

Water Level Variations and Attribution Analysis of Typical Lakes on the Northern Slope of the Kunlun Mountains, 2003–2022: Postprint

Authors: Liu Yuting, Chen Yaning, Zhu Chenggang, Zhang Shuhua, Huang Xinyao, Chen Yaning

Date: 2024-12-03T00:00:00+00:00

Abstract

Lake water level variation is an important indicator of lake system dynamics and is of great significance to lake ecological environment and water resource management. Based on multi-source altimetry satellite data from ICESat-1, CryoSat-2, EnviSat, and ICESat-2, water level data for Aksayqin Lake, Ayakkum Lake, Aqikkol Lake, Jingyu Lake, Changhong Lake, and Salijilghan South Lake, as well as temperature, precipitation, and land use data for their catchment areas, were extracted for the period 2003–2022. Using trend analysis, Mann-Kendall test, and Pearson correlation analysis, the characteristics of lake water level variations were quantitatively analyzed and the influencing mechanisms were explored. The results indicate: (1) The accuracy of multi-source altimetry satellite water level data was validated against water level datasets, demonstrating consistent trends with all correlation analyses passing the significance F-test. (2) Over the past 20 years, except for Salijilghan South Lake, the remaining lakes exhibited significant rising trends, with Changhong Lake showing the maximum rising rate of $0.71 \text{ m} \cdot \text{a}^{-1}$ and Aksayqin Lake showing the minimum rising rate of $0.29 \text{ m} \cdot \text{a}^{-1}$. (3) Climate factors in the lake catchments showed considerable variation, with all temperatures exhibiting increasing trends whereas precipitation displayed varied patterns. Water levels of Aqikkol Lake, Ayakkum Lake, and Jingyu Lake were positively correlated with precipitation, while water levels of all lakes except Salijilghan South Lake showed positive correlations with temperature. This study utilizes multi-source altimetry satellite data to analyze lake water level variations, aiming to reveal the hydrological variation patterns of lakes on the northern slope of the Kunlun Mountains and provide a scientific basis for lake ecological environment management.

Full Text

Water Level Changes and Attribution of Typical Lakes on the Northern Slope of Kunlun Mountains from 2003 to 2022

LIU Yuting¹, CHEN Yanning², ZHU Chenggang², ZHANG Shuhua³, HUANG Xinyao¹

¹School of Life and Geography Sciences, Kashi University/Key Laboratory of Biological Resources and Ecology of Pamir Plateau in Xinjiang Uygur Autonomous Region, Kashi 844000, Xinjiang, China

²State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China

³College of Geomatics, Xi'an University of Science and Technology, Xi'an 710000, Shaanxi, China

Abstract

Lake water level changes serve as crucial indicators of dynamic variations in lake systems, holding significant implications for lake ecological environments and water resource management. This study utilizes multi-source altimetry satellite data from ICESat-2, CryoSat-2, ICESat-1, and EnviSat to extract water level information for Aksai Chin Lake, Ayak Kum Lake, Aqqikkol Lake, Jingyu Lake, Changhong Lake, and Surigh Yilganing Kol Lake on the northern slope of Kunlun Mountains. Combined with temperature, precipitation, and land use data from lake catchment areas spanning 2003–2022, we employ trend analysis, Mann-Kendall tests, Pearson correlation analysis, and other methods to quantitatively characterize lake water level variations and explore their underlying mechanisms.

The results reveal three key findings. First, water levels extracted from multi-source altimetry satellites were validated against reference water level datasets, demonstrating consistent trends with all correlation analyses passing the significance F-test. Second, over the past two decades, all typical lakes except Surigh Yilganing Kol Lake exhibited significant rising trends, with Changhong Lake showing the highest increase rate at $0.71 \text{ m} \cdot \text{a}^{-1}$ and Aksai Chin Lake the lowest at $0.29 \text{ m} \cdot \text{a}^{-1}$. Third, climatic factors varied substantially across lake catchment areas, with temperatures showing consistent upward trends while precipitation displayed spatial heterogeneity. Positive correlations were identified between water levels and precipitation for Aqqikkol Lake, Ayak Kum Lake, and Jingyu Lake, whereas water levels of all typical lakes except Surigh Yilganing Kol Lake showed positive correlations with temperature. By leveraging multi-source altimetry satellite data to analyze lake water level changes, this study aims to elucidate hydrological variation patterns of lakes on the northern slope of Kunlun Mountains and provide a scientific basis for lake ecological environment management.

Keywords: satellite altimetry; lake water level; temperature; precipitation; land use; northern slope of Kunlun Mountains

Introduction

Lakes constitute vital components of natural resources and the water cycle. Alpine lakes, due to their unique geographical locations and ecological environments, play critical roles in maintaining ecological balance and regulating climate. Most alpine lakes on the northern slope of Kunlun Mountains are inland saline lakes featuring distinctive natural landscapes and ecosystems. Consequently, comprehensive understanding of lake changes and their driving factors in this region provides essential scientific support for ecological conservation and water resource management in alpine areas.

Lake water level represents a key indicator for monitoring water resource changes in lakes. Before satellite altimetry technology matured, continuous observations from ground-based hydrological stations were the primary method for obtaining lake water level information. However, due to remote lake locations, relatively underdeveloped local economies, and personnel shortages, establishing observation stations around lakes for long-term monitoring presents considerable challenges. In recent years, various altimetry satellites have been applied to monitor water level changes in typical lakes.

Satellite altimetry technology offers convenient and precise means for monitoring lake water level changes. Previous studies have integrated multiple satellite altimetry datasets including Topex/Poseidon, EnviSat, Jason, CryoSat-2, and Sentinel-3 for monitoring mountain lakes. Jiang et al. utilized ICESat altimetry data to investigate seasonal trends and cycles of lake levels on the Tibetan Plateau, while Tian et al. employed ICESat-2 data to calculate water levels for Poyang Lake, validating high accuracy against in-situ measurements. This study focuses on medium-to-large lakes larger than 50 km² on the northern slope of Kunlun Mountains from 2003–2022, using ICESat-1, EnviSat/RA-2, CryoSat-2, and ICESat-2 altimetry data to monitor water level changes in typical lakes. We examine spatiotemporal variation characteristics of climate factors and land use within lake catchment areas, and investigate response mechanisms of lake water levels to climate factors and land use, aiming to reveal hydrological variation patterns and provide scientific support for future environmental protection and resource management.

1.1 Study Area Overview

The northern slope of Kunlun Mountains (35°–39°N, 80°–94°E) is located in northwestern China with complex terrain encompassing mountains, alpine valleys, plateaus, and river valleys, with elevations ranging from 1,530 to 6,738 m. The region features a cold alpine climate characterized by cold, dry conditions with long, cold winters and short, cool summers. Precipitation concentrates in summer while winter precipitation is minimal. The ecosystem includes alpine

spruce forests, alpine meadows, and alpine lakes that are crucial for maintaining regional biodiversity.

Ayak Kum Lake (37°04 N, 88°23 E) lies on the northern edge of the Tibetan Plateau within the Altun and Kunlun watersheds, ranking among China's ten largest lakes. Aqqikkol Lake (36°19 N, 89°26 E) and Jingyu Lake are geographically proximate to Ayak Kum Lake, all situated within the Altun Mountain Nature Reserve. Changhong Lake (36°02 N, 85°58 E) is located in the Kunlun Mountains with a relatively small water area. Aksai Chin Lake (35°12 N, 79°52 E) represents the largest natural lake on the Xinjiang side of the Eastern Qiangtang Plateau, bordered by the Kunlun Mountains to the northeast and the Aksai Chin Tagh branch range to the southwest. Surigh Yilganing Kol Lake (34°40 N, 79°41 E) is a saltwater lake located in the basin between the Karakoram and Shirokozong mountains.

1.2 Data Sources

Multi-source altimetry satellites: This study employs EnviSat, ICESat-1, CryoSat-2, and ICESat-2 altimetry data. The reference ellipsoid is WGS84 with the geoid model EGM2008. EnviSat operated three waveform retracking algorithms (Ice-1, Ice-2, Ocean), with the Ice-1 algorithm being most suitable for inland water body elevation extraction. ICESat-1 data products include GLA01, GLA02, GLA14, and GLA15 Version 34, with WGS84 reference ellipsoid and EGM96 geoid. CryoSat-2 carries the advanced Synthetic Aperture Radar Altimeter (SIRAL) operating in low-resolution mode (LRM), synthetic aperture radar mode (SAR), and synthetic aperture radar interferometry mode (SARIn). ICESat-2 data products comprise four levels from Level-1 to Level-3B, with this study utilizing Level-3A ATL13 data suitable for inland water body elevation research. The digital elevation model (DEM) data for extracting lake catchment areas are sourced from SRTM.

Climate data: Monthly-scale precipitation and temperature data from 2001–2022 are obtained from the ERA5 dataset with spatial resolution of 0.1°.

Land use data: Land use data with 30 m resolution are sourced from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences.

Reference water level datasets: Water level reference datasets for Aksai Chin Lake, Ayak Kum Lake, Aqqikkol Lake, and Jingyu Lake are derived from reference [17], calculated based on satellite observation data.

1.3.1 Water Level Calculation

Based on the fundamental principles of multi-source altimetry satellites, lake water level (H) is calculated as:

$$H = h_{alt} - r_{ran} - \Delta r_{cor} - h_{geoid} - r_{set} + \Delta r_{iono} + \Delta r_{wet} + \Delta r_{dry} + \Delta r_{solid} + \Delta r_{pole}$$

where h_{alt} is the satellite height relative to the reference ellipsoid, r_{ran} is the corrected distance from the satellite to the nadir point (ground) (without waveform retracking, this term is not counted), Δr_{cor} is the geophysical environment correction, h_{geoid} is the geoid height, and Δr represents various corrections including ionospheric, wet tropospheric, dry tropospheric, solid earth tide, and polar tide corrections.

Among the lake water level points calculated by each spaceborne altimeter, some anomalous values with large deviations can cause substantial errors in daily lake water level values and subsequent analyses. First, obvious outliers are manually removed through visual interpretation, then differenced from the overall mean water level, and finally visually interpreted again to eliminate apparent anomalies. For daily data, the 2.5σ criterion is applied to remove outliers, and the remaining water level values are averaged to obtain daily lake water level elevation:

$$V_i = X_i - \bar{X}$$

where n is the number of daily water level points after overall removal; X_i is the water level value at the i -th point; \bar{X} is the mean water level; V_i is the residual error at the i -th point; and σ is the standard deviation. When $|X_i - \bar{X}| > 2.5\sigma$, X_i is removed. Daily water level values obtained based on averages may still contain smaller anomalies, requiring further outlier removal to obtain more accurate daily water levels.

1.3.2 Mann-Kendall Method

The Mann-Kendall test is a widely used non-parametric statistical method for detecting trend changes in water level time series without requiring prior knowledge of data distribution. For a water level time series X_1, X_2, \dots, X_n , the test statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(X_j - X_i)$$

where n is the length of the water level time series and sign is the sign function. The mean of statistic S is 0, and its standard deviation is:

$$\sigma = \sqrt{\frac{n(n-1)(2n+5)}{18}}$$

The standardized normal statistical variable (Z) is expressed as:

$$Z = \begin{cases} \frac{S-1}{\sigma} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sigma} & S < 0 \end{cases}$$

When $Z > 0$, it indicates an increasing trend, and when $Z < 0$, a decreasing trend. When $|Z| \geq 1.96$, the trend passes the significance test at $\alpha = 0.05$; when $|Z| \geq 2.58$, it passes the significance test at $\alpha = 0.01$.

1.3.3 Coefficient of Variation Analysis

The coefficient of variation (C_v) is a statistical measure used to quantify data dispersion, calculated as:

$$C_v = \frac{\sigma}{\mu}$$

where σ and μ represent the standard deviation and mean of meteorological elements, respectively.

1.3.4 Pearson Correlation Analysis

Pearson correlation analysis was employed to examine relationships between climate factors and water levels in lake catchment areas, calculated as:

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

where r is the correlation coefficient; n is the sample size; K_i is the water level in year i ; \bar{K} is the mean water level; Y_i is the climate factor (temperature or precipitation) in year i ; and \bar{Y} is the mean climate factor.

2.1 Lake Water Level Data Validation

Based on lake area boundaries, water levels for Aksai Chin Lake, Ayak Kum Lake, Aqqikkol Lake, and Jingyu Lake were extracted from ICESat-1, EnviSat, CryoSat-2, and ICESat-2 altimetry data. The extracted water levels were compared against lake surface height reference datasets to evaluate accuracy and reliability. The study found that extracted lake water level data showed consistent trends with reference datasets.

Correlation coefficients, estimated standard errors (S_e), and F significance tests were calculated to assess the reliability of extracted water level values. Ayak Kum Lake and Aksai Chin Lake demonstrated significant linear relationships

with correlation coefficients $r > 0.9$ and estimated standard errors of 0.08 m and 0.13 m, respectively, indicating high reliability. Jingyu Lake and Aqqikkol Lake showed correlation coefficients $r > 0.7$ with estimated standard errors of 0.25 m and 0.23 m, respectively, confirming the data's applicability for analyzing lake water level trends.

2.2 Typical Lake Water Level Changes

Trend analysis of lake water level changes provides quantitative understanding of lake water level variation patterns. Linear regression analysis was applied to lake water level variation data, with results statistically tested using Mann-Kendall and F significance tests. Analysis of multi-source altimetry satellite data revealed water level changes for typical lakes on the northern slope of Kunlun Mountains.

From 2003–2022, all typical lakes except Surigh Yilganing Kol Lake showed significant upward trends. Changhong Lake exhibited the most rapid increase at $0.71 \text{ m} \cdot \text{a}^{-1}$, rising from 4,915.46 m in 2003 to 4,923.29 m in 2022—a total increase of 6.83 m. Jingyu Lake ranked second with an increase rate of $0.57 \text{ m} \cdot \text{a}^{-1}$, rising from 4,908.63 m to 4,919.28 m, with negative growth only in 2014. Aqqikkol Lake increased at $0.55 \text{ m} \cdot \text{a}^{-1}$, rising from 4,713.64 m to 4,723.06 m, showing the largest variation amplitude with a 10.14 m increase from 2003–2022. Ayak Kum Lake increased at $0.40 \text{ m} \cdot \text{a}^{-1}$, rising from 4,849.38 m to 4,856.00 m. Aksai Chin Lake showed the slowest increase at $0.29 \text{ m} \cdot \text{a}^{-1}$, rising from 4,254.80 m to 4,264.94 m. Surigh Yilganing Kol Lake displayed distinct behavior with non-significant water level changes, fluctuating between 5,193.42 m and 5,195.42 m.

2.3.1 Precipitation and Temperature Changes

Climate change spatial characteristics profoundly impact regional ecological environments and resource utilization. Taking typical lake catchment areas on the northern slope of Kunlun Mountains as examples, we examined climate factor variations. Surigh Yilganing Kol Lake catchment was delineated using flow accumulation thresholds of 1,000, while other lake catchments used thresholds of 500 based on drainage systems.

Climate variations differed significantly across lake catchment areas from 2001–2022. Ayak Kum Lake catchment had the highest mean temperature at $-3.816 \pm 0.532^\circ\text{C}$, while Surigh Yilganing Kol Lake had the lowest at $-10.457 \pm 0.757^\circ\text{C}$. Aqqikkol Lake showed the highest annual precipitation at $454.508 \pm 50.439 \text{ mm}$, followed by Jingyu Lake at $454.508 \pm 50.439 \text{ mm}$.

Temperatures increased across all catchment areas, with Surigh Yilganing Kol Lake showing the highest warming rate at $0.355^\circ\text{C} \cdot (10\text{a})^{-1}$ and Ayak Kum Lake the slowest at $0.172^\circ\text{C} \cdot (10\text{a})^{-1}$. Temperature increase areas accounted for 80.32% to 98.65% of catchment areas, with spatial differences primarily related

to altitude, climate conditions, radiation characteristics, and terrain.

Precipitation showed spatiotemporal heterogeneity. Ayak Kum Lake, Jingyu Lake, and Aqqikkol Lake catchments exhibited increasing precipitation trends with rates of $1.249 \text{ mm} \cdot (10\text{a})^{-1}$, $0.224 \text{ mm} \cdot (10\text{a})^{-1}$, and $10.980 \text{ mm} \cdot (10\text{a})^{-1}$, respectively. Conversely, Changhong Lake, Aksai Chin Lake, and Surigh Yilganing Kol Lake showed decreasing trends with rates of $-5.880 \text{ mm} \cdot (10\text{a})^{-1}$, $-6.682 \text{ mm} \cdot (10\text{a})^{-1}$, and $-6.515 \text{ mm} \cdot (10\text{a})^{-1}$, respectively. Precipitation increase areas in the former three lake catchments accounted for 47.68% to 83.33% of total area, while decrease areas in the latter three accounted for 68.83% to 95.51%.

2.3.2 Land Use Changes

Land use spatial characteristics in lake catchment areas are illustrated in [Figure 7: see original paper] and [Figure 8: see original paper]. In 2000, typical lake catchment land use types included only grassland, water bodies, and unused land. By 2020, cultivated land, forest land, and urban/industrial/mining/residential land were added. From 2000–2020, grassland area decreased significantly while water body area increased substantially, and unused land area also increased markedly.

Ayak Kum Lake catchment is dominated by grassland, water bodies, and unused land, with area proportions of 16.04%, 19.12%, and 64.84% in 2000, respectively. Grassland pixel count decreased by 1.4×10^6 during 2000–2020, while water body pixel count increased by 1.4×10^6 . *Jingyu Lake catchment grassland accounted for 44.65×10^6 . Surigh Yilganing* and 6.7×10^6 in 2000, respectively, with change rates of 10.94% and 30.14% by 2020.

2.4 Correlation Analysis

Pearson correlation analysis examined relationships between typical lake water levels on the northern slope of Kunlun Mountains and catchment climate factors. Aqqikkol Lake, Ayak Kum Lake, and Jingyu Lake water levels showed positive correlations with annual precipitation, with correlation coefficients of 0.42, 0.31, and 0.28, respectively. Aksai Chin Lake, Aqqikkol Lake, Ayak Kum Lake, Jingyu Lake, and Changhong Lake water levels showed positive correlations with temperature, with coefficients of 0.21, 0.18, 0.15, 0.13, and 0.12, respectively, while Surigh Yilganing Kol Lake water level showed a slight negative correlation with temperature (coefficient -0.09).

Alpine lakes serve as important water storage reservoirs in mountainous regions, with their changes reflecting comprehensive impacts of climate change on alpine water resources. Climate warming and wetting trends, glacier retreat, and permafrost water release have increased water supply to lakes in the Tianshan and Karakoram regions, resulting in increased lake volume and area and generally rising water levels—consistent with findings of rising lake levels on the Tibetan Plateau and expanding lakes on the northern Kunlun foothills.

The northern slope of Kunlun Mountains features large elevation differences and is located in the center of the Eurasian continent, where water vapor is difficult to reach, causing spatial precipitation distribution variations. Windward slopes at relatively high altitudes intercept water vapor, creating richer precipitation that supplements water sources for mountain lakes and contributes to rising water levels.

Global warming has accelerated melting of glaciers, river ice, and snow, increasing meltwater from alpine glaciers and creating new changes in alpine glacial lakes. Water level changes result from multiple factors with diverse and complex causes, including temperature increases/decreases (affecting meltwater), precipitation and evaporation changes, reduced upstream glacier melt, and regional terrain factors that may influence glacial lake expansion rates.

Aksai Chin Lake, Jingyu Lake, Changhong Lake, and Aqqikkol Lake are primarily fed by snow and ice meltwater during warm seasons, with relatively abundant glaciers distributed in their watershed catchments. Lake level increase rates reached $0.29\text{--}0.71\text{ m}\cdot\text{a}^{-1}$. In contrast, lake catchment areas with less or no glacier cover experienced slower water level increases due to limited glacial meltwater supply. For example, Ayak Kum Lake and Surigh Yilganing Kol Lake have relatively small glacial areas in their catchments, lacking substantial glacial meltwater 补给, with water level increase rates of $0.40\text{ m}\cdot\text{a}^{-1}$ and $0.03\text{ m}\cdot\text{a}^{-1}$, respectively.

References

- [1] Bai Jie, Chen Xi, Li Junli, et al. Changes of inland lake area in arid Central Asia during 1975–2007: A remote sensing analysis[J]. *Journal of Lake Sciences*, 2011, 23(1): 80-88.
- [2] Yang Guishan, Ma Ronghua, Zhang Lu, et al. Lake status, major problems and protection strategy in China[J]. *Journal of Lake Sciences*, 2010, 22(6): 799-810.
- [3] Heino J, Alahuhta J, Bini L M, et al. Lakes in the era of global change: Moving beyond single lake thinking in maintaining biodiversity and ecosystem services[J]. *Biological Reviews*, 2021, 96(1): 1-21.
- [4] Han Fei, Liu Tie, Huang Yue, et al. Advance in the studies of responses of alpine lakes to climate change[J]. *Arid Land Geography*, 2023, 46(2): 233-242.
- [5] Yan L J, Zheng M P. Influence of climate change on saline lakes of the Tibet Plateau, 1973–2010[J]. *Geomorphology*, 2015, 246: 68-78.
- [6] Li Junli, Chen Xi, Bao Anming. Spatial and temporal characteristics of lake level changes in Central Asia during 2003–2009[J]. *Acta Geographica Sinica*, 2011, 66(9): 1219-1229.
- [7] Guo Qing, Wang Xingze. Water level measurement system by ultrasonic wave[J]. *Water Resources & Hydropower of Northeast China*, 1999(2): 39-40,

16, 49.

[8] Zhao Jianhu, Zhou Fengnian, Zhang Hongmei. Research on method of determining tide on water with GPS[J]. *Bulletin of Surveying and Mapping*, 2001(Suppl. 1): 1-3.

[9] Li Zhennan, Lei Weiwei, Wang Yifan, et al. Water level variation of Qinghai Lake based on multi-source satellite altimetry data[J]. *Science of Surveying and Mapping*, 2023, 48(5): 140-151.

[10] Liu Junyan, Wang Shijie. Monitoring of water level change in Hulun Lake based on ICESat-2 satellite altimetry data[J]. *Arid Zone Research*, 2023, 40(9): 1438-1445.

[11] Chen Jianru, Xu Jia, Wang Dongmei. Long time series monitoring of water level change in Gaoyou Lake based on multi-source satellite data[J]. *Yangtze River*, 2024, 55(1): 120-126.

[12] Tang Xinming, Li Guoyuan. Development and prospect of laser altimetry satellite[J]. *Space International*, 2017(11): 13-18.

[13] Jiang L G, Nielsen K, Andersen O B. Improvements in mountain lake monitoring from satellite altimetry over the past 30 years: Lessons learned from Tibetan lakes[J]. *Remote Sensing of Environment*, 2023, 295: 113702, doi: 10.1016/j.rse.2023.113702.

[14] Xu F L, Zhang G Q, Yi S, et al. Seasonal trends and cycles of lake level variations over the Tibetan Plateau using multi-sensor altimetry data[J]. *Journal of Hydrology*, 2022, 604: 127251, doi: 10.1016/j.jhydrol.2021.127251.

[15] Tian Shiyue, Wang Chang, He Jiayang, et al. Water level sequence construction and water level prediction of Poyang Lake based on ICESat-2 laser altimetry data[J]. *Science of Surveying and Mapping*, 2023, 48(12): 105-114.

[16] Gao Xiaoyu, Hao Haichao, Zhang Xueqi, et al. Responses of vegetation water use efficiency to meteorological factors in arid areas of northwest China: A case of Xinjiang[J]. *Arid Land Geography*, 2023, 46(7): 1111-1120.

[17] Zhang Yuanmei, Sun Guili, Lu Yan, et al. Biomass estimation models for two dominant desert shrubs on the northern slopes of Kunlun Mountain[J]. *Arid Land Geography*, 2024, 41(2): 284-292.

[18] Li X D, Long D, Huang Q, et al. High temporal resolution water level and storage change data sets for lakes on the Tibetan Plateau during 2000–2017 using multiple altimetric missions and Landsat-derived lake shoreline positions[J]. *Earth System Science Data*, 2019, 11(4): 1603-1627.

[19] Liao Jingjuan, Zhao Yun, Chen Jiaming. A dataset of lake level changes in High Mountain Asia using multi-altimeter data[J]. *China Scientific Data*, 2020, 5(1): 140-151.

- [20] Duan Weili, Zou Shan, Chen Yanning, et al. Analysis of water level changes in Lake Balkhash and its main influencing factors during 1879–2015[J]. *Advances in Earth Science*, 2021, 36(9): 950-961.
- [21] Li Xiang, Zhang Xueqin, Xu Xiaoming. Climate change and its effects on the water level of Lake Baikal region since the 1980s[J]. *Journal of Lake Sciences*, 2022, 34(1): 219-231.
- [22] Cohen I, Huang Y, Chen J, et al. Pearson correlation coefficient[J]. *Noise Reduction in Speech Processing*, 2009: 1-4, doi: 10.1007/978-3-642-00296-0_5.
- [23] Zhang Q F, Chen Y N, Li Z, et al. Why are glacial lakes in the eastern Tianshan Mountains expanding at an accelerated rate?[J]. *Journal of Geographical Sciences*, 2023, 33(1): 121-150.
- [24] Chen Yanning, Li Zhi, Fang Gonghuan, et al. Impact of climate change on water resources in the Tianshan Mountains, Central Asia[J]. *Acta Geographica Sinica*, 2017, 72(1): 18-26.
- [25] Yao Tandong, Liu Shiyin, Pu Jianchen, et al. Recent retreat of high Asian glaciers and its impact on water resources in northwest China[J]. *Scientia Sinica (Terrae)*, 2004, 34(6): 535-543.
- [26] Li Xiaofeng, Yao Xiaojun, Sun Meiping, et al. Spatial-temporal variations in lakes in northwest China from 2000 to 2014[J]. *Acta Ecologica Sinica*, 2018, 38(1): 96-104.
- [27] Yuan Kang, Tan Debao, Wen Xiongfei, et al. Dynamic monitoring of water level change in Kusai Lake and analysis of climatic driving forces[J]. *Journal of Changjiang River Scientific Research Institute*, 2022, 39(2): 153-158.
- [28] Peng Haiyue. Construction and variation analysis of lake water level series in Qinghai-Tibet Plateau[D]. Xining: Qinghai University, 2022.
- [29] Ma Shanmu, Gan Fuping, Wu Huaichun, et al. ICESat-2 data-based monitoring of 2018–2021 variations in the water levels of lakes in the Qinghai-Tibet Plateau[J]. *Remote Sensing for Natural Resources*, 2022, 34(3): 164-172.
- [30] Jiang Yuanan, Liu Jing, Shao Weiling, et al. Climatic characteristics and historical evolution of precipitation in different time scales in Xinjiang from 1961 to 2013[J]. *Journal of Glaciology and Geocryology*, 2014, 36(6): 1363-1375.
- [31] Wang Y T, Hou S G, Huai B J, et al. Glacier anomaly over the western Kunlun Mountains, northwestern Tibetan Plateau, since the 1970s[J]. *Journal of Glaciology*, 2018, 64(246): 624-636.

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

Source: ChinaXiv — Machine translation. Verify with original.