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Ice regime on Khuvsgul lake, Mongolia, detection by time series movement from threshold value with MODIS

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ABSTRACT

It is essential that any investigation of regime changes be grounded in long-term observational measurements and data. Ice transportation on Lake Khuvsgul plays a vital role in the socio-economic life of the surrounding region. A critical factor for ensuring the safety of ice transportation is the load-bearing strength of the ice. Accordingly, this study is designed to characterize ice phenology and dynamics over the 2003–2024 period using eight-day interval datasets, with ice volume as the principal parameter. In this study, we used MODIS satellite surface-temperature products to estimate ice-volume parameters via the Weinberg equation. Threshold values for the ice-volume parameter were established using Youden's method, based on the load-bearing strength of the ice. Threshold value distinguishing young or melting ice from growing ice were established at 1089.655 $m^3 t^{-1}$ and 1090.015 $m^3 t^{-1}$. The onset of ice formation occurs when the ice-surface temperature drops below 0 °C, and melting initiates once it rises above 0 °C. This underscores the exceptional purity of Lake Khuvsgul's ice.

KEYWORDS

Khuvsgul lake, Ice formation, Ice temperature, Ice volume, Land surface temperature

1. INTRODUCTION

Ice phenomena are a major factor in regulating and limiting aquatic biodiversity. They also have significant socio-economic impacts through aspects such as water supply, ice roads, crossings and winter tourism [1].

Ice phenomena are explained by hydrophysics. Lake ice phenology is divided into the three stages such as ice formation, stable ice cover, ice break-up based on natural environmental characteristics [1].

Lake ice phenology research can be classified into two main approaches: continuous observational research and experimental investigations.

The experimental research method is used to validate theories and hypotheses about natural phenomena and processes. Continuous observational studies are primarily used to identify and establish the patterns of the ice regime.

Recent remote-sensing technology has enabled spatially extensive observations to quantitatively delineate the activity patterns of glaciers and ice-covered waters, such as the size changes in ice marginal lake, the sail height of sea-ice pressure ridges, ice velocity, lake ice phenology and river ice distribution [2].

The time-series displacement of lake ice in Lake Khuvsgul is estabilished using the sub-pixel offset technique with multi-temporal Sentinel-2 optical images [3]. The lake ice displacement results covered three stages from ice formation to ice break-up.

Ice phenology of the lake Khuvsgul and it's reason is determined by pixel-tracking method on both SAR data and optical remote-sensing data [4]. Based on these results of the ice motion pattern and magnitude, the ice movement of Khuvsgul Lake may have been caused by a normal faulting event striking parallel to the long axis of the lake.

There is also a study that identified Lake Khuvsgul's ice phenology and movement of Lake Khuvsgul using long-term time-series Sentinel-2 L2A optical images from 2016 to 2023 [5]. These lake ice movement results covered eight sub stages from ice-on to ice-off on lake khovsgol such as freeze onset or border ice, freeze-up of River Eg, freeze-up of border lagoons, stable ice cover or complete ice cover on the lake for ice formation and dates of break-up of River Eg, border lagoon break-up, ice cover break-up initiation and ice-off starts for the break-up processes.

A comparative appraisal of the two investigations reveals temporal offsets of over 20 days in the onset of primary ice formation, more than 10 days in the development of a stable ice cover and approximately 10 days in the period of ice melting. Despite divergences in ice phenology, these studies produce broadly consistent characterizations of ice-motion dynamics.

Discrepancies in ice phenology indicators stem from differences in the temporal coverage of the studies: the onset of primary ice formation, the period of stable ice cover, and the timing of ice break-up are all highly sensitive to meteorological conditions, so variations in observation periods inevitably produce divergences in these metrics [5], [6], [7].

Long-term satellite observations archives of cryospheric conditions provide a robust basis for quantifying lake-ice kinematics and elucidating their controlling processes, thereby enabling sub-seasonal precision in estimating the onset of primary ice formation, the period of stable ice cover, and the initiation of ice melting.

A critical parameter for winter transportation on ice is the load-bearing strength of the ice. Although a variety of satellite-derived spectral indices can reliably delineate ice from other surface types, they are inadequate for fully quantifying the mechanical strength and load-bearing capacity of the ice.

The objective of this study is to compute ice volume parameters and determine the ice regime using long-term satellite data.

2. RESEARCH METHODS

Table 1 provides an overview of the datasets employed in this study, including MODIS satellite products and high-resolution Google Earth imagery.

Table 1. Data

Data source	Variable	Spatial /temporal resolution	Date
MODIS	MOD21A1	1 km/8day	2003-2024
Google earth platform			2016.04.07 2022.03.22 2024.05.17 2024.05.30

MOD21A1 were selected to generate a local long-term LST from 2003 to 2024.

The Terra satellite was launched on 18 December 1999, and has 10:30 a.m./p.m. equatorial overpass times. It carries the MODIS sensor, which provides high temporal frequency, spatially detailed, and accurate earth observations. In this paper, The MYD21 LST algorithm differs from the algorithm of the MYD11 LST products, in that the MYD21 algorithm is based on the ASTER Temperature/Emissivity Separation (TES) technique, whereas the MYD11 uses the split-window technique. The MYD21 TES algorithm uses a physics-based algorithm to retrieve dynamically both the LST and spectral emissivity simultaneously from the three MODIS thermal infrared bands 29, 31, and 32. The pixel resolution of these MODIS products explored in this article is 1 km.

Ice density is the principal parameter characterizing the load-bearing capacity of the ice. Ice formed from ultra-pure water at 0 °C under standard atmospheric pressure has a density of 917 kg m^{-3}, which is lower than that of liquid water.

As the water temperature decreases, the density of ice increases while its volume contracts. Weinberg formulated the water temperature dependent relationship governing ice density and specific volume. (equation 2, 3). Because accurate determination of ice density requires knowledge of its porosity, we therefore calculated the ice volume in this study. "Ice specific volume" denotes the volume occupied by one tonne of ice and is expressed in cubic metres (m^3). Given the linear relationship between specific volume and density, we infer that the ice regime can be adequately characterized using either of these parameters.

$$\rho = 917 * (1 - 0.000158 * t) * (1 - h) \quad (1)$$

$$V = 1090 * (1 + 0.000158 * t) \quad (2)$$

Here:
ρ- ice density, kg/m^3
V- ice volume, m^3
t- water temperature, degree celsius
h- porosity cofficient

Water temperature was derived from the satellite land-surface temperature product using the following equation.

$$LST = Pixel\ value * 0.02 + 273.15 \quad (3)$$

To classify ice and other surface using ice volume data derived from the above equations, a threshold value is required. The selection of a threshold is critical to the performance of a selected index's ability to identify ice phenomena. The threshold value was determined using the Youden index method [8].

$$J = Max_c(Sensitivity_c + Specificity_c - 1) \quad (10)$$

Ice is classified into three categories: young ice, melting ice, and growing ice. For each of these categories, calculating the threshold value requires sampling points derived from high-resolution satellite imagery. Sample points were selected by stratified random sampling method using Google earth platform (table 2).

Table 2. Sampling point

Ice classification	Sample point
Young ice, melting ice	249
Growing ice	587
Water surface	30

3. RESULT AND DISCUSSION

Figure 1 illustrates the mean, minimum, and maximum water surface temperatures of Lake Khuvsgul. Analysis determined that Lake Khuvsgul's water-surface temperature spans a range of 56.1 °C, with mean values varying between –18.9 °C and 7.5 °C over the period from October 31 to June 25. Begining December 2, the mean water-surface temperature declines to –0.9 °C below zero degree celsius whereas from April 22 onward it rises to 0.4 °C above zero degree celsius.

Figure 1. Minimum, maximium and mean value of water surface temperature

Lake Khuvsgul ice was categorized using ice volume thresholds as follows:

- Ice volume value below 1089.655 m^3/ton is classified as consolidated high-density ice.
- Ice volume value between 1089.655 m^3/ton and 1090.015 m^3/ton is classified as young or melting (low-density) ice.
- Ice volume exceeding 1090.015 m^3 / ton correspond to open water.

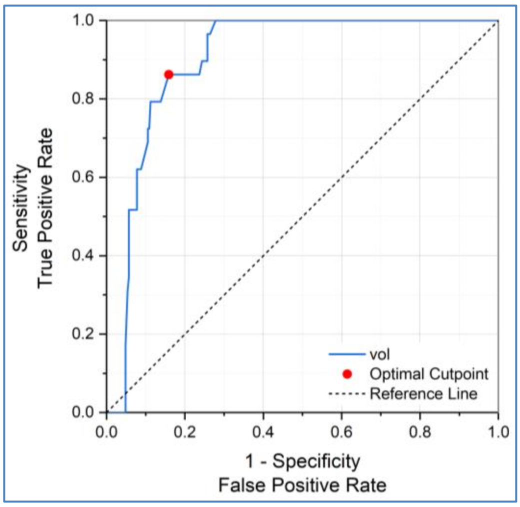

Figure 2. ROC curve for determining the 1089.655 m³/t threshold of the ice-volume parameter

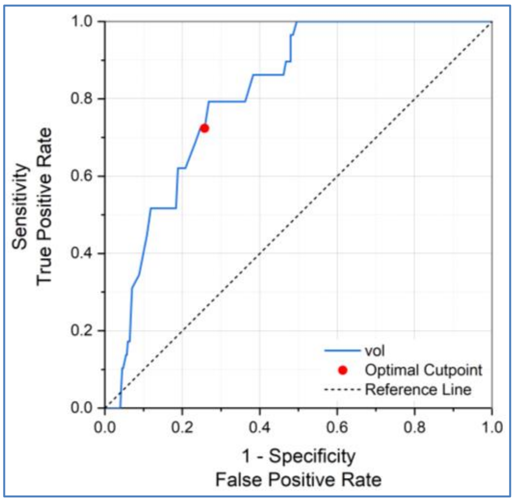

Figure 3. ROC curve for determining the 1090.015 m³/t threshold of the ice-volume parameter

The 22-year mean ice volume for each 8-day interval of the cold season was computed and then classified using threshold values of 1089.655 $m^3\ t^{-1}$ and 1090.015 $m^3\ t^{-1}$.

These results indicate that ice formation on Lake Khuvsgul begins on November 8 in the shallow zone along the eastern shore of lake and at the headwater zone of the Eg River.

At this stage, the ice around the headwaters of the Eg River reaches a volume of 1089.655 m^3 per ton, corresponding to the higher-density classification.

In the shallow zones along the eastern shoreline, ice volume ranges from 1089.655 to 1090.015 m^3 per ton, corresponding to the lower-density classification.

Eight days later, ice density increases in the shallow zones near Noyon, Sevsuuliin Tokhoi, and Kankh along the eastern shore, causing the ice to expand outward from the shoreline. At the same time, the northern and northwestern reaches of the lake begin to become ice covered. In this manner, the ice formation process on Lake Khuvsgul continues until December 18. The period from November 8 through December 18 can be regarded as the ice-cover formation stage.

Other studies have respectively defined the ice-cover formation period as December 7 to January 3 [3], and November 17 to December 25 [5].

The strong concordance between our results and those obtained from long-term averaged time series highlights the essential role of sustained monitoring in accurately characterizing Lake Khuvsgul's ice regime.

The second stage often termed the growing ice cover period extended from December 18 to April 06 (see Figure 4 and 5). From April 6 onward, ice density begins to decline in the southern sector of Lake Khuvsgul, particularly immediately south of Modon Khui Island.

The density-decline phase persists for 16 days following April 6; thereafter, the ice melting process commences. The ice-melting phase continues until May 24.

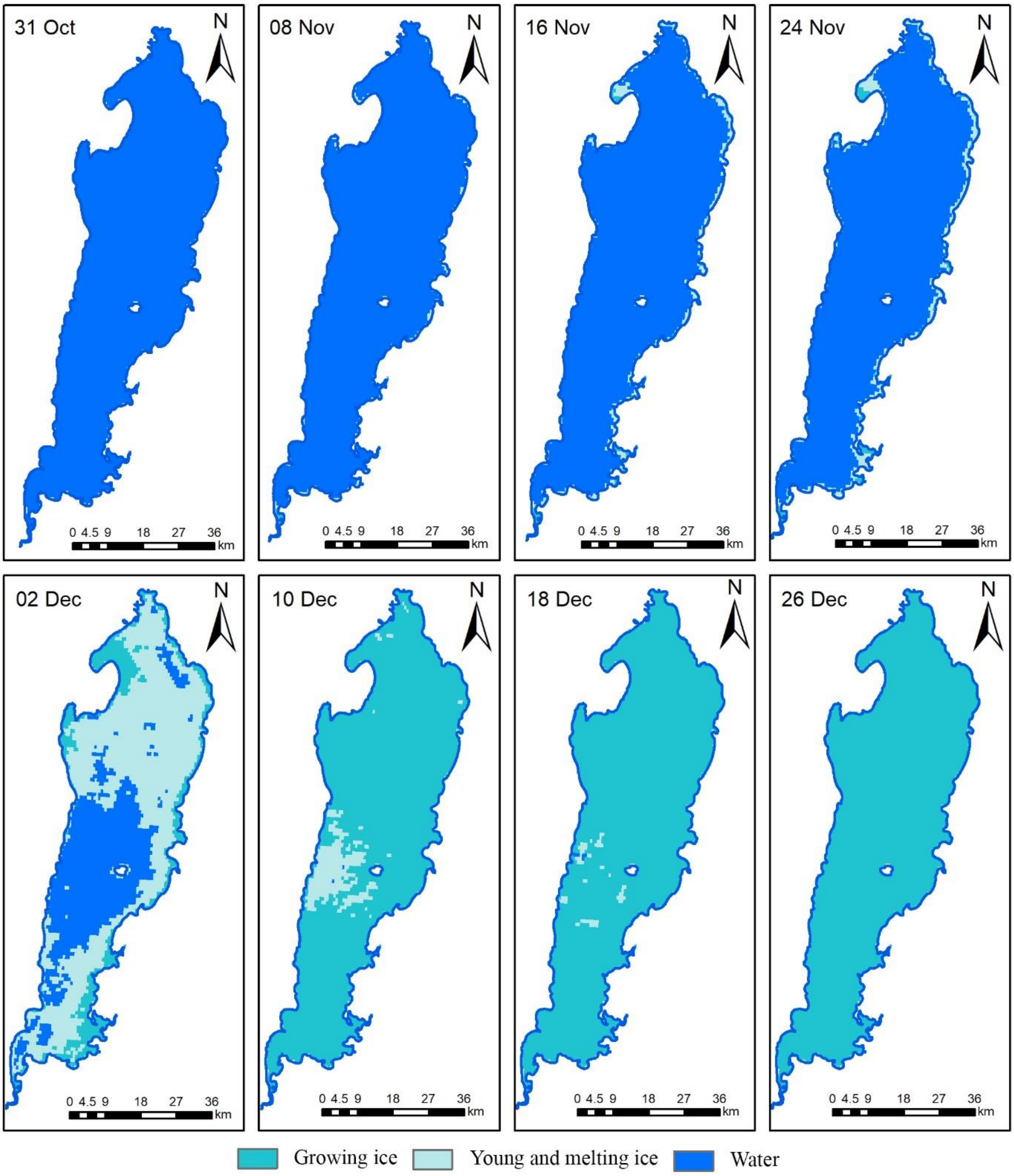

Figure 4. Ice cover formation on Lake Khuvsgul in 2003-2024.

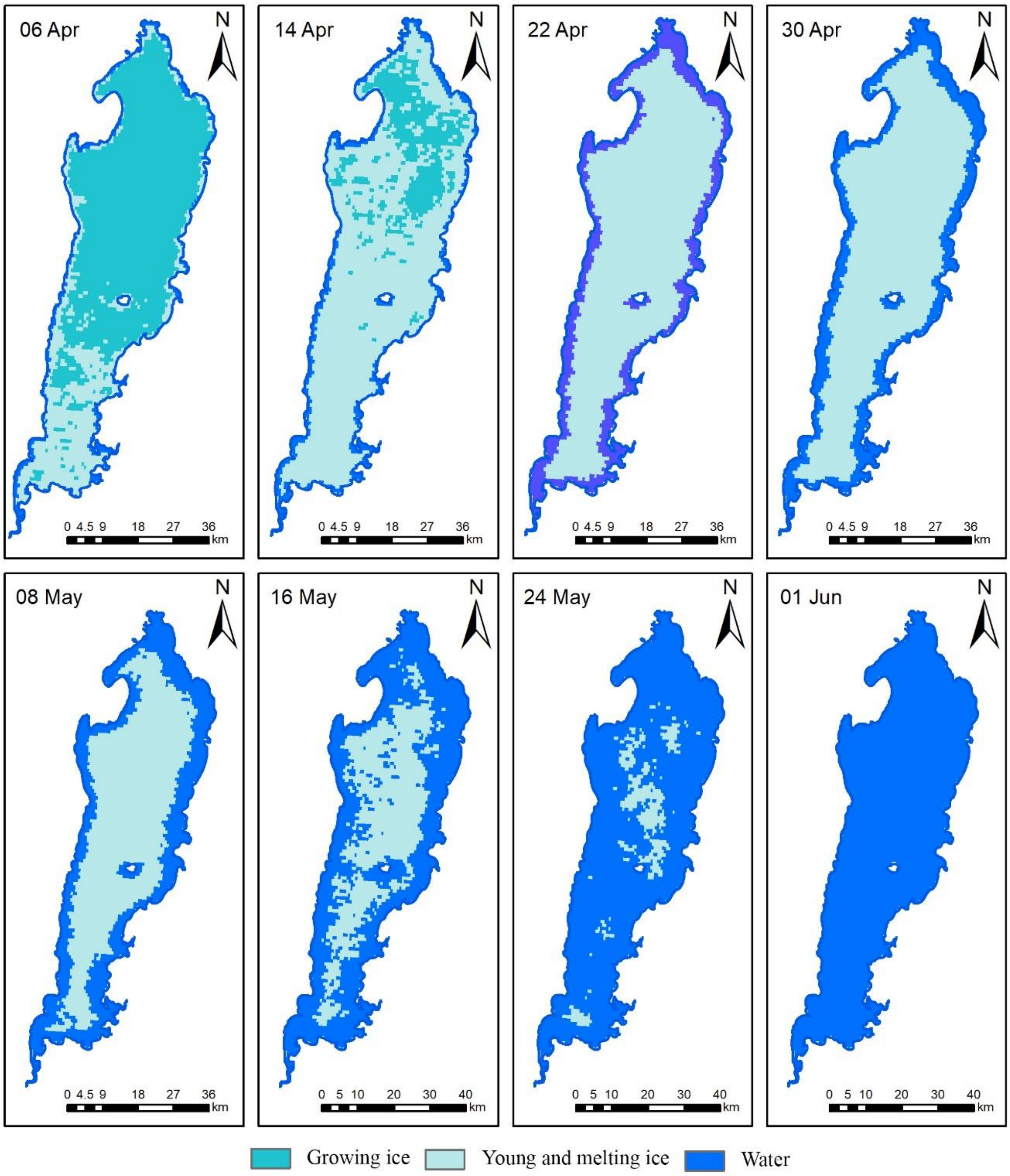

Figure 5. Ice covers break-up processes on Lake Khuvsgul in 2003-2024

Figure 6 illustrates the variations in surface air temperature (i.e., ice temperature) during the onset of ice formation and the subsequent ice cover formation and growing ice stages.

The ice-temperature amplitude during this period is 19.71 °C, and this variability is linked to fluctuations in air temperature (Figure 7).

The average ice temperature at the onset of freezing is 0.75 °C, i.e., approximately 0 °C.

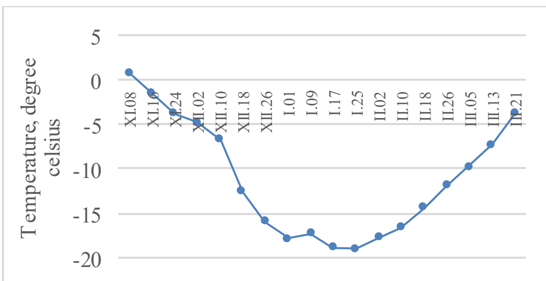

Figure 6. Temporal variation of ice temperature

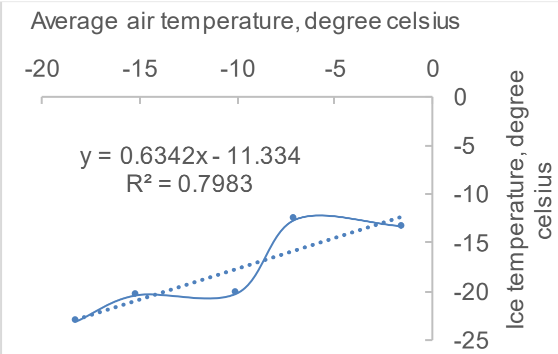

Figure 7. The relationship between mean ice temperature and air temperature

Our results indicate that when the ice-surface temperature falls below 0 °C, ice edges begin to form in the lake's shallow zones.

4. CONCLUSION

1. The ice regime can be effectively characterized by applying Weinberg's ice volume formula in combination with the MODIS satellite-derived land surface temperature (LST) product.
2. A four-stage classification framework for ice phenology comprising the stages of ice cover formation, growing ice, thinning ice, and ice cover break-up was developed based on Weinberg's ice volume formula.
3. When the surface temperature of the ice drops below 0 °C, ice begins to form; once the temperature exceeds 0 °C, the ice starts to thin. This behavior is closely related to the exceptionally low mineral content and high purity of Lake Khuvsgul's water.

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