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Spatiotemporal Variations in Lake Ice Phenology of Large Lakes in Central Asia, 2000–2020: Postprint

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Abstract

Lake ice phenology characteristics serve as one of the sensitive indicators of regional climate change. In recent decades, due to the influences of global warming and anthropogenic activities, the climate in the Central Asia region has undergone significant changes, and accurate monitoring of lake ice phenology holds important scientific significance for understanding climate change in Central Asia. Through comprehensive analysis of long-term surface reflectance data, meteorological data, and lake information from 2000 to 2020 for seven large lakes in Central Asia (Karakul Lake, Balkhash Lake, Aral Sea, Alakol Lake, Zaysan Lake, Chatyr-Kul Lake, and Markakol Lake, with area >100 km2), GIS-related techniques were employed to investigate their lake ice phenology characteristics and influencing factors. The results indicate: (1) Lakes in the Central Asia region begin to freeze between mid-September and early November, becoming completely frozen from late November to late December, with an average freezing duration of 35 d; lake ice begins to melt from late March to mid-May, becoming completely melted from early April to early June, with an average melting duration of 18 d. (2) During 2000–2020, five of the seven lakes in Central Asia showed a delayed trend in freeze onset date, with an average delay rate of 4.86 d · (10a)-1, while Balkhash Lake showed an advanced trend in freeze onset date, with an advance rate of 1.44 d · (10a)-1. The complete melt date showed an advanced trend, with an average advance rate of 2.90 d · (10a)-1. The average ice cover duration of the seven lakes was 171 d, among which four lakes showed a shortening trend in ice cover duration, and the complete freezing period showed an overall shortening trend, with Balkhash Lake showing the most significant shortening at a rate of 9.02 d · (10a)-1. (3) The freeze-melt spatial patterns of lake ice for the seven lakes in Central Asia can be mainly divided into two types: lake water gradually freezes from both banks toward the lake center, and melts from shore to opposite shore during melting; lake water freezes from shore to shore, with areas that freeze earlier

melting earlier. (4) Lake ice phenology changes in the Central Asia region are influenced by multiple factors including lake characteristics (elevation and area) and climate (air temperature and precipitation), with air temperature being the key factor affecting lake ice phenology—the higher the temperature, the shorter the ice cover duration; area primarily affects lake freeze onset date, with larger lakes having shorter ice cover duration; lake ice phenology also exhibits certain elevation dependence, with ice cover duration increasing as elevation rises.

Full Text

Temporal and Spatial Variations of Lake Ice Phenology in Large Lakes of Central Asia from 2000 to 2020

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Abstract

Lake ice phenology serves as a sensitive indicator of regional climate change. Over recent decades, significant climate changes have occurred in Central Asia due to global warming and anthropogenic activities, making accurate monitoring of lake ice phenology scientifically crucial for understanding regional climate dynamics. This study comprehensively analyzed long-term surface reflectance data, meteorological data, and lake information for seven large lakes (Karakul Lake, Balkhash Lake, Aral Sea, Alakol Lake, Zaysan Lake, Chatir Kol Lake, and Markakol Lake, all >100 km^2) in Central Asia from 2000 to 2020. Using GIS-related techniques, we examined lake ice phenological characteristics and their influencing factors. The results show that: (1) Lakes in Central Asia began freezing between mid-September and early November, achieving complete freeze-over from late November to late December, with an average freezing duration of 35 days. Ice melt commenced from late March to mid-May, with complete melt occurring between early April and early June, averaging 18 days. (2) From 2000 to 2020, five of the seven lakes exhibited delayed freeze onset dates, averaging 4.86 $d \cdot (10a)^{-1}$, while Balkhash Lake showed an advancing trend at 1.44 $d \cdot (10a)^{-1}$. Complete melt dates displayed an advancing trend, with an average rate of 2.90 $d \cdot (10a)^{-1}$. The mean ice-covered period was 171 days, with four lakes showing a shortening trend. The complete freezing period showed overall shortening, most notably in Balkhash Lake at 9.02 $d \cdot (10a)^{-1}$. (3) The freeze-thaw spatial patterns of the seven lakes primarily fall into two categories: ice forming from shore to opposite shore, with earlier frozen areas melting first; and ice forming

progressively from both banks toward the center, melting from one shore to the opposite. (4) Lake ice phenology changes in Central Asia are influenced by multiple factors including lake characteristics (altitude and area) and climate (temperature and precipitation). Temperature is the key factor affecting lake ice phenology—higher temperatures correspond to shorter ice-covered periods. Area primarily influences freeze dates, with larger lakes having shorter ice-covered periods. Ice phenology also shows altitude dependence, with ice-covered periods extending at higher elevations.

Keywords: lake ice phenology; climate change; Central Asia; MODIS

Introduction

Climate change represents a critical global challenge. The IPCC Sixth Assessment Report indicates that global surface temperatures have already risen by 1.09°C relative to pre-industrial levels, with an accelerating warming trend. Climate change has profoundly impacted terrestrial and marine ecosystems worldwide, adversely affecting human production and livelihoods, making it imperative to understand climate response mechanisms. Various natural media can serve as climate indicators, including sea level, glaciers, permafrost, and lakes. Lakes play vital roles in global water cycling, and their area, water level, and ice phenology can all indicate regional climate change, with lake ice phenology being particularly sensitive.

Early lake ice phenology research relied primarily on field observations, but this approach was limited by weather, environmental conditions, and technical constraints, preventing acquisition of accurate, long-term, large-scale data. Recent advances in remote sensing technology have enabled retrieval of lake ice phenology information from high spatiotemporal resolution imagery. Remote sensing methods for lake ice monitoring include microwave and optical remote sensing. Passive microwave remote sensing offers high temporal resolution (daily) but relatively coarse spatial resolution (>10 km), making it suitable for large lakes like Qinghai Lake on the Tibetan Plateau and Great Bear Lake and Great Slave Lake in Canada. Active microwave remote sensing provides higher spatial resolution (<30 m in azimuth direction, <26.3 m in range direction) for monitoring ice formation and melt processes, but its lower temporal resolution (e.g., Radarsat 24 days) cannot meet high-frequency detection needs.

MODIS imagery, with high temporal resolution (daily) and moderate spatial resolution (250 m), has been widely applied to monitor lake ice phenology. Previous studies have examined ice phenology in various regions, but research on Central Asian lakes remains limited and less precise. This study extracts lake ice phenology information for seven Central Asian lakes from 2000–2020 MODIS surface reflectance data, analyzes phenological characteristics, and discusses the impacts of temperature, precipitation, lake area, and altitude on lake ice phenology using meteorological data and lake information.

1 Study Area

Central Asia generally includes Turkmenistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan. The region features higher terrain in the southeast and lower in the northwest, with an arid climate, scarce precipitation, and large diurnal temperature variations. Central Asia constitutes the world' s largest nonzonal arid region, representing a significant portion of global arid and semi-arid areas. Severe water scarcity makes lakes critically important water resources, with total lake area exceeding 88,000 km^2 and over 4,000 lakes larger than 1 km^2. Due to unique climatic conditions, most Central Asian lakes are fed by glacier melt, mountain precipitation, and river runoff.

This study selected seven lakes with stable ice cover periods and areas >100 km^2 (characterized by low cloud cover, minimal pixel misclassification, and clear freeze-thaw cycles): Karakul Lake, Balkhash Lake, Aral Sea, Alakol Lake, Zaysan Lake, Chatir Kol Lake, and Markakol Lake. Table 1 provides detailed information on these lakes, including elevation, area, and type.

2 Data and Methods

2.1 Data Sources

2.1.1 MODIS Surface Reflectance Data MODIS is a key sensor aboard NASA' s Terra and Aqua satellites. This study used the daily MOD09GQ surface reflectance product (250 m spatial resolution) from Terra to extract lake ice phenology for the seven lakes after data processing.

2.1.2 Landsat Data The Landsat program, a joint NASA-USGS initiative, provides the world' s longest continuous space-based observation record. This study used Landsat imagery to construct area models and estimate maximum and minimum water volumes. Landsat 7 and Landsat 8 data (30 m spatial resolution, 16-day temporal resolution) were used to validate MODIS-derived lake ice area percentages.

2.1.3 Reanalysis Meteorological Data Due to sparse meteorological stations and short observation periods in Central Asia, this study used the CRUTS v4.05 reanalysis dataset (monthly temporal resolution, 0.5° spatial resolution) to analyze relationships between lake ice phenology and climate factors.

2.2 Methods

2.2.1 Lake Ice Information Extraction Ice exhibits high reflectance in visible and near-infrared bands, while water shows low reflectance. Based on this difference, threshold methods were applied to distinguish ice from water. The specific formula is:

$$\text{Lake ice} = \begin{cases} \text{Band1} - \text{Band2} > a \\ \text{Band1} > b \\ \text{Band2} < c \end{cases}$$

where Band1 and Band2 represent red and near-infrared bands, and a, b, c are thresholds. When Band1 - Band2 > a, Band1 > b, and Band2 < c, the pixel is classified as lake ice.

For Landsat data, the Normalized Difference Snow Index (NDSI) was used:

$$\text{NDSI} = \frac{\text{Band2} - \text{Band5}}{\text{Band2} + \text{Band5}}$$

where Band2 is the green band and Band5 is the shortwave infrared band. Thresholds were determined through histogram analysis and visual interpretation.

Following the method of Kropáček et al. [30], 10% lake ice area coverage was used as the threshold for phenology extraction:

- **Start freeze date (FUS):** First day when ice area exceeds 10% of total lake area
- **Complete freeze date (FUE):** First day when ice area exceeds 90% of total lake area
- **Start melt date (BUS):** Last day when ice area exceeds 90% of total lake area
- **Complete melt date (BUE):** Last day when ice area falls below 10% of total lake area

2.2.2 Validation To assess MODIS ice extraction accuracy, Landsat and MODIS data were compared for cloud-free images during freeze-thaw periods. The coefficient of determination (R^2) was 0.92, mean absolute error was 1.15%, and bias was 0.58%, indicating high accuracy suitable for Central Asian lakes.

3 Results and Analysis

3.1 Cross-Validation of MODIS and Landsat Ice Extraction

Comparison of lake ice area percentages derived from Landsat and MODIS data yielded $R^2 = 0.92$, MAE = 1.15%, and bias = 0.58%, confirming that MODIS data can accurately extract lake ice area in Central Asia.

3.2 Lake Ice Phenology Characteristics (2000-2020)

The seven lakes began freezing from mid-September to early November, with complete freeze-over from late November to late December (average freezing period: 35 days). Ice melt started from late March to mid-May, with complete melt from early April to early June (average melt period: 18 days). The mean ice-covered period was 171 days, ranging from 127 days (Aral Sea) to 237 days (Chatir Kol). The mean complete freezing period was 126 days, with Chatir Kol showing the longest (170 days) and Balkhash the shortest (71 days).

3.3 Lake Ice Phenology Trends (2000-2020)

Five lakes showed delayed freeze onset dates, averaging 4.86 $d \cdot (10a)^{-1}$, while Balkhash Lake advanced at 1.44 $d \cdot (10a)^{-1}$. Complete melt dates advanced at an average rate of 2.90 $d \cdot (10a)^{-1}$. Four lakes exhibited shortening ice-covered periods, with an average reduction of 5.70 $d \cdot (10a)^{-1}$. The complete freezing period showed overall shortening, most pronounced in Balkhash Lake (9.02 $d \cdot (10a)^{-1}$).

3.4 Spatial Patterns of Freeze-Thaw Processes

Two dominant spatial patterns were identified:

1. **Shore-to-shore freezing:** Ice forms from one shore to the opposite, with earlier frozen areas melting first. This pattern applies to Karakul, Balkhash, Alakol, Zaysan, and Markakol lakes. Balkhash Lake exemplifies this pattern, with ice forming from southwest to northeast due to salinity differences (western freshwater zone <0.5 $g \cdot L^{-1}$, eastern brackish zone up to 3 $g \cdot L^{-1}$).
2. **Bank-to-center freezing:** Ice forms progressively from both banks toward the center, melting from one side to the other. This pattern characterizes Chatir Kol Lake, where ice forms on north and south banks in late December and spreads inward.

4 Discussion

4.1 Meteorological Influences on Lake Ice Phenology

Lake ice phenology is influenced by climate conditions and lake physicochemical properties. Temperature, precipitation, solar radiation, wind speed, and direction all affect ice formation, with temperature being the key factor.

Validation of CRUTS v4.05 data against Karakul Lake meteorological station data showed $R^2 = 0.99$ and MAE = 1.807%, confirming its suitability for Central Asian climate studies. Correlation analysis revealed strong relationships between annual mean temperature and ice-covered period (R = -0.82), complete freezing period (R = -0.79), and melt dates (negative correlation). Precipitation showed minimal impact on lake ice phenology.

4.2 Relationships with Lake Area

Lake area significantly influences ice phenology. Larger lakes show later freeze onset and earlier melt, resulting in shorter ice-covered periods. The rate of change in ice-covered period correlates negatively with lake area (R = -0.66), while the rate of change in complete freezing period correlates positively (R = 0.69), indicating that larger lakes experience faster changes in freezing period.

4.3 Relationships with Lake Altitude

Altitude also affects lake ice phenology. Higher elevation lakes exhibit earlier freeze onset, later melt, and longer ice-covered periods. The rates of change in ice phenology parameters show positive correlations with altitude, suggesting accelerated changes at higher elevations.

4.4 Dimensionless Analysis

Standardized dimensionless analysis was performed to quantify relative influences:

For Balkhash Lake: - Ice phenology parameters (except freeze onset) are primarily influenced by altitude - Temperature is the dominant factor controlling ice phenology - Precipitation has relatively minor effects - Area significantly affects freeze onset timing

5 Conclusions

This study analyzed long-term lake ice phenology for seven Central Asian lakes using MODIS, Landsat, and meteorological data. Key findings include:

1. Central Asian lakes freeze from mid-September to early November and melt completely by early April to early June, with average freezing and melting periods of 35 and 18 days, respectively.

2. From 2000–2020, five lakes showed delayed freeze onset (average: 4.86 $d \cdot (10a)^{-1}$) while Balkhash Lake advanced (1.44 $d \cdot (10a)^{-1}$). Complete melt dates advanced (average: 2.90 $d \cdot (10a)^{-1}$). Four lakes exhibited shortening ice-covered periods, with Balkhash Lake showing the most significant reduction in complete freezing period (9.02 $d \cdot (10a)^{-1}$).

3. Two primary freeze-thaw spatial patterns were identified: shore-to-shore freezing and bank-to-center freezing.

4. Lake ice phenology is controlled by multiple factors including temperature (key factor), lake area, and altitude. Higher temperatures shorten ice-covered periods; larger lakes have shorter ice periods; higher elevations extend ice periods.

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