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Spatiotemporal Variations in Lake Ice Phenology of Large Lakes in Xinjiang, 2000–2019: A Postprint

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Abstract

Variations in lake ice phenology serve as an important indicator of global climate change processes. Based on lake datasets extracted from long-term time series MODIS data and Landsat data, this study comprehensively analyzed the variation characteristics of lake ice phenology for large lakes in Xinjiang from 2000 to 2019. The results show that: (1) Over the past two decades, the freeze onset dates of large lakes in Xinjiang exhibited two distinct trends: advancing and delaying. Lakes showing a delaying trend in freeze onset dates include Bosten Lake, Sayram Lake, Ebinur Lake, Jili Lake, Ulungur Lake, Salijilegan South Kule Lake, and Jingyu Lake, with most lakes exhibiting delaying trends ranging from 0.51–1.53 $d \cdot a^{-1}$. Three lakes displayed an advancing trend in freeze onset dates: Ayakekumu Lake (trend of -1.04 $d \cdot a^{-1}$), Aksayqin Lake (trend of -0.41 $d \cdot a^{-1}$), and Aqikekule Lake (-0.31 $d \cdot a^{-1}$). (2) The complete ice cover period represents a crucial lake ice parameter, where its prolongation or shortening directly indicates regional climate change processes. Most lakes in Xinjiang showed a shortening trend in ice cover period, with lakes distributed in the north-central region of Xinjiang, such as Ebinur Lake, Jili Lake, and Bosten Lake, showing relatively significant shortening with trends of -1.76 $d \cdot a^{-1}$, -2.13 $d \cdot a^{-1}$, and -0.81 $d \cdot a^{-1}$, respectively. Three lakes exhibited prolonged complete ice cover periods: Ayakekumu Lake, Aqikekule Lake, and Jingyu Lake, with trends of 3.51 $d \cdot a^{-1}$, 1.54 $d \cdot a^{-1}$, and 1.37 $d \cdot a^{-1}$, respectively; these lakes are evenly distributed on the northern flank of the Kunlun Mountain plateau. (3) The variation characteristics of lake ice phenology for large lakes in Xinjiang result from the combined effects of multiple factors, including their intrinsic conditions (lake morphometric factors, lake area, etc.) and climate change (air temperature, precipitation, etc.). This study explored the freeze-thaw trends and variation patterns of lake ice phenology for large lakes in Xinjiang under a changing climate environment, while simultaneously applying different remote

sensing data and research methods to identify lake ice, thereby confirming the feasibility of retrieving lake ice phenology from MODIS data.

Full Text

Temporal and Spatial Variations of Lake Ice Phenology in Large Lakes of Xinjiang from 2000 to 2019

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Abstract

Lake ice phenology serves as a crucial indicator of global climate change processes. Using long-term time series data to extract lake datasets, this study comprehensively analyzed the variation characteristics of lake ice phenology in large lakes of Xinjiang from 2000 to 2019. The freeze-up start dates of large lakes in Xinjiang exhibited both advancing and delaying trends. Lakes showing delayed freeze-up start dates include Bosten Lake, Sayram Lake, Ebinur Lake, Jili Lake, Ulunggur Lake, Salijilegan South Kol Lake, and Whale Lake, with most lakes showing delay trends between 0.51–1.53 $d \cdot a^{-1}$. Lakes showing advanced freeze-up start dates include Ayakkum Lake (trend of -1.04 $d \cdot a^{-1}$), Aksayqin Lake (trend of -0.81 $d \cdot a^{-1}$), and Aqikkol Lake (trend of -0.31 $d \cdot a^{-1}$). The complete ice cover period is an important lake ice parameter, and its extension or shortening can directly represent regional climate change processes. Most lakes in Xinjiang showed a shortening trend in ice cover period, particularly Ebinur Lake, Jili Lake, and Bosten Lake in north-central Xinjiang, with trends of -1.76 $d \cdot a^{-1}$, -2.13 $d \cdot a^{-1}$, and -0.81 $d \cdot a^{-1}$ respectively. Lakes with extended ice cover periods include Ayakkum Lake, Aqikkol Lake, and Whale Lake, with trends of 3.51 $d \cdot a^{-1}$, 1.54 $d \cdot a^{-1}$, and 1.37 $d \cdot a^{-1}$ respectively, distributed uniformly on the northern flank of the Kunlun Plateau. The lake ice phenology characteristics of large lakes in Xinjiang result from combined effects of their own conditions (lake morphology factors, lake area, etc.) and climate change (temperature, precipitation, etc.). This study explored the freezing-thawing trends and variation patterns of lake ice phenology in Xinjiang's large lakes under a changing climate, while applying different remote sensing data and research methods to identify lake ice, confirming the feasibility of using MODIS data to retrieve lake ice phenology [Figure 5952: see original paper].

Keywords: large lakes; lake ice phenology; variation characteristics; multi-band threshold method; MODIS

Introduction

Lakes constitute a vital component of the hydrosphere, terrestrial water cycle, and global water balance, playing a significant role in global climate and ecological environment changes [1]. Lake water circulation processes not only influence local climate change but also maintain close relationships with human activities, with these effects being particularly pronounced in arid regions. Most lakes in Xinjiang are distributed across mountainous and oasis areas, providing essential water resources for human production activities and ecological environment balance [2]. Lake ice serves as an important indicator for recording lake environmental changes, with lake ice phenology, thickness, and morphology being closely related to climate change processes. The formation, disappearance, and duration of lake ice are directly affected by climate change, and in some cases, lake ice phenology can record regional climate changes more accurately than air temperature [3]. Lake ice provides venues for human recreational activities; the Ice and Snow Festival held at Bosten Lake receives tens of thousands of domestic and foreign tourists annually, and thousands of tourists participate in marathon races along Bosten Lake each year, promoting local economic development. Additionally, lake ice plays an important role in wildlife habitat space. Bosten Lake is one the wild bird habitats in China's northwest arid region; as temperatures drop in winter, Bosten Lake welcomes tens of thousands of water birds for wintering [4]. Therefore, accurate extraction of lake freezing and thawing dates is crucial for both human activities and wildlife habitat.

In previous studies of lake ice phenology, the main research methods involve using spectral remote sensing and microwave remote sensing data to extract lake ice based on the reflectance characteristics of ice and water. Currently, there are few automated extraction methods for lake ice phenology in domestic and international research, such as MODIS snow and ice products for monitoring lake ice phenology [5]. Additionally, the band threshold method is widely used in lake ice research. Latifovic and Pouliot [6] applied the band threshold method to Advanced Very High Resolution Radiometer (AVHRR) data to analyze lake ice phenology in northern Canada from 1985 to 2004, with results showing strong correlation with measured data. Gong Zhi [7] used AVHRR and MODIS data to study lake ice phenology characteristics of 59 lakes on the Tibetan Plateau. MODIS remote sensing data offers advantages in multispectral and high spatiotemporal resolution. However, due to interference from clouds and snow in winter, the extraction accuracy of spectral remote sensing data for lake ice is affected. Therefore, some scholars have used microwave remote sensing to extract lake ice phenology [8]. Dibike et al. [9] used RADARSAT-2 data to extract lake ice phenology characteristics in northern Canada. These studies demonstrate that although microwave remote sensing can reduce interference from snow and clouds when extracting lake ice, the low temporal and spatial resolution of microwave remote sensing may yield poor results for lake ice phenology extraction in regions like Xinjiang with sparse and small lakes [10].

Magnuson et al. [1] research indicates that between 1846 and 1995, the start freezing dates of many lakes and rivers in the Northern Hemisphere showed significant delays, with a trend of 5.80 $d \cdot (100a)^{-1}$, while lake ice start melting dates also advanced significantly, with a trend of 6.50 $d \cdot (100a)^{-1}$. Overall, the lake ice cover period in the Northern Hemisphere shortened significantly. Latifovic's analysis of Canadian lake ice phenology from 1950 to 2004 shows that lake ice start freezing dates advanced, with a trend of -0.12 $d \cdot a^{-1}$, while start melting dates advanced with a trend of -0.18 $d \cdot a^{-1}$ [6]. Wang Zhiying et al. [11] analyzed lake ice phenology of 49 lakes larger than 100 km^2 on the Tibetan Plateau from 2000 to 2017, finding that lakes in the northern Tibetan Plateau freeze earlier and melt completely later, with longer complete freezing periods, while southern Tibetan lakes freeze later and melt earlier, with shorter ice duration, and ice condition changes are mainly affected by natural factors such as temperature and wind speed.

This study examines 11 large lakes in Xinjiang (excluding Aqikkol Lake with area less than 100 km^2), using MOD09GQ and MYD09GQ data with 250 m spatial resolution to study long-term lake ice phenology and variation patterns, while analyzing lake development processes and lake element changes. This research uses optical imagery, remote sensing inversion, algorithm models, and statistical analysis to elucidate lake ice phenology characteristics of Xinjiang's large lakes, revealing ice phenology change patterns under climate change backgrounds, laying theoretical and technical foundations for water cycle and climate change in arid regions, and providing methodological guidance for large lake management and ecological protection in Xinjiang.

1 Study Area Overview

Xinjiang is located in the arid region of northwest China, featuring a temperate continental climate with unique mountain-desert ecosystems, covering approximately 1.66 million km^2 (one-sixth of China's total land area) and serving as the core area of the "Belt and Road" economic belt. Xinjiang lies between the Altai Mountains in the north and Kunlun Mountains in the south, with the Tianshan Mountains traversing the region. Additionally, the Tarim Basin and Junggar Basin are situated among three mountain ranges, forming a unique "three mountains 夹 two basins" topography (Figure 1). Xinjiang's edges feature snow-covered mountains surrounding basins, with deserts and oases widely distributed within the basins. This unique landform creates a distinctive landscape of alpine glaciers surrounding deserts. Due to Xinjiang's dry climate, scarce precipitation, and evapotranspiration exceeding precipitation, most areas have low vegetation coverage and fragile ecosystems, making them sensitive to climate change and human activities. The Tianshan Mountains serve as the source of the Tarim River and the main water resource for the Tarim Basin, playing a crucial role in the ecological environment of oases and human production activities [12].

2 Data and Methods

2.1 Data Sources

This study primarily uses MODIS surface reflectance products, including MOD09GQ and MYD09GQ data. These products provide data from the Terra and Aqua satellites respectively, with a spatial resolution of 250 m, covering two surface reflectance bands with a spectral range of 0.620–0.876 m. The available time range for MOD09GQ is from 2000 to present, while MYD09GQ has been continuously observing Earth from 2002 to present, providing nearly 20 years of remote sensing monitoring records.

Landsat satellite data, with multispectral data at 30 m resolution imaging the entire Earth's surface approximately every 16 days, is used in this study. Landsat images with cloud coverage less than 10% from 1987 to 2020 were selected to obtain lake area data for Xinjiang's large lakes and extract lake vector data (Table 1). The Digital Elevation Model (DEM) achieves global surface terrain simulation through certain terrain elevation data. The DEM data selected for this study comes from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn), which is SRTM V4.1 provincial data generated from organized and mosaicked SRTM data using WGS84 ellipsoid projection.

2.2.1 Water Body Extraction

The modified normalized difference water index (mNDWI) and enhanced vegetation index (EVI) are used to extract surface water and effectively eliminate vegetation and other interference factors. The water classification criterion is: when mNDWI > EVI and EVI < 0.1, the surface feature is classified as water; when these conditions cannot be met, it is classified as non-water [13]. The index calculation formulas are as follows:

$$NDVI = \frac{Nir - Red}{Nir + Red}$$

$$mNDWI = \frac{Green - Swir}{Green + Swir}$$

$$EVI = 2.5 \times \frac{Green - Red}{Nir + 6Red - 7.5Blue + 1}$$

where Red, Green, Blue, Nir, and Swir represent the reflectance of Landsat data's red band (630–630 nm), green band (525–600 nm), blue band (450–515 nm), near-infrared band (885 nm), and short-wave infrared band (1560–1660 nm), respectively.

2.2.2 Lake Ice Phenology Extraction

Based on the classification characteristics of ice and water in multispectral remote sensing, it is generally found that the reflectance of both water and ice in the near-infrared band is lower than their reflectance in the infrared band, while vegetation, soil, and other surface features have lower reflectance in the infrared band than in the near-infrared band. Therefore, according to the reflectance difference between near-infrared and infrared bands, lake ice can be accurately extracted, and partial atmospheric effects and systematic errors can be effectively eliminated. In the image after band subtraction, lake ice has relatively high reflectance in the near-infrared band, while lake water has low reflectance. Therefore, the band difference value combined with the threshold method can effectively monitor lake ice, with the calculation formula as follows [14]:

$$\begin{cases} Band1 - Band2 > a \\ Band2 > b \end{cases}$$

where Band1 and Band2 represent the reflectance of near-infrared band (841–876 nm) and infrared band (620–670 nm) from MODIS data, respectively; a and b are thresholds for lake ice monitoring obtained through visual interpretation or histogram methods, meaning when the band reflectance difference is greater than a and Band2 reflectance is greater than b, the pixel is defined as lake ice.

To automatically extract time node information for different lake ice states, this study defines the lake freeze-up start date as the date when the lake ice ratio (i.e., the ratio of lake ice area to lake area) reaches 10% in the second half of the year; the complete freeze date as the date when the ratio reaches 90% in the second half of the year; and the start break-up and complete break-up dates as the dates when the ratio reaches 90% and 10%, respectively, in the first half of the year. The complete ice cover period is a phenological element recording lake ice change processes, and its variation can directly represent regional climate change characteristics, especially for typical arid regions like Xinjiang. The calculation method is as follows [15]:

$$\begin{gathered} FUS\text{,if } IA \geq 0.1 \times LA \\ FUE\text{,if } IA \geq 0.9 \times LA \\ BUS\text{,if } IA \geq 0.9 \times LA \\ BUE\text{,if } IA \geq 0.1 \times LA \end{gathered}$$

where FUS, FUE, BUS, and BUE represent lake freeze-up start date, complete freeze date, start break-up date, and complete break-up date, respectively; LA and IA represent lake area and lake ice area.

3 Results

3.1 Spatial-Temporal Variation of Large Lake Areas in Xinjiang

From 1987 to 2020, the total area of 11 lakes in Xinjiang experienced a process of “first decreasing significantly then increasing rapidly” (Figure 2). The total area was 5873.91 km^2 in the 1970s, decreasing to 5263.71 km^2 in the 1990s, then increasing to 5952.38 km^2 by 2020, with a net increase of 7446.94 km^2. The areas of large lakes distributed in different geographical locations showed significant spatial differences. Among them, Ebinur Lake’s area showed an increasing trend but with inconsistent patterns, increasing fluctuatingly from 1987 to 2000, then decreasing from 2000 to 2020, with the smallest area of 1034.58 km^2 in 2015 (Figure 3). Bosten Lake’s area change trend was more complex, increasing significantly from 947.48 km^2 in 1987 to 1125.34 km^2 in 2002, then retreating to 925.27 km^2 by 2020, with a total reduction of 200.03 km^2 (-17.80%). Sayram Lake, Ulunggur Lake, and Jili Lake in northern Xinjiang showed no significant overall area changes. Sayram Lake’s area fluctuated between 455.89 km^2 and 461.01 km^2. Ulunggur Lake’s area increased by 13.25 km^2 from 1987 to 2020, with the southeastern lake shore showing a decreasing trend. Jili Lake’s area remained stable overall without significant changes (Figure 3). Ayakkum Lake’s area showed a fluctuating increasing trend (Figure 3), with a total increase of 187.54 km^2 from 1987 to 2020, and the most prominent increase occurring after 2000, with a total area increase of 228.77 km^2.

3.2 Spatial-Temporal Variation of Lake Ice Phenology

Figure 4 shows the spatial distribution of lake ice phenology patterns in Xinjiang’s large lakes from 2000 to 2019. The changes in freeze-up start date, complete ice cover period, start break-up date, and complete break-up date are combined into a complete bar chart, where the direction of each bar indicates advancing or delaying trends—upward indicates delaying trends, while downward indicates advancing trends. The freeze-up start dates of Xinjiang’s large lakes showed both advancing and delaying trends. Lakes with delayed freeze-up start dates include Bosten Lake, Sayram Lake, Ebinur Lake, Jili Lake, Ulunggur Lake, Salijilegan South Kol Lake, and Whale Lake, with most delay trends between 0.51–1.53 $d \cdot a^{-1}$. Lakes with advanced freeze-up start dates include Ayakkum Lake (trend of -1.04 $d \cdot a^{-1}$), Aksayqin Lake (trend of -0.81 $d \cdot a^{-1}$), and Aqikkol Lake (trend of -0.31 $d \cdot a^{-1}$). Regarding break-up start dates, 8 lakes showed advancing trends, mainly distributed in north-central Xinjiang including Bosten Lake, Ebinur Lake, Sayram Lake, Jili Lake, Salijilegan South Kol Lake, and Ulunggur Lake, with trends of -0.57 $d \cdot a^{-1}$, -0.61 $d \cdot a^{-1}$, -0.28 $d \cdot a^{-1}$, -0.78 $d \cdot a^{-1}$, -0.36 $d \cdot a^{-1}$, and -0.41 $d \cdot a^{-1}$, respectively. Lakes with delayed break-up start dates are mainly distributed in the Kunlun Plateau region, with Ayakkum Lake and Whale Lake showing significant delays.

The complete ice cover period is a phenological element recording lake ice change processes, and its variation can directly represent regional climate change characteristics, especially for typical arid regions like Xinjiang. Most lakes in Xinjiang showed significant shortening of the complete ice cover period, with Ebinur Lake, Jili Lake, and Bosten Lake in north-central Xinjiang showing the most significant shortening, with trends of -1.76 $d \cdot a^{-1}$, -2.13 $d \cdot a^{-1}$, and -0.81 $d \cdot a^{-1}$, respectively. Three lakes showed extended ice cover periods: Ayakkum Lake, Aqikkol Lake, and Whale Lake, with trends of 3.51 $d \cdot a^{-1}$, 1.54 $d \cdot a^{-1}$, and 1.37 $d \cdot a^{-1}$, respectively, distributed uniformly on the northern flank of the Kunlun Plateau.

3.3 Interannual Variation of Complete Ice Cover Period

The complete ice cover period is an important parameter of lake ice phenology that can directly represent lake ice change processes. Figure 5 shows the interannual variation of complete ice cover periods for Xinjiang's large lakes from 2000 to 2019. Over the past 20 years, most lakes showed shortening trends in complete ice cover period, though some showed extension. Ayakkum Lake did not freeze completely in 2015 and 2016. Lakes with extended complete ice cover periods include Ayakkum Lake, Aqikkol Lake, and Whale Lake, with trends of 3.51 $d \cdot a^{-1}$, 1.54 $d \cdot a^{-1}$, and 1.37 $d \cdot a^{-1}$, respectively. Lakes with shortened complete ice cover periods include Bosten Lake, Ebinur Lake, Ulunggur Lake, Jili Lake, Sayram Lake, Aksayqin Lake, and Salijilegan South Kol Lake, with trends of -0.61 $d \cdot a^{-1}$, -2.31 $d \cdot a^{-1}$, -1.84 $d \cdot a^{-1}$, -1.76 $d \cdot a^{-1}$, -0.17 $d \cdot a^{-1}$, -0.11 $d \cdot a^{-1}$, and -0.81 $d \cdot a^{-1}$, respectively. The analysis shows that lakes located in the Kunlun Plateau generally show increasing complete ice cover periods, with Ayakkum Lake showing the largest increase, while lakes in plain areas generally show decreasing complete ice cover periods, with Jili Lake showing the most significant decrease.

4 Discussion

This study analyzed lake ice phenology characteristics of Xinjiang's large lakes from 2000 to 2019. Lake ice phenology features are sensitive indicators of regional climate change. Zhang Yin et al. [16] research indicates that both annual average temperature and annual average precipitation in Xinjiang showed overall increasing trends in recent years, though regional spatial variation patterns are not obvious, making this study an important reference for regional climate change research. Under global climate change background, many studies have found that most lakes in the Northern Hemisphere show trends of delayed freeze-up start dates and advanced break-up start dates. Dibike et al. [9] results show that for Northern Hemisphere lakes from 2002 to 2015, complete freeze dates and complete break-up dates changed at rates of 0.03–0.16 $d \cdot a^{-1}$ and -0.05–0.19 $d \cdot a^{-1}$, respectively, while complete ice cover period changed at -0.07 to -0.43 $d \cdot a^{-1}$. Although some lakes still showed ice cover, this trend indicates significant shortening of lake ice cover period in the Northern Hemisphere.

From Figure 6, we can see that in 2015, although Ayakkum Lake's surface did not have ice cover, most other areas still showed lake ice. This trend indicates that among the 11 large lakes in Xinjiang, the freezing-thawing changes of lake ice are consistent with global change patterns. Figure 6 shows Sayram Lake's freeze-up start date change characteristics: on November 8, 2002, Sayram Lake began to freeze, while on November 18, 2019, ice layers appeared on the lake surface. This trend shows that during the study period, Sayram Lake's freeze-up start date showed a delaying trend, thus shortening Sayram Lake's complete ice cover period. Figure 6 also shows Jili Lake's ice freezing-thawing process: on March 25, 2001, Jili Lake's ice completely melted, while on March 8, 2019, the lake ice completely melted. This shows that Jili Lake's complete break-up date advanced, leading to shortened ice cover period.

Many studies have pointed out that lake freezing-thawing conditions are mainly affected by lake characteristics [26,28]. For example, Ayakkum Lake's freeze-up start date showed significant advancement from 2000 to 2019, mainly related to significant lake area expansion, which led to decreased lake salinity, thus causing advanced freeze-up start dates and extended ice cover periods. Qin Qiyong et al. [27] found that Sayram Lake's freeze-up start date showed an advancing trend, which differs from this study's results; however, their finding that Sayram Lake's freeze-up start date showed a delaying trend and complete ice cover period showed a shortening trend is consistent with our results.

5 Conclusion

This study used MOD09GQ and MYD09GQ optical remote sensing data to extract lake ice phenology through multi-band threshold methods. The extracted lake ice phenology results were validated using Landsat data. Additionally, the study summarized Xinjiang lake ice freezing-thawing processes under climate change background and analyzed lake ice phenology variation patterns. The main conclusions are:

1) Using 250 m spatial resolution MOD09GQ and MYD09GQ datasets, this study extracted lake ice phenology for Xinjiang's large lakes. Previous studies used MODIS snow and ice datasets to research Xinjiang lake ice phenology, while this study applied band threshold methods based on higher spatiotemporal resolution datasets to accurately extract multiple lake ice phenology parameters.

2) The complete ice cover period is an important lake ice parameter, and its extension or shortening can directly represent regional climate change processes. Most lakes in Xinjiang showed shortening trends in complete ice cover period, particularly Ebinur Lake, Jili Lake, and Bosten Lake in north-central Xinjiang, with trends of -1.76 $d \cdot a^{-1}$, -2.13 $d \cdot a^{-1}$, and -0.81 $d \cdot a^{-1}$, respectively.

3) Lake area, lake salinity, and other lake characteristics can directly affect lake freezing-thawing processes. Therefore, during the study period, saline lakes such as Ayakkum Lake and Whale Lake showed significant area expansion trends, which caused decreased lake salinity and consequently

advanced freeze-up start dates and extended complete ice cover periods for these lakes.

Due to the lack of measured lake ice phenology data in this study, precision evaluation of remote sensing monitored lake ice phenology could not be conducted during the research process. Additionally, to further systematically explore the driving mechanism of lake ice phenology, future research could consider factors such as permafrost change trends and glacier areas in lake regions.

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