearly related. The  $r$  value ranges from -1 to 1, with larger absolute values indicating stronger correlation.  $r = 0$  indicates no linear correlation,  $r = 1$  indicates perfect positive correlation, and  $r = -1$  indicates perfect negative correlation.

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### 3. Results

#### 3.1 Spatiotemporal Variation Characteristics of Glacial Lakes

**3.1.1 Overall Changes in Glacial Lake Number and Area** From 2000 to 2020, glacial lakes in the Kunlun Mountains showed an overall trend of increasing number and area, with consistent changes between the two metrics (Fig. 3). In 2000, there were 1094 glacial lakes with a total area of 28.03 km<sup>2</sup>. By 2020, the number increased to 1524 and the area reached 50.83 km<sup>2</sup>. The total number increased by 39.25% and the total area by 81.35%, with average annual growth rates of 3.65% and 2.22%, respectively. The average annual area expansion rate was 1.09 km<sup>2</sup>.

The changes can be divided into two stages. Before 2010, the total number and area were relatively small, with significant interannual variation showing periodic increases followed by decreases. From 2000–2005, the number increased, then decreased from 2005–2008 to pre-rise levels. From 2010–2020, the number increased substantially and continued stable growth. The area showed no significant interannual variation, increasing steadily.

**3.1.2 Regional Variation Characteristics** Using 85°E as the boundary, the Kunlun Mountains were divided into eastern and western parts. Results show a distribution pattern of more lakes in the west and fewer in the east (Fig. 4). Western Kunlun glacial lakes account for 73.60% of the total number and 81.11% of the total area. The western mountains have higher elevations and extensive glacier coverage, with meltwater accumulating in valleys, favoring glacial lake development. The eastern region has gentler terrain with larger precipitation-fed lakes.

Western Kunlun glacial lakes increased at an average rate of 17.8 lakes/year, while eastern Kunlun showed near-zero annual growth, with many years experiencing negative growth. Area changes were consistent between regions, with western Kunlun area increasing at 4.26%/year and eastern Kunlun at 3.78%/year. Overall, western Kunlun glacial lakes dominate in quantity and growth rate, indicating significant future expansion potential.

**3.1.3 Variation Characteristics by Lake Size** Glacial lake size varies significantly due to the large study area and complex terrain, ranging from 0.01 km<sup>2</sup> to 9.53 km<sup>2</sup> (average 0.18 km<sup>2</sup>). The vast majority (84.36%) are smaller

than  $0.1 \text{ km}^2$ , with larger lakes being less numerous. In terms of area contribution, lakes  $>0.2 \text{ km}^2$  account for 55.17%, followed by  $0.1\text{--}0.2 \text{ km}^2$  lakes (26.03%), while  $<0.1 \text{ km}^2$  lakes contribute the smallest proportion (17.84%).

Different size classes show consistent trends matching the total lake changes (Fig. 5). Lakes  $<0.1 \text{ km}^2$  are most numerous and fastest-growing, increasing at 15.2 lakes/year, indicating more dynamic evolution and higher sensitivity to climate change. This aligns with findings that small glacial lakes ( $<0.04 \text{ km}^2$ ) in High Asia show the most significant growth. Lakes  $>0.2 \text{ km}^2$  are more stable due to stronger regulation capacity.

**3.1.4 Elevation Distribution Characteristics** Glacial lake formation in alpine regions is closely related to surrounding topography. To analyze distribution and changes across elevations, the study divided the elevation range into 200 m intervals (Fig. 6). Glacial lakes are concentrated at 4600–5600 m, accounting for 71.58% of number and 70.51% of area. The distribution peaks at 5000–5200 m for number and 5200–5400 m for area, decreasing toward both ends.

The number increase concentrates at 4800–5000 m (18.25% of total increase), while area expansion concentrates at 5200–5400 m (20.32% of total increase). Small lakes ( $<0.1 \text{ km}^2$ ) peak at 5000–5200 m, medium lakes ( $0.1\text{--}0.2 \text{ km}^2$ ) at 5200–5400 m, and large lakes ( $>0.2 \text{ km}^2$ ) at 3600–3800 m. Eastern Kunlun shows anomalous area peaks at 3600–3800 m due to several large moraine-dammed lakes formed by Quaternary faulting and glacial erosion. Western Kunlun peaks at 5200–5400 m for both number and area.

## 3.2 Analysis of Driving Forces

**3.2.1 Impact of Climate Change** From 2000 to 2020, temperature decreased by 3.45% and precipitation by 6.27% in the Kunlun Mountains (Fig. 8). Temperature shows no significant trend, with a slight increase after 2015. Spatially, most areas show no significant temperature change, with only minor warming in the eastern region (Fig. 9). Precipitation shows nonlinear variation, decreasing from 164 mm to 159 mm. Eastern Kunlun generally shows decreasing precipitation, while western Kunlun shows large-scale increases, particularly significant increases at  $78^\circ\text{--}80^\circ\text{E}$ , providing abundant supply for glacier development and indirectly driving glacial lake expansion.

**3.2.2 Impact of Glacier Changes** Due to cold, dry climate with scarce rainfall and strong evaporation, glacier meltwater is the primary water source for Kunlun glacial lakes. With global warming, glaciers in High Asia are retreating rapidly, making glacier change a key factor affecting glacial lakes. This study extracted glaciers using supervised classification and compared them with China's Northwest Glacier Inventory (2018) to ensure reliability. Glacier area decreased continuously from  $12,739.46 \text{ km}^2$  in 2000 to  $10,045.51 \text{ km}^2$  in 2020, a total reduction of 21.15% with an average annual decrease rate of 2.12% (Fig.

10). Glaciers are mainly distributed in high-elevation western Kunlun, coinciding with the region of most numerous and fastest-growing glacial lakes.

**3.2.3 Correlations Between Temperature, Precipitation, Glacier Area and Glacial Lakes** Pearson correlation analysis shows that glacial lakes are not significantly correlated with temperature or precipitation but show strong negative correlation with glacier area (Table 1). Eastern Kunlun glacial lakes, mostly moraine-dammed lakes formed by geological hazards in glacial troughs, show no significant correlation with glacier area. Lakes  $>0.1 \text{ km}^2$ , which develop indirectly from small lakes, also show no significant correlation. However, most regional glacial lake numbers and areas are significantly negatively correlated with glacier area at the 0.05 level.

In the arid and semi-arid alpine region of Kunlun, temperature and precipitation mainly affect glacial lakes by influencing glacier area and melt rate, showing no direct significant correlation. Glacier meltwater, as the main water source for glacial lakes in arid regions, provides abundant supply for lake formation and expansion under warming conditions. The 21.15% glacier area retreat is the direct cause of rapid increases in glacial lake number and area in Xinjiang's Kunlun Mountains.

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## 4. Conclusions

Based on supervised classification using the GEE platform, this study analyzed spatiotemporal variation characteristics of glacial lakes in the Kunlun Mountains from 2000 to 2020 and examined driving forces from temperature, precipitation, and glacier area changes. The main conclusions are:

- 1) From 2000 to 2020, glacial lake number and area in the Kunlun Mountains showed overall increasing trends, though the growth rate has declined. By 2020, there were 1524 glacial lakes with a total area of  $50.83 \text{ km}^2$ , representing increases of 39.25% in number and 81.35% in area. The distribution shows a clear pattern of more lakes in the west and fewer in the east. Western Kunlun lakes increased by 17.8 lakes/year, while eastern Kunlun showed near-zero growth. Western Kunlun area increased at 4.26%/year compared to 3.78%/year in eastern Kunlun.
- 2) Different size classes respond differently to climate change. Lakes smaller than  $0.1 \text{ km}^2$  are most sensitive and fastest-growing, increasing at 15.2 lakes/year. Lakes  $>0.2 \text{ km}^2$  contribute the most to area (55.17%), followed by  $<0.1 \text{ km}^2$  lakes (26.03%). Glacial lakes are concentrated at 4600–5600 m elevation, accounting for 71.58% of number and 70.51% of area. Number increases concentrate at 4800–5000 m, while area expansion concentrates at 5200–5400 m.

- 3) Glacial lake number and area show no significant correlation with temperature or precipitation but are significantly negatively correlated with glacier area, indicating glacier area is the main controlling factor. The 21.15% glacier area retreat from 2000 to 2020 provided abundant meltwater, directly causing rapid increases in glacial lake number and area.

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*Note: Figure translations are in progress. See original paper for figures.*

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