Comparison to Changes of Lake Ice Phenology and Air Temperature over Northern Europe, Tibetan Plateau and Mongolian Plateau

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Abstract. Lake ice is a sensitive factor for the Earth's environment and climate change research. In the comparative study on climate change to the Earth three-pole (Antarctic, Arctic, and Tibetan Plateau), the lake ice phenology can be used to represent seasonal climate changes. In this paper, the lake ice phenology and the corresponding daily temperature for 48 lakes in Northern Europe, Tibetan Plateau and Mongolia Plateau were used as the typical case for comparative research. Based on passive microwave remote sensing data. The results showed that the average lake ice cover duration experienced a consistent decreasing for the three regions from 1978-2018. However, in the northern Tibetan Plateau, though the lake ice cover duration showed a shortening trend from 1978 to 2000, it displayed a prolonged trend from 2000 to 2018. Moreover, the air temperature changes of the lake area had a significant correlation with the changes of ice cover duration in each region, and the change of 0 °C isotherm in the Northern Europe lakes are more sensitive than the Mongolian Plateau and the Tibetan Plateau. The air temperature played a major role in the change of lake ice phenology, but there were still other factors that affected the lake ice phenology changes, especially in northern Tibetan Plateau. By comparing the analysis of the ice cover duration in the three regions and the effect of air temperature on the lake ice cover duration change, it provides more evidences for the study on climate change research in different regions.
1. Introduction
Lake ice phenology is a vital indicator of global climate change and a parameter that reflects historical, local, or regional climate change [1, 2]. A comparative study of climate change in the three pole areas (i.e., the Antarctic, Arctic, and the Tibetan Plateau) determined that lake ice phenology is an important indicator of the similarities or differences in climate change between various regions. Northern Europe is located within the Pan-Arctic region, and lakes are an essential part of its landscape [3]. The Tibetan Plateau is located in central Asia and has an average altitude of approximately 4,046 m. This plateau has a high density of lakes, with a total area of approximately 43,065.97 km² and contains more than 1,200 lakes that cover more than 1 km² [4, 5]. This is one of the areas with the highest densities of lakes in the world. The Mongolian Plateau is adjacent to the Tibetan Plateau and is located in the Asian hinterland. The Inner Mongolia Autonomous Region of China and the Mongolian People’s Republic are the main regions of the Mongolian Plateau, and they cover an area of approximately 275 km². Several lakes in the Mongolian Plateau are important international wetlands for endangered species and various migratory birds [6, 7].

Northern Europe, the Tibetan and Mongolian Plateaus have differing climatic conditions and different types of lakes [8, 9]. Hence, the ice phenology of the lakes in these areas also varies. Therefore, the effects of changes in temperature requires further comparative analysis from a global climate change perspective.

2. Data and Methods
2.1. Data
Based on the principle of passive microwave monitoring of the freeze/thaw cycles of lake ice, this study uses passive microwave data with an 18 GHz horizontal polarization [10, 11]. The data between October 1978 to October 2011 were collected from the Calibrated Passive Microwave Daily EASE-Grid 2.0 (CETB) [12] published by the National Snow and Ice Data Center. The passive microwave data between October 2011 to July 2012 were obtained from the Microwave Radiation Imager (MWRI) sensor on China's meteorological satellite Fengyun 3 (FY-3), and the data between July 2012 to April 2018 were obtained from the Advanced Microwave Scanning Radiometer 2 (AMSR-2); these data included raw orbital brightness temperature data released by the Japan Aerospace Exploration Agency (http://global.jaxa.jp/), which has a resolution of 22×14 km at 18.7 GHz.

Temperature data were provided by the European Centre of Medium-range Weather Forecast (ECMWF) and were in the Net CDF format. In this study, 2 m temperature data of 0.5° from January 1979 to April 2018 are examined. These include temperature values at 0, 3, 6, 9, 12, 15, 18, and 21 clock [13]. Accordingly, calculate the average value at different time periods of each day to obtain the daily average temperature.

2.2. Lake ice phenology extraction methods
To reduce the influence of land pixels at the lakeshore, this study uses the nearest neighbor method to extract the bright temperature signals of the lakes in northern Europe, the Tibetan Plateau Mongolian Plateau in order to acquire the lake ice phenology [14]. Long-term critical lake brightness temperature data, based on passive microwave enhanced resolution and original orbit data, were obtained, analyzed, and processed. Based on the difference between the emissivity of ice and water, the turning point of the temperature curve of the time series was used to determine the lake ice phenology (including freeze-up start (FUS), freeze-up end (FUE), break-up start (BUS), and break-up end (BUE)) [11]. Owing to a severe lack of available data, this study only compares the spatial-temporal changes in the parameters for FUS, BUE, and ice cover duration.

2.3. Temperature data processing
The coordinates and range values used while collecting air temperature data were similar to those used while collecting bright temperature signals of the lake ice. The daily temperature was processed using a 31-day running mean because of the large fluctuations in its values [2,15]. The first occurrence of a 0 °C temperature in autumn and spring was recorded, and a correlation analysis was performed with the FUS and the BUE. To calculate the accumulated temperature, it was necessary to initially use a five-day moving filter to determine the start and end dates when the daily average temperature was continuously above 0 °C (or below 0 °C). During the year, the average daily temperature of any five consecutive days had to be greater than 0 °C (or less than 0 °C), and the date of the first day was considered as the start date of the extended period, while the date of the last day was considered as the end date. We calculated the average daily temperature between the start date and the end date, then obtained the accumulated temperature.

3. Comparative analysis of the lake ice cover duration
This study obtained the lake ice phenology and the corresponding daily temperature values of 91 lakes in northern Europe, the Tibetan Plateau and the Mongolian Plateau. The area of the smallest lake in these regions was 24.33 km² [4]. The ice cover duration is defined as the period between the FUS date and the BUE date of the lake ice, and this parameter can comprehensively reflect the lake ice coverage. The average ice cover duration in northern Europe lakes could reach 165 days, and the average ice cover duration of the northern region was approximately 30 days longer than that of the southern region. The average ice cover duration of the lakes of the Mongolian Plateau was approximately 178 days. Northern Europe and the Mongolian Plateau display a specific difference in latitude. The average ice cover duration of lakes in the Tibetan Plateau was approximately 150 days, however, it presented a spatial agglomeration phenomenon. According to China's climate zoning, the average ice cover duration of lakes in northern Tibetan Plateau and mid-Tibetan Plateau was 189 days and 126 days, respectively, which is a difference of 63 days.

With regard to the determination of the years that observed the longest ice cover duration for each region, the anomalous values indicated that the year of 2000 was pivotal, because the values showed different changes before and after this time period. The three regions are divided into two time periods (1978-1999, 2000-2017), respectively. The results of the comparison showed that the ice cover duration in northern Europe was extended by 0.25 days/year from 1978 to 1999. During the period from 2000 to 2017, the ice cover duration reduced by -0.59 days/year. However, both time periods
were not significantly correlated. Similar to a previous analysis, the Tibetan Plateau was divided into two regions for evaluation: the northern Tibetan Plateau (12 lakes) and the mid-Tibetan Plateau (6 lakes). Over the two time periods, the ice cover duration in mid-Tibetan Plateau displayed a decreasing trend and the shorten was more significant from 1978 to 1999. In the northern Tibetan Plateau, there were no obvious increasing or decreasing trends of the ice cover duration from 1978 to 1999; however, the ice cover duration from 2000 to 2017 showed an increasing trend (0.74 days/year, P<0.1). The ice cover duration in the Mongolian Plateau was significantly (P<0.05) shortened, with reductions of -0.44 days/year and -0.78 days/year for the two periods, respectively.

The above comparative analysis of the ice cover duration variations from 1978 to 2017 indicated that the warming trend in northern Europe was more severe than that in other regions. For the time series, the year of 2000 was a pivotal point with regard to the lake ice cover duration for the three regions. In the northern Tibetan Plateau, in particular, which showed a trend of a prolonged ice cover duration after 2000, a delay in the BUE played a more significant role than the advancement of the FUS.

4. Response of lake ice phenology to temperature change

4.1. Temperature and lake ice phenology
The accumulated temperature is an important indicator of the heat conditions of a region. This study analyzed the correlation between the accumulated temperature below 0 °C and the ice cover duration from 1978 to 2017. Analyses of the three regions showed that the ice cover duration was significantly negatively correlated with the negative accumulated temperature. For every 1000 °C decrease in the accumulated temperature, the ice cover duration of Tibetan Plateau, northern Europe and Mongolian Plateau was extended by 52.5 days, 40.3 days and 16.6 days, respectively. However, the scatter plot of the Tibetan Plateau presents two different states. According to the climatic zone of the Tibetan Plateau mentioned above, the correlation analysis of the mid-Tibetan Plateau and northern Tibetan Plateau showed that for every 1000 °C reduction in accumulated temperature, the lake ice cover duration was extended by 15.4 days and 21.3 days, respectively.

![Figure 1. Correlation between the accumulated temperature below 0 °C and ice cover duration.](image)

From summer to autumn, an analysis of the first 0 °C date and the FUS date revealed that when a 0° C isotherm appeared ten days later than expected, the FUS was delayed by 4.7 days, 4.1 days, and 5.6 days in the mid-Tibetan Plateau, northern Tibetan Plateau, and northern Europe, respectively. From winter to summer of the following year, an analysis of the first date that exceeded 0 °C and the BUS showed that if a 0° C isotherm appeared ten days in advance, the BUE would be 3.5 days, 3.6 days, 7.3
days, and 7.0 days earlier in the mid-Tibetan Plateau, northern Tibetan Plateau, Mongolian Plateau, and northern Europe, respectively. With a change of below 0 °C duration, the ice cover duration change rate of the northern Europe lakes was the largest, which indicated that lakes in this region were more sensitive to the changes of 0 °C isotherm than those in the Mongolian and Tibetan Plateaus. The Pearson correlation coefficient results showed that a 0 °C isotherm played a significant role in lake ice phenology change; however, the lake ice phenology could also be affected by other factors.

|                      | Freeze-up start | Break-up end | Ice cover duration |
|----------------------|-----------------|--------------|--------------------|
|                      | Change rate     | R            | Change rate        | R            | Change rate | R            |
| Mid-Tibetan Plateau  | 0.47            | 0.16         | 0.35               | 0.23         | 0.37        | 0.27         |
| Northern-Tibetan Plateau | 0.41         | 0.24         | 0.52               | 0.36         | 0.55        | 0.40         |
| Mongolian Plateau    | /               | /            | 0.96               | 0.73         | 0.40        | 0.39         |
| Northern Europe      | 0.56            | 0.46         | 0.60               | 0.70         | 0.78        | 0.67         |

To analyze the role of temperature in the change in lake ice cover duration, this study used two periods (1978 to 1999 and 2000 to 2017) for a time-series analysis of the ice cover duration at below 0 °C temperatures. As shown in Figure 2, a correlation analysis showed that there was a significant correlation between the ice cover duration and the below 0 °C duration of the period from 1978 to 1999 in the mid-Tibetan Plateau and northern Europe, and the correlation coefficients were 0.56 (P<0.01) and 0.59 (P<0.01). In contrast, the relationship was weak in the northern Tibetan Plateau and Mongolian Plateau. For the period between 2000 to 2017, there was a significant correlation between the ice cover duration and the below 0 °C duration in northern Europe, the Tibetan Plateau and Mongolian Plateau, the correlation coefficients were 0.49 (P<0.05), 0.80 (P<0.001), and 0.77(P<0.001), respectively. In contrast, the ice cover duration in the northern Tibetan Plateau had no significant relationship with the below 0 °C duration. From the above analysis, the ice cover duration of the northern Europe lakes during the period between 1978 to 2017 was most susceptible to the below 0 °C duration. After 2000, the ice cover duration of the lakes in the Mongolian Plateau was significantly affected by temperature changes, while the change in the ice cover duration in the northern Tibetan Plateau was more affected by other factors (i.e. salinity) than temperature.
4.2. Time series analysis of the extension of the lake ice cover duration

We performed a time-series analysis of the temperatures and lakes with an extended ice cover duration from 1978 to 2018. There were four lakes in the Tibetan Plateau and two lakes in the northern Europe that had an extended lake ice cover duration. However, as the ice cover duration rates of the two lakes in the northern Europe and the two lakes in the Tibetan Plateau were less than 0.5 days, considering the errors in the data source, the ice cover duration and the below 0°C duration were analyzed only for the lakes with a lake ice duration extension of more than 0.5 days.

Dorsoidong Lake covered an area of 378.99 km² and its sampling coordinates were 89.87E, 33.40N. Aqqikkol Lake covered an area of 354.71 km² and its sampling coordinates were 88.42E, 37.08N. Additionally, Aqqikkol Lake has a salinity of 78.19 g/L and is thus categorized under the subtype brine salt lake of magnesium sulfate. Lake water is mainly recharged by surface runoff [4,16]. The results indicated that, during the period from 1978 to 2017, the below 0°C duration of the Dorsoidong and Aqqikkol Lakes displayed a relatively stable trend, although the ice cover duration of the two lakes currently fluctuates with changes in temperature. However, the ice cover duration was extended over the entire time-series, especially after the year 2000. When the analysis of the lake ice phenology on the Tibetan Plateau was considered with the relationship between the temperature and ice cover duration, it could be inferred that, in addition to the temperature, the changes in lake ice phenology should have other major or secondary effects on the Tibetan Plateau. These effects may be due to regional influences or may be caused by changes in the individual lakes, such as changes in the salinity levels.

5. Conclusions

Lake ice phenology is an important indicator of regional and global climate change. The lake ice phenology of the northern Europe, the Tibetan Plateau and the Mongolian Plateau were compared
from 1978 to 2017, and the temperature was added to explain the similarities and differences of lake ice phenology changes between the three regions.

From 1978 to 2017, the ice cover duration changes of 48 lakes in the northern Europe, Tibetan Plateau and Mongolian Plateau indicated a warmer climate, but the ice cover duration in the northern Tibetan Plateau has extended since 2000. By comparing the temperature changes, it can be seen that the northern Europe lakes were more sensitive to the 0 °C isotherm than the Mongolian Plateau the Tibetan Plateau. Although temperature played a major role in the changes in lake ice phenology, there are other factors that also affect it, especially in northern Tibetan Plateau.

Limited by the resolution of passive microwave remote sensing, only the lake ice phenology of large-sized lakes were obtained. In future works, the decomposition model of mixed pixels will be developed based on optical remote sensing and temperature data to obtain more information on the lake ice phenology of small-sized lakes. The impact of changes in lake area, salinity, and depth on lake ice phenology will also be studied in the future.

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