

Postprint: Response of Glaciers and Lakes to Climate Change in the Whale Lake Basin, East Kunlun

Authors: Chen Lihua, Che Yanjun, Cao Yun, Zhang Mingjun, Gu Lailei, Jiakang Wu, Lü Weiwei

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Abstract

Taking the Jingyu Lake basin in East Kunlun as the study area, the extent of glaciers and lakes within the basin from 1990 to 2023 was obtained through interpretation of Landsat series imagery. Simultaneously, water level datasets from the Inland Water Hydrological Time Series Database and global glacier mass balance datasets were utilized to analyze the variations in glacier area, volume, and mass balance, as well as changes in Jingyu Lake's area, water level, and storage volume. Furthermore, by integrating ERA5 reanalysis data, the changes in glaciers and lakes within the basin and their response processes to climate change were investigated. The results show that: (1) From 1990 to 2023, Jingyu Lake exhibited a significant expansion trend, expanding from 266.00 km² to 399.30 km², with an area increase of 133.30 km² and an expansion rate of 4.66 km² · a⁻¹. From 2013 to 2023, the lake water level rose by 5.19 m, with a water level rise rate of 0.55 m · a⁻¹. The lake water volume increased by 1.31 km³, with an annual increment of 0.16 km³. (2) From 1990 to 2023, glaciers in the basin showed a significant retreat trend, with glacier area decreasing by 4.59 km² at a rate of -0.12 km² · a⁻¹, and glacier storage volume decreasing by 0.38 km³ at a rate of -0.01 km³ · a⁻¹. The multi-year average mass balance of glaciers from 2000 to 2020 was -1.22×10^{-4} m w.e. (3) From 1990 to 2021, the annual mean temperature in the basin increased significantly, with an annual warming rate of 0.02 °C · a⁻¹, but summer warming was not significant. Annual precipitation increased significantly at a rate of 2.11 mm · a⁻¹, with precipitation concentrated in summer, accounting for 78.9% of annual precipitation. (4) Precipitation in the basin is the primary factor driving lake expansion. This study reveals the response of glaciers and lakes in the Jingyu Lake basin to climate change, which can provide a reference for local governments to optimize water resource allocation and management.

Full Text

Responses of Glaciers and Lakes to Climate Change in the Jingyu Lake Basin, East Kunlun Mountains

CHEN Lihua¹², CHE Yanjun¹², ZHANG Mingjun³⁴, GU Lailei³⁴, WU Jiakang¹², LYU Weiwei¹²

¹School of Geography and Environment, Jiangxi Normal University, Nanchang 330022, Jiangxi, China

²Department of Geographical Science, Yichun University, Yichun 336000, Jiangxi, China

³College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, Gansu, China

⁴Key Laboratory of Resource Environment and Sustainable Development of Oasis, Gansu Province, Lanzhou 730070, Gansu, China

Abstract: Glaciers and lakes are critical components of terrestrial surface water cycling and are highly sensitive to climate change, serving as natural indicators of climatic variations. This study examines the Jingyu Lake Basin in the eastern Kunlun Mountains as the research area. By interpreting Landsat series imagery from 1990 to 2023, we extracted glacier and lake boundaries within the basin. Concurrently, utilizing the DAHITI water level dataset and the global glacier mass balance dataset, we analyzed the characteristics of glacier area, volume, and mass balance changes, as well as variations in Jingyu Lake's area, water level, and storage. Furthermore, combined with ERA5 reanalysis data, we investigated the response processes of glaciers and lakes in the basin to climate change. The results demonstrate that Jingyu Lake exhibited a significant expansion trend from 1990 to 2023, increasing from [initial area] to [final area] km², representing an expansion of 133.30 km² with an annual increment of 0.16 km³ and a change rate of 4.66 km² · a⁻¹. Between 2013 and 2023, the lake level rose by 5.19 m at a rate of 0.55 m · a⁻¹, while lake volume increased by 1.31 km³. During the same period, glaciers in the basin showed a significant retreat trend, with glacier area decreasing by 4.59 km² at a rate of 0.12 km² · a⁻¹, and glacier volume declining by 0.38 km³ at a rate of 0.01 km³ · a⁻¹. The average annual mass balance from 2000 to 2020 was -1.22×10^{-4} m w.e., indicating substantial mass loss. From 1951 to 2021, the basin experienced significant warming with an annual temperature increase of 0.02 °C · a⁻¹, though summer warming was not significant. Annual precipitation increased significantly at a rate of 2.11 mm · a⁻¹, concentrated in summer which accounts for 78.9% of total precipitation. Precipitation is identified as the primary factor driving lake expansion in the basin. This study reveals the response of glaciers and lakes in the Jingyu Lake Basin to climate change, providing a scientific basis for local governments to optimize water resource allocation and management.

Keywords: climate change; glaciers; lakes; Jingyu Lake Basin; east Kunlun Mountains

1.1 Study Area Overview

The Jingyu Lake Basin is located in the Altun Mountain Nature Reserve at the junction of Xinjiang, Tibet, and Qinghai provinces in the southeastern part of Ruoqiang County (89°26 E, 36°19 N). It is the largest lake at the intersection of the three provinces and the highest-altitude closed saline lake in the Kumkuli Basin of the eastern Kunlun Mountains [Figure 1: see original paper]. The selected Jingyu Lake Basin covers an area of approximately 4,000 km², with the lake area accounting for about 400 km² (10% of the basin area) in 2023. The basin elevation ranges from 4,723 m to 5,800 m, with glaciers covering 58 km² (1.45% of the basin area) in 1990. The multi-year average temperature from 1990 to 2021 was -9.49 ± 0.82 °C, with an average annual precipitation of 417.39 mm. The main vegetation type is grassland. Closed alpine lakes are primarily fed by precipitation and meltwater from snow and ice. Influenced by the westerly circulation and orographic uplift, precipitation in the basin is concentrated in summer.

1.2 Data Sources

1.2.1 Remote Sensing Data This study utilized Landsat series imagery to extract glacier and lake boundaries and obtain information on their extents from 1990 to 2023. The imagery included Landsat-5 TM, Landsat-7 ETM+, and Landsat-8/9 OLI/TIRS data. To minimize the impact of clouds and snow cover on glacier and lake extraction and improve accuracy, we prioritized images with minimal cloud and snow influence, primarily selecting summer scenes (June–September). A total of 33 images were acquired. All Landsat data were obtained from the United States Geological Survey (USGS) Earth Explorer (<https://earthexplorer.usgs.gov>). Due to the failure of the Landsat-7 ETM+ scan line corrector in 2003, we used the fill.sav tool to repair striping artifacts in the affected images [24].

1.2.2 Water Level Data The DAHITI (Database for Hydrological Time Series of Inland Waters) dataset was used to analyze water level changes in Jingyu Lake. Developed in 2015, DAHITI employs multiple altimetry satellites (ENVISAT, TOPEX/Poseidon, ERS-1/2, CryoSat-2, Jason-1/2/3, ICESat, SARAL/Altika, Sentinel-3A/B) to estimate water levels for lakes, reservoirs, rivers, and wetlands [25]. The processing involves preprocessing, Kalman filtering, and reprocessing, with Kalman filtering being the key step for water level estimation, yielding root-mean-square errors of 8–114 cm for lakes and 4–36 cm for rivers. For Jingyu Lake, altimetry data from Sentinel-3B and SARAL were used, covering 2013–2023. Due to limited data in 2013 and lack of summer measurements, we used available months (mainly June–September) for analysis, with occasional use of other months when necessary. Data were downloaded from https://dahiti.dgfi.tum.de/en/products/water_{{level}}_{{altimetry}}/.

1.2.3 Glacier Mass Balance Dataset Glacier mass balance, representing the difference between accumulation and ablation, directly reflects glacier health [33]. We employed the global glacier mass balance dataset established by Hugonnet et al. [27] based on remote sensing observations to analyze mass balance in the Jingyu Lake Basin. This dataset primarily uses ASTER and Landsat imagery, ArcticDEM, TanDEM-X, and ICESat/ICESat-2 data, with cross-validation to ensure accuracy. The dataset covers 2000–2020, providing annual mass balance estimates.

1.2.4 Meteorological Data Due to the lack of ground observations in this remote region, we used ERA5-Land reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) to analyze local climate change. ERA5-Land provides global gridded climate products derived from the ECMWF Integrated Forecast System, offering extensive spatial coverage at $0.1^\circ \times 0.1^\circ$ resolution [28]. We downloaded monthly temperature and precipitation data for 1951–2021 from <https://cds.climate.copernicus.eu/> to analyze climate trends in the basin.

1.3 Methods

1.3.1 Glacier and Lake Boundary Extraction Glacier coding follows river/lake basin codes indicating which water body the glacier feeds. The Jingyu Lake Basin code is 5Z142, so we extracted glaciers coded as 5Z142. However, few glaciers directly feed Jingyu Lake, and most are small and heavily snow-affected. Given the limited number of glaciers and the need for high accuracy, we employed manual visual interpretation, the most traditional and accurate method for delineating glacier and lake boundaries [29], despite being time-intensive. Before interpretation, we preprocessed Landsat imagery to enhance glacier and lake features through radiometric calibration, atmospheric correction (FLAASH), and band composition (using Landsat-5 TM, Landsat-7 ETM+, and Landsat-8/9 OLI/TIRS shortwave infrared bands). High-resolution Google Earth historical imagery and field observations were used for validation and boundary correction.

1.3.2 Volume Calculations **Lake Volume Calculation:** We assessed lake volume changes using water level and area data. The formula is:

$$\Delta V = (H_2 - H_1) \times (S_1 + S_2)/2$$

where ΔV is the change in water storage, H_1 and H_2 are water levels at different times, and S_1 and S_2 are corresponding lake areas [31, 32].

Glacier Volume Calculation: Due to the lack of ground observations for glacier thickness in the basin, we estimated glacier volume using an empirical formula [33, 34]:

$$V = 0.0365 \times A^{1.375}$$

where V is glacier volume and A is glacier area.

1.3.3 Climate Analysis Given the plateau's climatic 特殊性, we divided the year into summer (warm season, June–September) and winter (cold season, October–May) based on glaciological and hydrological characteristics. We analyzed trends in summer, winter, and annual average temperature and precipitation for the basin.

2.1 Jingyu Lake Area and Water Level Changes

Jingyu Lake area expanded continuously from 1990 to 2023, with significant expansion primarily toward the northwest and southeast [Figure 2: see original paper]. The lake area increased by 133.30 km² at a rate of 4.66 km² · a⁻¹. The maximum area occurred in 2023 at [value] km², while the minimum was 245.59 km² in 1990. The lake experienced three evolution phases: (1) 1990–2000: area contraction at 4.27 km² · a⁻¹ (significant); (2) 2000–2010: fluctuating but relatively stable area with slight decrease of 0.14 km² · a⁻¹ (not significant); and (3) 2010–2023: rapid expansion at 6.05 km² · a⁻¹ (significant). Notably, rapid expansions exceeding 10 km² occurred between adjacent years multiple times during 2010–2023, including increases of 17.13 km² (2015–2016), 10.57 km² (2017–2018), 13.27 km² (2019–2020), and 15.62 km² (2021–2022).

The lake water level rose correspondingly with area expansion. From 2013 to 2023, the level increased from 4716.88 ± 0.018 m to 4722.07 ± 0.005 m, a total rise of 5.19 m at 0.55 m · a⁻¹ [Figure 3: see original paper]. The rise accelerated after 2017, reaching 0.75 m in 2020–2021. Due to limited 2013 data, that period shows larger uncertainty. Seasonally, summer water levels exceed winter levels due to increased glacier melt and permafrost thaw, showing a fluctuating upward trend [Figure 3: see original paper]. The rate of water level rise during 2017–2023 (0.75 m · a⁻¹) was significantly faster than during 2013–2017 (0.41 m · a⁻¹).

2.2 Glacier Area and Mass Balance Changes in the Jingyu Lake Basin

Glaciers are mainly distributed in the eastern part of the basin (94.4% of total glacier area), with smaller amounts in the north [Figure 4: see original paper]. In 1990, the basin contained 62 glaciers covering 58.03 km², decreasing to 55 glaciers and 53.44 km² by 2023—a reduction of 7 glaciers and 4.59 km² at a rate of 0.12 km² · a⁻¹ (significant). The basin primarily hosts small glaciers (average 1.14 km² in 1990), making boundaries susceptible to snow cover. The largest glacier, covering 12.61 km² in 1990 and 11.70 km² in 2023, accounted for 19.83% of total area loss.

Glacier mass balance directly reflects dynamic changes. From 2000 to 2020, the average annual mass balance was -1.22×10^{-4} m w.e., with a cumulative balance of -4.39×10^{-3} m w.e., showing a significant declining trend [Figure

4: see original paper]. Mass balance was positive during 2000–2005 but turned negative after 2005, indicating a shift from accumulation to deficit.

2.3 Volume Changes of Jingyu Lake and Glaciers

Corresponding to area changes, Jingyu Lake volume increased significantly by 1.31 km^3 from 1990 to 2023 at $0.16 \text{ km}^3 \cdot \text{a}^{-1}$ [Figure 5: see original paper]. The most substantial increases occurred in 2015–2016 (0.32 km^3) and 2021–2022 (0.31 km^3). Conversely, glacier volume decreased significantly from 3.81 km^3 in 1990 to 3.43 km^3 in 2023—a loss of 0.38 km^3 at $0.01 \text{ km}^3 \cdot \text{a}^{-1}$ [Figure 5: see original paper].

2.4 Climate and Lake/Glacier Change Correlation Mechanism Analysis

2.4.1 Climate Change in the Jingyu Lake Basin From 1951 to 2021, the basin's average annual temperature was $-9.16 \pm 0.82^\circ\text{C}$, with a significant warming trend of $0.02^\circ\text{C} \cdot \text{a}^{-1}$ [Figure 6: see original paper]. Winter warming ($0.04^\circ\text{C} \cdot \text{a}^{-1}$) dominated the annual trend, while summer warming was not significant ($0.01^\circ\text{C} \cdot \text{a}^{-1}$). The multi-year average precipitation was $492.13 \pm 24.41 \text{ mm}$, with a significant increasing trend of $2.11 \text{ mm} \cdot \text{a}^{-1}$. Summer precipitation averaged 373.77 mm , accounting for 76% of the annual total, while winter precipitation showed a slight decreasing trend ($-0.07 \text{ mm} \cdot \text{a}^{-1}$). Thus, annual precipitation changes were dominated by summer precipitation.

2.4.2 Climate Drivers of Glacier and Lake Area Changes Correlation analysis reveals that glacier area correlates negatively with both temperature and precipitation (both significant) [Figure 7: see original paper]. Increased temperature drives glacier ablation, while increased summer precipitation (mostly liquid at these elevations) provides latent heat that accelerates melting. Precipitation accumulation cannot offset temperature-driven ablation, making temperature the dominant factor controlling glacier retreat, consistent with other Tibetan Plateau regions [35].

Lake area correlates positively with both temperature and precipitation (both significant) [Figure 7: see original paper]. As a closed lake above 4700 m, Jingyu Lake is fed by both precipitation and meltwater [30]. Climate affects lake evolution directly through increased precipitation and indirectly through enhanced glacier melt. However, with glacier coverage of only 1.45% and high annual precipitation ($\sim 473 \text{ mm}$), precipitation is the primary driver of lake expansion in this basin.

Conclusions

This study integrated Landsat imagery, DAHITI water level data, global glacier mass balance data, and ERA5 reanalysis to investigate glacier and lake changes

in the Jingyu Lake Basin and their response to climate change. Key findings include:

1. **Significant lake expansion:** From 1990–2023, Jingyu Lake expanded by 133.30 km^2 at $4.66 \text{ km}^2 \cdot \text{a}^{-1}$. From 2013–2023, water level rose 5.19 m ($0.55 \text{ m} \cdot \text{a}^{-1}$) and volume increased by 1.31 km^3 ($0.16 \text{ km}^3 \cdot \text{a}^{-1}$).
2. **Glacier retreat:** From 1990–2023, glacier area decreased by 4.59 km^2 ($0.12 \text{ km}^2 \cdot \text{a}^{-1}$) and volume by 0.38 km^3 ($0.01 \text{ km}^3 \cdot \text{a}^{-1}$). The 2000–2020 average mass balance was $-1.22 \times 10^{-4} \text{ m w.e.}$, indicating substantial loss.
3. **Climate trends:** From 1951–2021, annual temperature increased significantly at $0.02 \text{ }^\circ\text{C} \cdot \text{a}^{-1}$ (winter-dominated), while annual precipitation increased at $2.11 \text{ mm} \cdot \text{a}^{-1}$, concentrated in summer (78.9%).
4. **Driving mechanisms:** Precipitation is the primary factor for lake expansion, while temperature is the main driver of glacier retreat, though summer precipitation also contributes to glacier ablation.

These findings provide essential data for water resource management in the Jingyu Lake Basin.

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Abstract: Glaciers and lakes are highly sensitive to climate change. This study examines the boundaries of glaciers and lakes in the Jingyu Lake Basin, east Kunlun Mountains from 1990 to 2023 using Landsat series imagery. In addition, the DAHITI water level dataset and the global glacier mass balance dataset were utilized to analyze changes in glacier area, volume, and mass balance, as well as the area, water level, and volume of the Jingyu Lake Basin. ERA5 meteorological reanalysis data were employed to assess the response of glaciers and lakes in the basin to climate change. The results indicate a significant expansion trend in the Jingyu Lake. From 1990 to 2023, Jingyu Lake expanded by 133.30 km^2 at a rate of $4.66 \text{ km}^2 \cdot \text{a}^{-1}$. Between 2013 and 2023, the lake's water level rose by 5.19 m, with an annual increase rate of $0.55 \text{ m} \cdot \text{a}^{-1}$, and its volume increased by 1.31 km^3 , averaging an annual increment of 0.16 km^3 . During the same period, the glacier area decreased by 4.59 km^2 at a rate of $0.12 \text{ km}^2 \cdot \text{a}^{-1}$, and the glacier volume declined by 0.38 km^3 at a rate of $0.01 \text{ km}^3 \cdot \text{a}^{-1}$. The average annual glacier mass balance from 2000 to 2020 was $-1.22 \times 10^{-4} \text{ m w.e.}$ The average annual temperature in the Jingyu Lake Basin increased significantly from 1990 to 2021, with an annual warming rate of $0.02 \text{ }^\circ\text{C} \cdot \text{a}^{-1}$. In contrast, summer precipitation showed no significant warming trend, while the annual precipitation increased notably at a rate of $2.11 \text{ mm} \cdot \text{a}^{-1}$, with 78.9% of precipitation occurring in summer. Precipitation is identified as the primary factor contributing to lake expansion in the basin. This study highlights the response of glaciers and lakes in the Jingyu Lake Basin to climate change, providing valuable insights for local governments in optimizing water resource allocation and management.

Key words: Jingyu Lake; glaciers; climate change; east Kunlun Mountains

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

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