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High-Resolution Mapping of Ice Cover Changes in Over 33,000 Lakes Across the North Temperate Zone

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Key Points:

- We provide the first long-term wall-to-wall mapping of lake ice cover over the entire Northern Temperate Zone
- We found a remarkable reduction in median ice cover occurrence (61-43%)
- Extensive lake ice retreats were found in central and southern Europe, the northern US, and central and southeastern Asia

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

More than 50% of global lakes periodically freeze, and their lake ice phenology is sensitive to climate change. However, spatially detailed quantification of the changes in lake ice at the global scale is not available. Here, we map ice cover in >33,000 lakes throughout the North Temperate Zone (23.5°–66.5°N) using 0.55 million Landsat images from 1985 to 2020. Over this period, we found a remarkable reduction in median ice cover occurrence (ICO) (61% to 43%), which was strongly related to warming terrestrial mean surface temperatures ($R^2 = 0.94$, $p < 0.05$). Lakes in Europe showed the most pronounced ice loss (median ICO decreased from 50% to 24%), and extensive lake ice losses were also detected in the northern US, and central and eastern Asia. An overall increase in ice cover was identified from P2 (1999–2006) to P3 (2007–2014) due to regional decreased temperatures associated with the "global warming hiatus." The high-resolution mapping of lake ice here provides essential baseline information which can be used to elucidate ice loss-induced environmental and societal impacts.

Plain Language Summary

Widespread reductions in lake ice have been detected recently worldwide, yet spatially detailed characterization of global lake ice is currently unavailable. Using 0.55 million Landsat satellite images from 1985 to 2020, we provide the first long-term wall-to-wall mapping of lake ice cover over the entire Northern Temperate Zone, comprising >33,000 lakes representing 48% of the global lake area in total. We track spatially detailed changes in lake ice across the entire Northern Temperate Zone, and examine how ice change patterns have differed geographically and temporally in response to climate change.

1. Introduction

Half of the world's lakes (approximately 50 million) periodically freeze (Verpoorter et al., 2014). The phenology of lake ice (i.e., freeze/thaw dates and duration) not only influences physical conditions (such as heat storage, temperature, mixing) of underlying ecosystems (Hampton et al., 2017; O'Reilly et al., 2015; Salonen et al., 2009), but also provides important opportunities for transportation, recreation, and fishing for hundreds of millions of people worldwide (Brammer et al., 2015; Knoll et al., 2019; Prowse et al., 2011). Recently, widespread reductions in lake ice have been detected at both regional and global scales due to recent climate warming (Magnuson et al., 2000; Sharma et al., 2019), and this problem is projected to become more severe in the future due to ongoing warming trends and escalating climate extremes (Benson et al., 2012; Sharma, Blagrave, et al., 2020; Shuter et al., 2013).

Observations from both field surveys and satellite remote sensing have been widely used to identify historical trends in lake ice cover (Benson et al., 2012; Brown & Duguay, 2010; Magnuson et al., 2000; Sharma, Meyer, et al., 2020). Unfortunately, even with the well-maintained *in situ* data set from the National Snow and Ice Data Center (NSIDC) (Benson et al., 2012; Sharma et al., 2019), field records are available for only 631 lakes, and only ~40 lakes have four decades of continuous records (Sharma, Meyer, et al., 2020). Furthermore, the *in situ* lake ice records from NSIDC were spatially biased: few records were collected in Asian lakes or lakes located south of 40°N in the other continents (Benson et al., 2012; Sharma et al., 2019). Although satellite remote sensing offers large-scale and frequent observations, the currently available applications are restricted to individual large lakes or lake districts (Cai et al., 2019; Kropácek et al., 2013; Latifovic & Pouliot, 2007). Meanwhile, the past and future global patterns of lake ice may be simulated using process-based models (Walsh et al., 1998; Weyhenmeyer et al., 2011); however, the thermodynamics of large lakes are difficult to characterize due to the substantial impacts of lake-specific features (i.e., morphology, depth, fetch, etc.) (Brown & Duguay, 2010; Bueche et al., 2017; Walsh et al., 1998). Currently, a spatially detailed quantification of the changes in lake ice at the global scale is not available.

Here, we provide the first long-term wall-to-wall mapping of lake ice cover over the entire Northern Hemisphere temperate zone (23.5°–66.5°N), where the majority of global lakes are located (Verpoorter et al., 2014). We examined 33,333 lakes in total (27,446 in North America, 2,823 in Europe, and 3,064 in Asia), representing 48% of the global lake area and 18% of the number of lakes >1 km^2 (Messager et al., 2016) (see how these lakes were determined in Supporting Information S1). We tracked four decades (i.e., 1985–2020) of changes in lake ice cover occurrence (ICO, defined as the frequency at which ice cover was detected within a certain time period, see detailed calculations below). We further examined the relationship of the changes in lacustrine ICO and climate variability, and identified how lake-specific features (i.e., lake size, depth, and shoreline complexity) could impact such a relationship.

2. Methods

We mapped lake ice cover over the entire North Temperate Zone using 30-m resolution Landsat satellite observations from 1985 to 2020. All Landsat images in our analysis were collected within the first quarter of the year (January to March) during the 36-year period (Figure S1), with a total of 0.55 million images (see details in Supporting Information S1). The first quarter was selected instead of the commonly used boreal winter months (December to February) because lake ice cover is greater in the January–March period than in the December–February period (Figure S2), similar to previously detected patterns for snow cover (Pulliainen et al., 2020). We examined the lake ice changes across four different periods between 1985 and 2020: 1985–1998 (P1), 1999–2006 (P2), 2007–2014 (P3), and 2015–2020 (P4). These periods represent different air temperature changing phases; the years between 1999 (start year of P2) and 2014 (end year of P3) represent the period when global temperature remained stable, which is often termed the "global warming hiatus" in the scientific community (Karl et al., 2015; Kosaka & Xie, 2013; Medhaug et al., 2017).

We determined lake ice extent for each Landsat image using the Fmask algorithm, which classifies snow/ice pixels using several thresholds (Normalized Difference Snow Index >0.15, Brightness Temperature <0.38, NIR band reflectance <0.11, and green band reflectance >0.1) (Zhu & Woodcock, 2012). To estimate the ICO of a lake within a given period, we used the following procedure (see flow chart in Figure S3). First, we counted (a) the number of times when a pixel was labeled snow/ice (N_{ice}) and (b) the number of valid Landsat observations (N_{vo}) (pixel was not labeled as clouds or cloud shadows) in the first quarter of all years within the period. Second, we normalized N_{ice} against N_{vo} to calculate the ICO at the pixel level. Pixels with limited valid observations (N_{vo} <10) were removed from further analysis to avoid meaningless statistics. Third, we estimated the mean value of all pixel-level ICO values within a predefined lake area, representing the ICO of this lake within this period. The predefined lake area was determined by using both the static lake polygon in HydroLAKES and water occurrence from the GSWO database (Pekel et al., 2016) including pixels with water occurrence of >95% within the HydroLAKES polygon (Messager et al., 2016). If a lake was completely frozen within the first quarter of a time period, the associated ICO calculation is 100%. Validations with *in situ* records from various lakes distributed globally demonstrated the high reliability of using the Fmask algorithm to classify the status of lake ice from individual images (Figure S4, overall accuracy = 93.9%) and for ICO calculations at different periods (Figure S5) (see detailed validations in Supporting Information S1). Note that the Fmask algorithm has also been used by previous research to classify lake ice (Zhang & Pavelsky, 2019), while our current study provides the first comprehensive validation using a global *in situ* data set (Figures S4 and S5).

We estimated the absolute differences in mean temperature between different periods and examined the spatial consistencies of the ICO changes and temperature variability. To explore the impacts of temperature on individual lakes, we performed logistic regression between ICO values of the examined lakes and the corresponding mean temperature. The logistic regressions were also conducted for lakes with different groups of sizes, depths, and shoreline complexities, to explore the impacts of lake-specific features (see details of temperature data processing in Supporting Information S1).

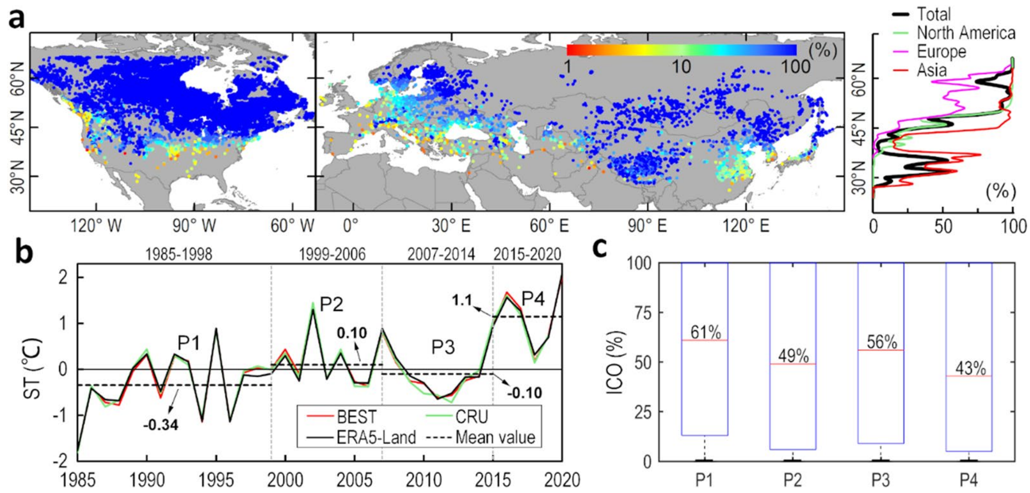

Figure 1. Lake ice cover occurrence (ICO) in the North Temperate Zone. (a) Mean ICO for each lake for the entire study period. Latitudinal profiles for the entire area and three continents are shown on the right (averaged by 1°). An ICO value of 50% means that 50% of the Landsat observations of a lake during the first quarter of the year has been identified as ice. (b) Terrestrial mean surface air temperature of the North Temperate Zone from three different data sets, presented as anomalies with respect to the long-term average (1985–2019). The four examined periods (P1: 1985–1998, P2: 1999–2006, P3: 2007–2014, and P4: 2015–2020) and their mean temperature anomalies (ERA5-Land) are annotated. (c) Box plots of ICO values (median and quartiles) for the four periods.

3. Results

3.1. Patterns and Long-Term Changes

The lake ice patterns varied markedly between different continents (Figure 1a). The highest frequent lake ice cover (ICO = 100%) was detected in North America and Asia at latitudes above 50°N; ICO values within the latitude band of 50°–60°N in these two continents were nearly twice those of lakes located in Europe. The southern limit of lake ice in the Northern Hemisphere was found to be ~30°N in southern China, where lake ice characteristics have been rarely investigated by either modeling or observational efforts (Sharma et al., 2019; Walsh et al., 1998). Moreover, the impacts of elevation were confirmed (Walsh et al., 1998), with more lake ice identified in high-altitude areas (such as the Tibetan Plateau in Asia and Rocky Mountains in North America) than in other regions at similar latitudes.

Throughout the entire period from P1 to P4, widespread lake ice losses were detected, with a remarkable reduction in median ICO (61-43%) observed for the full scope of the North Temperate Zone (subsequently referred to as "global"). Continental statistics demonstrated that lakes in Europe showed the most pronounced ice loss, where median ICO decreased from 50% in P1 to 24% in P4 (Figure 2). Extensive lake ice retreats (ICO reductions >30%) were found in central and southern Europe, the northern US, and central and eastern Asia (Figure 3a); permanent loss of lake ice (i.e., ICO of ~0% in P4) occurred in some of these regions (Figure S6). In contrast, elevated ICO values were identified in scattered parts of North America and the Tibetan Plateau (Figure 3a).

Patterns of lake ice change also show considerable temporal discrepancies. From P1 to P2, median ICO decreased from 61% to 49%; Eastern Europe and Central Asia suffered the greatest declines (Figure 3b). From P2 to P3, almost all European lakes experienced substantial ice loss, while these changes were offset by extensive ice gain in North America and Asia (Figures 2 and 3a), leading to a slight increase in global median ICO (Figure 1c). From P3 to P4, the changes were mainly characterized by moderate ice retreats, except for some ice gains in central Europe and the Tibetan Plateau (Figure 3a); overall, median ICO decreased to the lowest level (43%) among the four periods (Figure 1c).

The magnitude of the variations in lake ice cover within the four time periods can be further revealed through the coefficient of variation in the ICO (Figure 3b). Massive cross-period dynamics were found

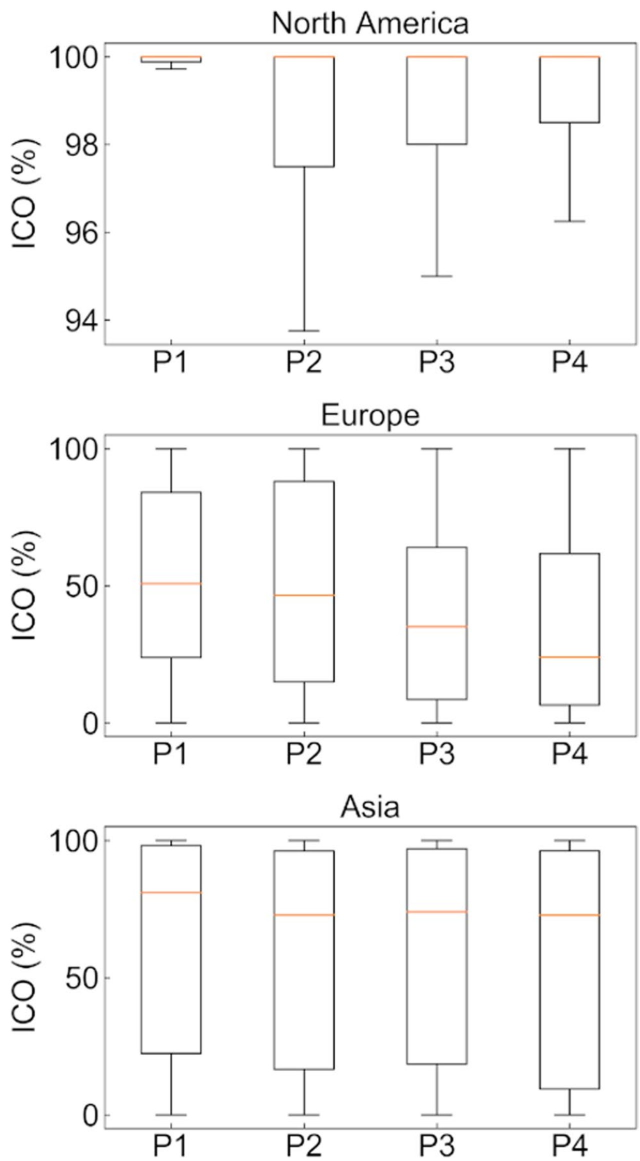

Figure 2. Boxplots of continental ice cover occurrence for different periods (median and quartiles). The numbers of examined lakes are 27,446 in North America, 2,823 in Europe, and 3,064 in Asia.

in southern and central Europe; however, lakes with large coefficients of variation (i.e., >0.3) were generally located in low-latitude regions in central and southeast Asia and the central US.

3.2. Linkage to Air Temperature

We found a strong relationship between observed widespread lake ice loss during the past four decades and terrestrial mean surface air temperature in the North Temperate Zone ($R^2 = 0.94$, $p < 0.05$; Figures 4a, 4b and Table S1), which increased by 1.44°C from P1 to P4 (Figure 1b). This result agrees with previous studies which also found analogous relationships between temperature and lake ice based on limited *in situ* data sets (Sharma, Blagrave, et al., 2020). However, we detected two regions where exceptional lake conditions caused deviations from the global pattern: lakes in Region 1 (Tibetan Plateau, $n = 633$) which are deep (up to >100 m) and found at high altitudes (>3,300 m) (Zhang et al., 2020), and lakes in Region 2 (Yangtze Plain, $n = 149$) which are shallow (mostly <2 m), exhibit great interannual changes in water depth, and have suffered from extensive human activities in recent decades (Hou et al., 2020).

Temporal and geographic differences in lake ice changes also correspond to regional climate effects. For example, changes in median ICO values (either for all examined lakes or for lakes from different continents) followed regional and temporal patterns of temperature (Figures 1b, 1c, S6, and S8a). Increases in ice cover in North America and central Asia from P2 to P3 spatially agreed well with decreases in temperature associated with the "global warming hiatus" in these same regions (Medhaug et al., 2017). Furthermore, lake ice gains in the Tibetan Plateau from P3 to P4 were also linked with regional decreases in temperature during this period (Figure 4a).

To explain why lakes in Europe show greater variations in ice cover than those in Asia and North America (Figure 3b), we examined the distribution of the mean surface temperatures of lakes on these continents (Figure S7a). We found that the air temperature of lakes in Europe fluctuated around 0°C and had small interquartile ranges (<5°C). As such, the frequent changes in ICO values in European lakes can be well explained by the logistic relationship between temperature and ICO (Figure 4b), where lake ice is most sensitive to surface temperature (i.e., large slope of the logistic relationship) when the temperature hovers around 0°C. In contrast, lakes on the other two continents are mostly located in cooler regions and have large interquartile ranges. Nevertheless, the lakes with large cross-period variability (i.e., coefficient of variation of ICO >0.3) in Asia and North America also show temperature levels with close proximity to 0°C and small ranges (Figure S7b).

We also examined the impacts of lake size, depth, and shoreline complexity on ice cover by partitioning the lakes into different groups (Figure 4c and Supporting Information S1). Large (or deep) lakes require lower temperatures to produce ICO values similar to those of small (or shallow) lakes (Figure 4c). This result is because large (or deep) lakes have greater heat storage than small (or shallow) lakes and need colder temperatures to freeze (Brown & Duguay, 2010; McFadden, 1965). The impacts of shoreline complexity were less important than those of size and depth (Figure 4c). These results further demonstrate the crucial role of morphometric characteristics in regulating lake freezing behavior (Brown & Duguay, 2010; Sharma et al., 2019; Walsh et al., 1998).

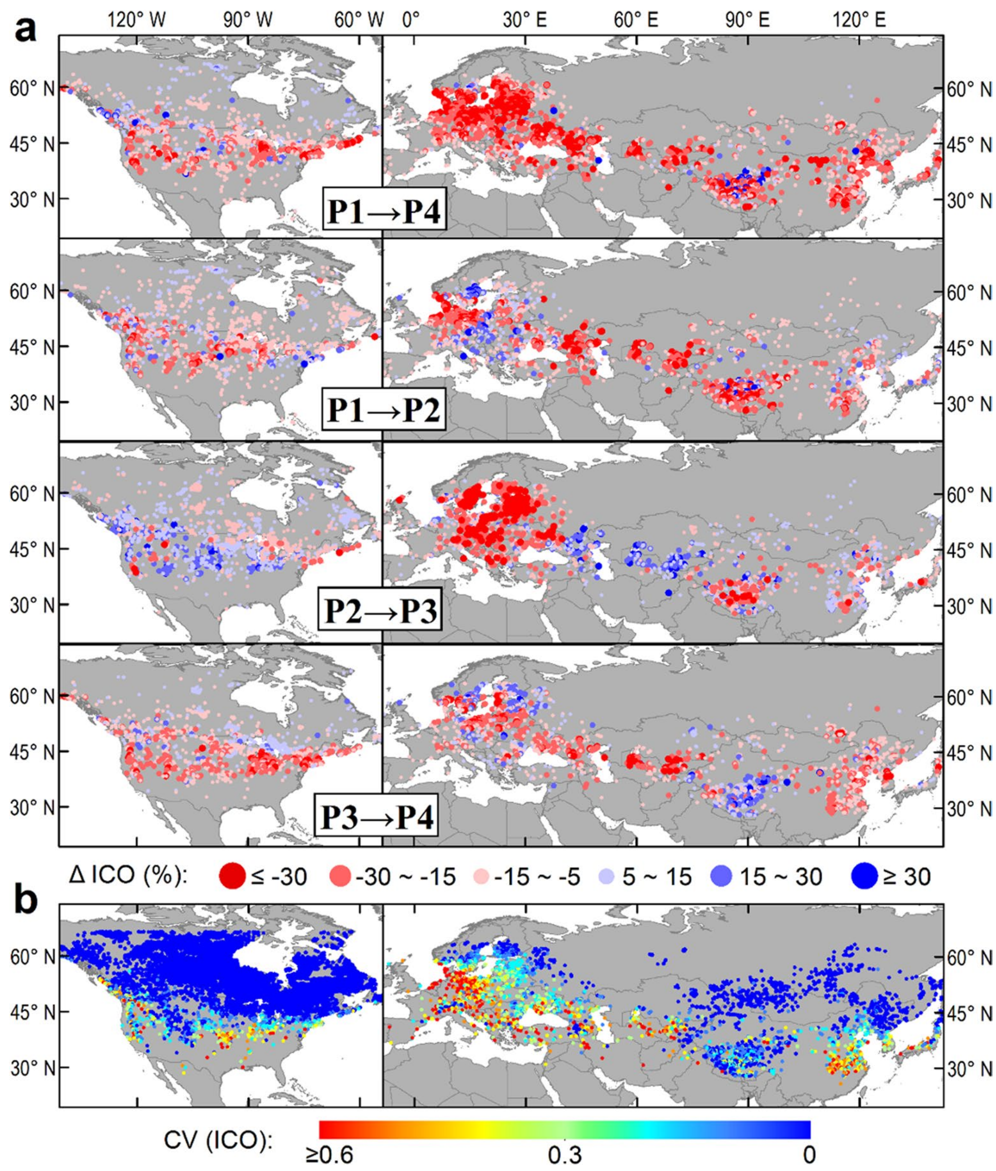

Figure 3. Long-term changes in ice cover occurrence (ICO). (a) Cross-period differences for ICO. A ΔICO value of −30% means that the probability of lake ice cover during the first quarter of the year has decreased by 30%. (b) Coefficient of variation (CV) of ICO between the 4-time periods.

4. Discussion and Conclusions

The freely accessible long-term Landsat observations allow us to exploit four decades of changes in ice cover frequency (ICO) throughout the North Temperate Zone. We acknowledge that a more comprehensive assessment of lake ice requires closer examinations of phenological indicators, including freeze/thaw dates, durations, and ICO values on an annual basis. However, such efforts are challenging by using Landsat observations alone, where the ice cover conditions may change considerably between subsequent observations (16 days apart), not to mention the potential contamination from cloud coverage. We conducted a sensitivity analysis using 10 time periods rather than four (Figure S8a), and the resulting ICO values were also highly correlated with surface temperatures (Figure S8b). Nevertheless, although other satellite missions (such as Moderate Resolution Spectroradiometer or MODIS and the Visible Infrared Imaging Radiometer Suite or VIIRS) provide much improved observational frequency (up to daily), their coarse spatial resolutions (hundreds or thousands of meters) make it difficult to map small lakes. Moreover, Landsat represents the

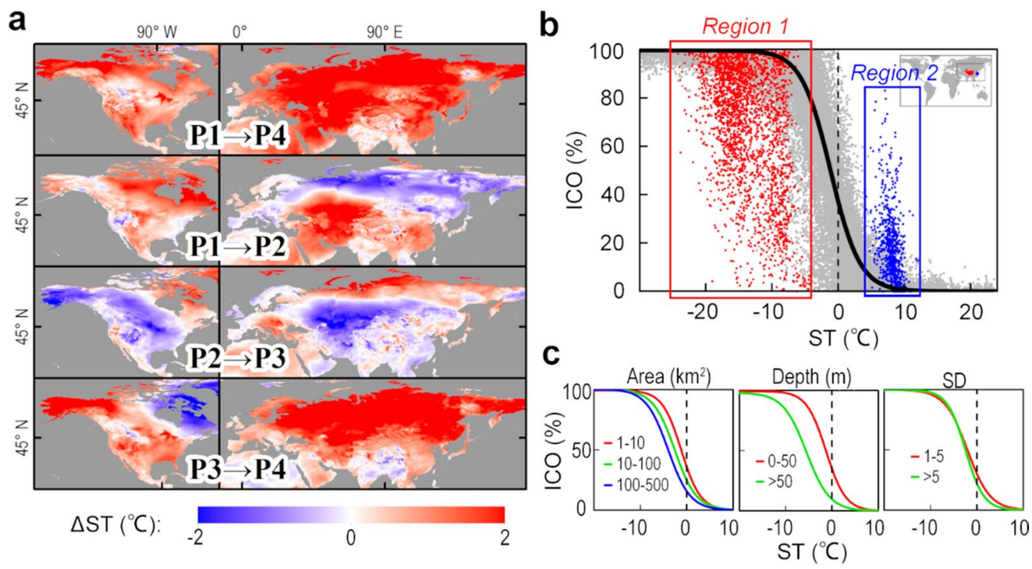

Figure 4. Impacts of temperature on ice cover occurrence (ICO). (a) Cross-period differences in surface temperature (ST). (b) Scatter plot between ICO and the corresponding mean surface temperature. Each point represents one lake in one of the four examined periods (P1–P4, so each lake is represented 4 times). Logistic regression (black line) was established using the gray points. Red and blue points represent lakes located in Region 1 (Tibetan Plateau, $n = 2{,}532$) and Region 2 (Yangtze Plain, $n = 656$), where exceptional lake conditions caused deviations from the global model (locations shown in the inset). (c) Logistic regression models established by partitioning lakes into different groups. The models for different sizes and depths were established with all gray points in (b), whereas the models for different shoreline complexities (represented using shoreline development or SD in (c)) were based on lakes with similar areas (20–50 km^2).

satellite observations with the longest global coverage, while the other missions are not available until circa 2000. Fortunately, with the rapid increases in moderate-resolution (tens of meters) satellite instruments (such as Sentinel satellites by the European Space Agency, Gaofen series of satellites launched by China), we expect that future lake ice phenology can be examined through both high spatial and high temporal satellite observations.

The gridded ERA5-Land temperature at the centroid of a lake was used to represent the temperature of the lake. However, the spatial resolution of ERA5-Land data sets is 0.1°, with a native resolution of 9 km (Sabater & Data, 2019). As such, the area of a cell grid size is ~81 km^2, which is larger than most examined lakes. Owing to the apparent temperature disparities between water and adjacent land, the extracted gridded temperature may not accurately represent the lake temperature. Such temperature mismatches can lead to uncertainties in the determined logistic correlations between ICO and temperature (Figures 4b and 4c), and the associated uncertainties may increase with decreasing lake size (larger land proportion within a grid). Future efforts are required to establish a global lake surface temperature data set, which can help to reduce such uncertainties and provide more accurate quantifications of the impacts of temperature on lake ice. Finally, dedicated efforts are required to develop numerical models to simulate past and future global lake ice patterns, with lake-specific models (especially for large lakes) to account for the complex dependences of lake ice on morphometric features and ambient human activities.

We revealed widespread lake ice loss throughout the North Temperate Zone using long-term high-resolution satellite observations, and further showed a strong relationship with global warming. Although lake ice loss has been identified through *in situ* measurements (Magnuson et al., 2000; Sharma et al., 2019), the number of lakes examined in this study (i.e., >33,000) is 2–3 orders of magnitude higher than previous studies. Indeed, the substantial disparities of lake ice at both temporal (four periods) and spatial scales (the entire North Temperate Zone) can only be revealed through long-term and continuous high-resolution satellite mapping. With ongoing climate warming, lakes in Europe, the central US, and central and southern Asia, regions where current surface temperatures hover around 0°C (Figure S7a), are expected to show pronounced ice retreats (or even permanent ice loss) in the near future.

Decreased ice cover can lead to alterations in the physical, chemical, and biological characteristics of lake ecosystems (Williamson et al., 2009). For example, reduced lake ice would result in decreases in surface albedo and prolonged exposure time of open water, both of which can directly lead to more energy absorption from solar radiation (Mironov et al., 2002; Stainsby et al., 2011). Indeed, changes in energy balance could not only cause lakes with less ice to warm further, but also lead to substantial enhancement in evaporation (up to 16% by 2,100 as predicted by Wang et al., 2018) and thereby contribute toward future drought events (Williams et al., 2020). Meanwhile, as the dominance of cyanobacteria has accelerated in the past ~200 years in the north temperate-subarctic lakes (Taranu et al., 2015), warming lake waters could increase the risks of harmful algal bloom, posing threats to both humans and aquatic ecosystems (Brooks et al., 2016). The unprecedented high-resolution mapping of lake ice here provides important baseline information to assess these ice loss-induced environmental and societal impacts and enhance our understanding of how global warming can affect the ecosystem services of lakes as a whole.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The Landsat data were provided by U.S. Geological Survey through Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog/landsat). The Global Lake and River Ice Phenology Database used to validate the satellite observations are available at National Snow and Ice Data Center (https://nsidc.org/data/G01377/versions/1). The HydroLAKES database was obtained from the website https://www.hydrosheds.org/page/hydrolakes. The Climatic Research Unit (CRU) temperature data was obtained from the University of East Anglia (via https://catalogue.ceda.ac.uk/uuid/89e1e34ec3554dc98594a5732622bce9), the Berkeley Earth Surface Temperatures (BEST) temperature data was from http://berkeleyearth.org/data/, and the ERA5-Land temperature data was from the Copernicus Climate Data Store (via https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=overview). The entire Landsat-derived ice cover occurrence data set in this study and the associated codes are available at https://figshare.com/projects/Lake_ice_mapping_across_the_North_Temperate_Zone/120306.

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