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Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL099022

Continuous Loss of Global Lake Ice Across Two Centuries Revealed by Satellite Observations and Numerical Modeling

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Key Points:

- We provide the first characterization of the changes in global lake ice phenology across two centuries (1900–2099) at lake level
- We examine >30,000 lakes across the Northern Hemisphere, accounting for 67% of the total area of frozen lakes globally
- We quantify the responses of global lake ice phenology to anthropogenic climate change over the past century

Supporting Information:

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

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Citation:

Wang, X., Feng, L., Qi, W., Cai, X., Zheng, Y., Gibson, L., et al. (2022). Continuous loss of global lake ice across two centuries revealed by satellite observations and numerical modeling. *Geophysical Research Letters*, *49*, e2022GL099022. https://doi.org/10.1029/2022GL099022

Received 4 APR 2022
Accepted 11 JUN 2022

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Funding acquisition: Lian Feng
Investigation: Xinchi Wang, Lian Feng
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Visualization: Xinchi Wang, Lian Feng
Writing – original draft: Xinchi Wang, Lian Feng
Writing – review & editing: Xinchi Wang, Lian Feng, Wei Qi, Xiaobin Cai, Yi Zheng, Luke Gibson, Jing Tang, Xiao-peng Song, Junguo Liu, Chunmiao Zheng, Brett A. Bryan

Abstract Lake ice loss has been detected worldwide due to recent climate warming, yet spatially and temporally detailed information on the changes in global ice phenology does not exist. Here, we build a global lake ice phenology database comprising three lake ice phenologies—freeze-up, break-up, and ice duration—for each year across two centuries (1900–2099). The timing of all three phenologies experienced mild but statistically significant warming trends in the 20th century; continued warming trends were detected in ~60% of the lakes from 2001 to 2020. Under a high emissions scenario (RCP 8.5), future global median ice duration would be shortened by 49.9 days by the end of the 21st century; such change can be substantially reduced under lower emission scenarios. We revealed continuous loss of global lake ice during the observed period, our generated database provides critical baseline information to evaluate the consequences of historical and future lake ice changes.

Plain Language Summary We provide the first spatially and temporally detailed quantification of the changes in global lake ice across two centuries (1900–2099). We found global lake ice changes toward later freeze-ups, earlier break-ups, or shorter ice durations over the past century, in response to global warming. Our projections revealed that continued lake ice loss would occur in the future, and the magnitude of changes increases with the increase in greenhouse gas emissions. Our analysis contributes the first comprehensive insight into how global lake ice changes over two centuries, and the data set provided here is critical for the evaluation of the consequences of historical and future lake ice changes.

1. Introduction

Lakes in the northern temperate and boreal regions are characterized by seasonal freezing and thawing cycles; these periodically frozen lakes account for ~50% of lakes globally (Verpoorter et al., 2014; Weyhenmeyer et al., 2011). The timing of lake ice events (also termed lake ice phenology) not only shapes the annual life cycle of all organisms in these lacustrine ecosystems (Christner et al., 2014; Hampton et al., 2017; Shuter et al., 2012), but also influences recreational and economic opportunities for human society (Brammer et al., 2015; Knoll et al., 2019; Prowse et al., 2011). For example, the timing of ice break-up in spring constitutes a major factor toward algal growth (Blenckner et al., 2007; Gronchi et al., 2021) by modulating the underwater light intensity and temperature (Berger et al., 2010; O'Reilly et al., 2015; Post et al., 2013). In addition, the duration of ice-covered seasons affects millions of people, for example, by influencing key transport routes and ice fishing in high-latitude lakes (Knoll et al., 2019; Prowse et al., 2011).

Lake ice phenology consists of three essential indicators: freeze-up, break-up, and ice duration (Brown & Duguay, 2010; Kirillin et al., 2012; Sharma et al., 2020). Freeze-up is defined as the first day of a year when the lake is completely frozen, break-up represents the last day on which ice is present before summer, and ice duration is the length between the two (Magnuson et al., 2000). For religious or cultural purposes, ice phenologies have been recorded for hundreds of years or even millennia for some lakes (B. Benson et al., 2020; Magnuson et al., 2000), which allows the tracking of long-term trends. For example, ~150-year data records from a few dozen lakes have been successfully used to identify shifts in lake ice phenologies (i.e., trends toward later freeze-ups, earlier break-ups, and shorter durations) and their accelerated rates of change in recent decades (B. J.

Benson et al., 2012; Korhonen, 2006; Magnuson et al., 2000; Sharma et al., 2021). Unfortunately, this problem is expected to worsen in the future due to the ongoing increase in global temperature and extreme climate events (Filazzola et al., 2020; Grant et al., 2021; Sherwood et al., 2020). A more comprehensive understanding of global lake ice phenology (GLIP) would help to identify patterns and predict consequences toward the lacustrine environment and human society.

Evaluating changes in lake ice phenology at global or continental scales with currently available field surveys is challenging. For example, although the recently updated National Snow and Ice Data Center database contains in situ data of ~700 lakes (B. Benson et al., 2020), long-term continuous records are available for only a few lakes with limited spatial coverage (72% of which are distributed in North America). These sporadic field measurements represent a major limitation for developing a generic thermodynamic model to simulate GLIP. In particular, in addition to the prevailing air temperature, ice formation is strongly dependent on lake heat storage (often related to water depth) (Brown & Duguay, 2010; Kirillin et al., 2012; X. Wang et al., 2021), and heat transportation processes are lake specific (B. J. Benson et al., 2012; Walsh et al., 1998; Weyhenmeyer et al., 2011). Satellite observations provide an alternative to characterize GLIP and their changes (Cai et al., 2019; Kouraev et al., 2007); however, spatially and temporally detailed information on the changes in ice phenology on a global scale does not exist. Here, we attempt to fill this gap by building a GLIP database and providing a lake-level quantification of the changes in global lake ice phenology over two centuries (i.e., 1900–2099).

2. Methods

2.1. Methods to Determine Lake Ice Phenologies Using Remote Sensing and Numerical Model

We developed a dual logistic regression model (DLRM) to determine the ice phenologies for each lake, based on the daily time series of 500-m resolution MODIS/Terra level-3 snow cover products (MOD10A1 (Riggs et al., 2015)), within a year (Figure 1a). The formalization of the DLRM combined two logistic regression models, which characterized the ice formation and melting processes; and the snow cover for each MOD10A1 image was weighted by the fraction of cloud-free observations within a lake when performing logistic regression, which is used to reduce the impacts of cloud contamination (see details in Supporting Information S1). Validation showed that the MODIS detected lake phenological indicators agreed well with both field records from the Global Lake and River Ice Phenology Database (GLRIPD, version 1) (B. Benson et al., 2020) and 10-m resolution satellite observations from Sentinel Sentinel MultiSpectral Instrument (MSI) (Figure S1 in Supporting Information S1). We found that the relatively larger discrepancies between in situ and satellite freeze-up values could have resulted from their inconsistent definition of the lakes or inaccurate geographical information of in situ data, rather than uncertainties in our dual logistic regression model (see Text S1 in Supporting Information S1). We created a time-series of freeze-up dates, break-up dates, and ice durations using daily MOD10A1 products between 2001 and 2020 (hereafter referred to as the "present period") (Figures 2a–2c).

To examine the lake ice changes over the past (i.e., 1900–1999) and future (i.e., 2021–2099) periods, we established numerical models to simulate ice phenologies (Figure 1b, see details in Text S1 in Supporting Information S1). Ice formation and melting of lakes are not only dependent on temperature, but also modulated by their depths, heat flux from bottom sediments, and warmer inflowing runoff (Bengtsson, 1996; Nõges & Nõges, 2014; Terzhevik et al., 2009). The impacts of these features are difficult to characterize (Brown & Duguay, 2010; Bueche et al., 2017; Walsh et al., 1998), which is a major limitation for developing a generic model to simulate lake ice phenology across the entire globe. Here, we established simulation models for individual lakes, assuming that the changes in the timing of freeze-up/break-up for the same lake should be related only to the preceding temperatures when lake-specific features remain unchanged (see details in Supporting Information S1). The key parameters in the model are the required temperature for freeze-up (or break-up), and the length of the preceding period that falls below (or above) the required temperatures. Indeed, the 20-year satellite-detected global lake ice phenologies and the availability of the ERA5-Land daily mean air temperature data sets (Sabater & Data, 2019) allow us to calibrate the model parameters for tens of thousands of lakes worldwide (see details in Supporting Information S1). The past and future air temperature data sets from four climate models (i.e., HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR, and MIROC5) were used to simulate the corresponding lake ice phenologies (Frieler et al., 2017). These projected temperature data sets were bias-corrected and are available from the Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b) (data set link: https://www.isimip.org/gettingstarted/details/27/). Our results also showed that the lake-specific model performed well

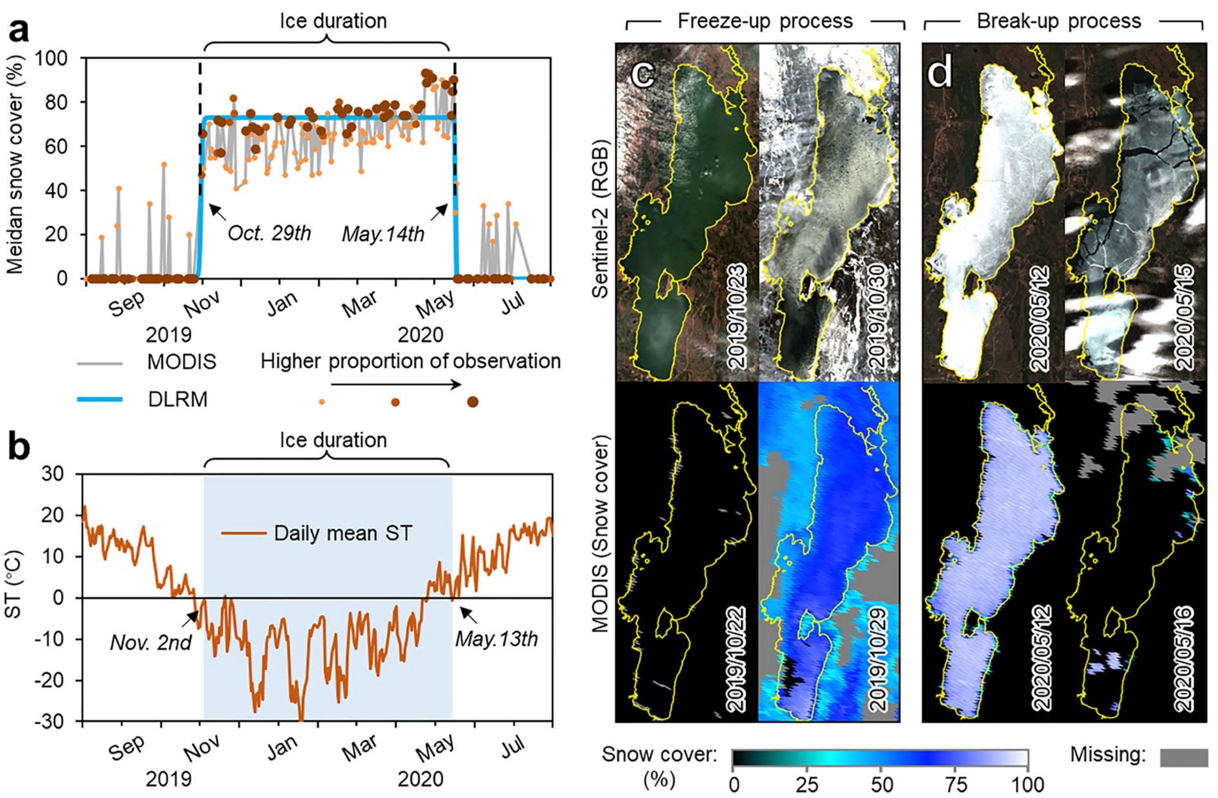

Figure 1. Example showing lake ice phenologies determined using satellite observations and numerical models. (a) Example of how the dual logistic regression model (DLRM) was used to identify the freeze-up date, break-up date, and ice duration using satellite observations. Annual time series of MODIS snow cover fraction within Montreal Lake, Canada, with larger points representing more valid satellite observations and thus greater weight in the dual logistic regression (see Text S1 in Supporting Information S1). The freeze-up and break-up dates were determined as 29 October and 14 May 14, respectively. (b) Simulated lake ice phenologies determined using the lake-specific models and daily mean surface temperatures (ST), which are 2 November and 13 May for freeze-up and break-up, respectively. (c) The freeze-up process for Montreal Lake observed using 10-m resolution Sentinel MultiSpectral Instrument (MSI) images (RGB true color) and 500-m resolution MODIS snow cover products. (d) Same as (c), but for the break-up process. MSI images show that the freeze-up and break-up dates were around 30 October and 15 May, which agreed well with the results determined by the dual logistic regression in (a) and numerical model in (b).

at reproducing the freeze-up and break-up dates using temperature data sets (Figure S6 in Supporting Information S1), as gauged by both in situ measurements and satellite observations. We further compared the performance of our model with the generic lake ice phenology model developed by Weyhenmeyer et al. (2011). The Weyhenmeyer model was calibrated using data sets from Swedish lakes, with air temperature and solar radiation (represented using latitude) as the model inputs. The simulations using our lake-specific models showed better agreement (Figures S6g–S6i in Supporting Information S1), underscoring the importance of incorporating lake-specific features in lake ice simulation models.

2.2. Establishing a GLIP Database

We built a GLIP database comprising global lake ice phenologies derived from satellite observations (i.e., present period) and temperature-based simulations (i.e., past and future periods).

We first determined the number of lakes that are included in the GLIP database. Using the HydroLAKES database (Messager et al., 2016), we selected lakes with a surface area of >1 km^2 and north of 23.5°N, resulting in a total number of 165,679 lakes. The masks for permanent water and the minimum valid observations (>3 valid MODIS image pixels are available within the lake) were applied, which reduced the number of lakes to 74,245 (i.e., the number of lakes with MODIS observations in the present period). We generated a permanent water mask using the Global Surface Water Occurrence (GSWO) data set (Pekel et al., 2016) for each lake, with a threshold of >95% (i.e., more than 95% of Landsat observations between 1984 and 2019 were classified as water). Then, to ensure sufficient lake ice phenologies in establishing lake-specific models, we excluded lakes with fewer than

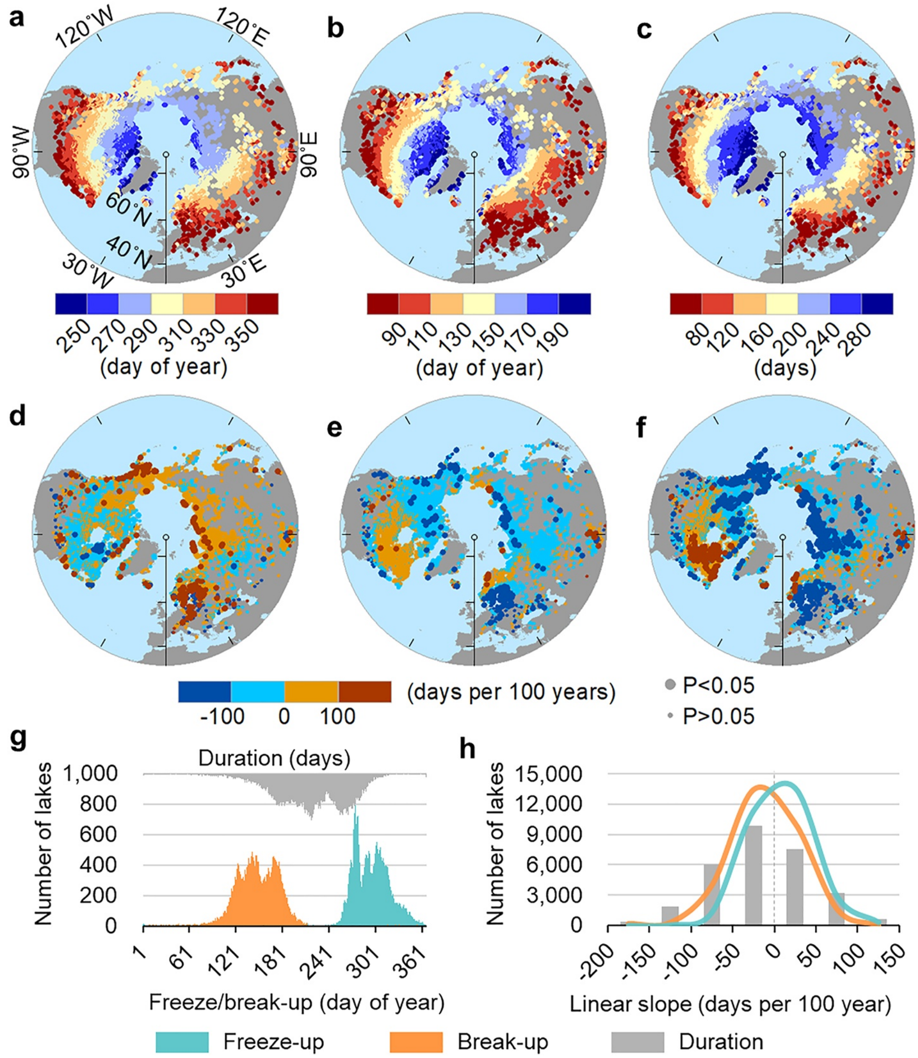

Figure 2. Lake ice phenologies detected using MODIS satellite images between 2001 and 2020 (a–c) Median values of the freeze-up date, break-up date, and ice duration for each of the 30,063 examined lakes during the 20 years studied. Note that the data are presented as day of year (DOY) (d–f) The associated linear trends (i.e., linear regression slope) and significance in freeze-up date, break-up date, and ice duration are shown in the middle panels, with statistically significant ($P < 0.05$) trends shown using larger dots. Each dot in a–f represents a lake. (g) Histogram distributions for a–c. (h) Histogram distributions for d–f.

ten ice-free years in the present period (i.e., 2001–2020); we further ensured similar preceding temperatures for freeze-up/break-up events across different years for the same lake (i.e., standard deviation of the preceding temperatures within the present period was <2°C, see details in Supplementary Materials), with the underlying assumption that the freeze-up/break-up of the same lake requires similar temperature conditions across different years. These criteria resulted in a total of 30,063 lakes across the Northern Hemisphere, where most of the lakes in the world are located (Verpoorter et al., 2014), accounting for 67.0% of the total area of global frozen lakes; a frozen lake is defined here as having more than ten ice-covered years in the present period from satellite observations.

We applied the dual logistic regression model to each of the 30,063 selected lakes and determined the freeze-up, break-up, and ice duration for each year during the present period (Figure 2). Then, we developed ice phenology simulation models for these lakes. For each lake, we used daily mean temperature data sets from four different climate models (i.e., HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR, and MIROC5) to simulate past and future lake ice phenologies for each year during the past and future periods, and the corresponding mean values

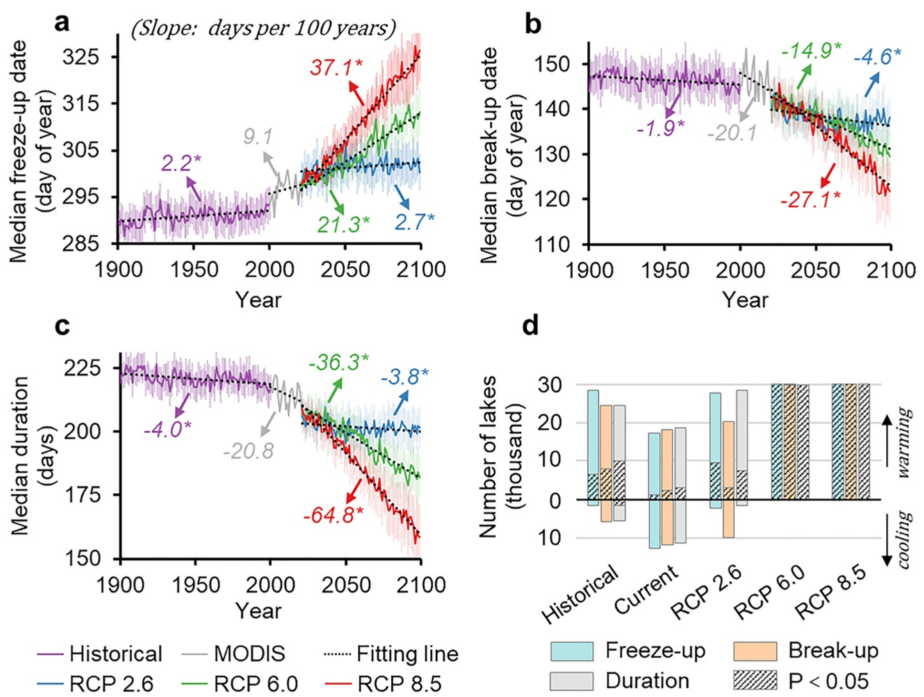

Figure 3. Past, present, and future trends of lake ice phenologies. (a–c) Linear slopes (i.e., rates of change) of the median values of freeze-up, break-up, and ice duration for global lakes. The slope values and their significance levels (student's *t-test*) for three periods are annotated within the panels. The data of the present period are from MODIS satellite observations; past and future data were simulated based on air temperature. The shaded areas associated with the past and future median values of each year represent standard deviations of the simulations from temperatures projected by four climate models. (d) The number of lakes with warming and cooling trends for different lake ice phenologies in the three periods, hatched shades represent significant trends.

were used to represent the ice conditions for a given lake. Furthermore, we conducted similar future simulations under three different anthropogenic greenhouse gas emission scenarios: the Representative Concentration Pathway (RCP) 2.6 (low-emissions), RCP 6.0 (medium-emissions), and RCP 8.5 (high-emissions); for each RCP, air temperatures simulated by the above four climate models were used to predict lake ice phenologies, we used the corresponding mean values in our GLIP database.

2.3. Assessment of Changes in Global Lake Ice Phenology Over Two Centuries

We calculated the trends for three lake ice phenologies of each lake over the past, present, and future periods (Figures 2 and 3d); the trends were represented as the slopes of the linear regressions for the lake ice phenologies, and the significance of the slope was examined using a student's *t-test*. We further estimated the annual median values of the three lake ice phenologies for all the examined lakes, and the associate trends (i.e., linear slope) of these annual median values were used to represent the globally averaged trends (Figures 3a–3c).

We compared the lake ice phenologies in the past and future periods to those in the present period, with the difference represented as the anomalies of the median values in 1900–1919 (i.e., the beginning of the past period) and 2080–2099 (i.e., the end of the future period) with respect to that in the present period (i.e., 2001–2020) (Figure 4). We did not perform anomaly calculations for ice-free lakes; we considered a lake to be ice-free when more than 15 of the 20 (i.e., >75%) examined years had no recorded ice (Figure 4).

3. Results

3.1. Present Changes and Their Linkages With Air Temperature

For the present period, all three lake ice phenologies detected from satellite observations showed pronounced latitudinal gradients (Figure 2). European lakes show less ice (later freeze-ups, earlier break-ups, and shorter ice

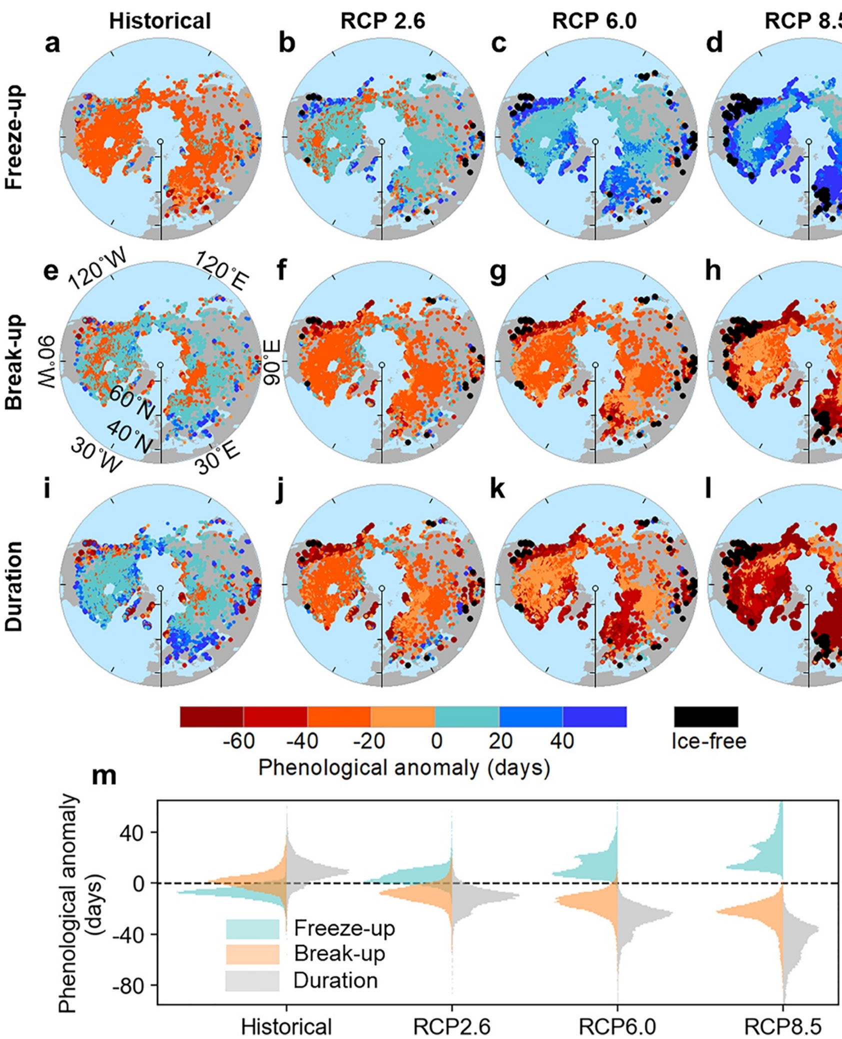

Figure 4. Past and future changes in lake ice phenologies. (a, e, i) Past period, (b, f, j) RCP 2.6, (c, g, k) RCP 6.0, and (d, h, l) RCP 8.5. The upper, middle, and bottom panels are the freeze-up, break-up, and ice duration, respectively. The changes were estimated as the anomalies of the model-simulated historical (i.e., 1900–1919) and future (i.e., 2080–2099) median values with respect to satellite-observed median values between 2001 and 2020 (see Text S1 in Supporting Information S1). Warming induced ice-free lakes are indicated using black dots. (m) Histograms of past and future changes for all lakes.

durations) than other lakes at similar latitudes (such as eastern North America), due to higher temperatures associated with the warming effects of the North Atlantic Current in winter (Rossby, 1996). The 2001–2020 median freeze-up date for all the examined lakes in the Northern Hemisphere (subsequently referred to as "global") was 22 October (i.e., day of year [DOY] 294.5), the median break-up date was 27 May 27 (i.e., DOY 146.5), and the median ice duration was 217.5 days (Figure 2g, Table S1 in Supporting Information S1).

Linear trend analysis over each lake revealed substantial spatial heterogeneity of lake ice phenologies from 2001 to 2020. Statistically significant warming trends (i.e., changes toward later freeze-ups, earlier break-ups, or shorter ice durations, $P < 0.05$) were identified mainly in Eurasia and northwestern North America; statistically significant cooling trends (i.e., changes toward earlier freeze-ups, later break-ups, or longer ice durations, $P < 0.05$) were detected primarily in northeastern North America. The number of lakes with a significantly shortened ice duration ($n = 2{,}853$, or 9.5%) was 7.7-fold greater than the number of lake with a significantly prolonged ice duration ($n = 372$, or 1.2%) during the 20-year present period. Globally, the trend for ice duration mirrored that of the break-up, in terms of both the spatial and histogram distributions (Figures 2e, 2f and 2h).

The distributions of lake ice trends between 2001 and 2020 demonstrated spatial agreements with the patterns in air temperature. For example, the earlier freeze-ups in lakes in northeastern North America were attributed to decreased air temperatures in October and November, the period of freeze-ups in these lakes (see Figures 2d–2f and Figure S7 in Supporting Information S1). Likewise, the significantly earlier break-ups in European lakes resulted from the evident temperature increase at their median break-up dates. Furthermore, the changing rates of freeze-up and break-up were significantly correlated with the changing rates of the temperatures in the preceding 15-day period ($P < 0.01$, *t-test*) (Figure S8 in Supporting Information S1), highlighting the validity of reproducing lake ice phenology using only air temperature.

3.2. Past and Future Trends

In the 20th century, global simulations showed that lake ice experienced mild but statistically significant warming trends for all three lake ice phenologies (+2.2 days/100 years for freeze-up, −1.9 days/100 years for break-up, and −4.0 days/100 years for ice duration) (Figures 3a–3c); All these global values in the 20th century differed significantly from those between from 2001 to 2020 (matched pair *t-test*, $P < 0.05$). However, as seen during the present period, changes during the past century can also be site-specific. We found 1,814 or 6.0% of the global lakes showed significantly increased ice duration. For example, lakes with earlier freeze-up and later break-up were detected in the Rocky Mountains, the Tibetan Plateau, and Greenland, resulting in large negative anomalies in ice duration (<−40 days, Figure 4; we define anomaly as a deviation from the present period); such sporadic lake ice increases were due to the regional decreases in air temperatures in these regions (X. Wang et al., 2021).

For the 21st century, we found that the magnitude of future changes in lake ice phenology increases with the severity of the RCP. Under RCP 8.5, the future rates of change for freeze-up and break-up are projected to increase by a rate more than an order of magnitude greater compared to those observed in the 20th century. As a result, we expect a global median loss of 49.9 days by the end of the 21st century (specifically referring to the average value over 2080–2099) (Figure 4, Table S1 in Supporting Information S1). Moreover, 160 (0.5%) of the examined lakes show permanent ice loss, occurring primarily in lakes located at low latitudes (Figure 4); this fraction is similar to the projection by Sharma et al. (2019), who estimated that 5,796 of the 1.3 million lakes (0.4%) will show permanent ice loss by 2100.

Under RCP 6.0, significant warming was projected to occur in almost all lakes, although the trends were markedly lower than those observed under RCP 8.5 (Figure 3). Under this scenario, the break-up trend decelerated from −27.1 to −14.9 days/100 years ($P < 0.05$), and the freeze-up changed from +37.1 to +21.3 days/100 years ($P < 0.05$). By the end of the 21st century, the associated global median shifts will be approximately half a month for freeze-up (14.6 days) and break-up (−15.9 days), leading to an ice duration anomaly of −33.1 days (Table S1 in Supporting Information S1).

Under RCP 2.6, although significant warming would still be observed for all lake ice phenologies, the rate of change will remain relatively low, similar to those seen in the 20th century. As a result, the global median ice duration anomaly would be −17.9 days by the end of the 21st century, and the number of increased permanent ice-free lakes would decrease from 49 under RCP 6.0 to 19 under RCP 2.6.

4. Discussions and Conclusions

One of the immediate impacts of lake ice change is the absorption of solar radiation, owing to discernible differences in albedo between water and ice (Mironov et al., 2002; Stainsby et al., 2011). The excessive absorption of solar energy associated with ice loss could heat the water column and amplify lake warming (Serreze & Barry, 2011), leading to higher warming rates in ice-covered than in ice-free lakes (O'Reilly et al., 2015). Several other vital ecological consequences are also associated with these projected changes in future lake ice phenology. For example, the lake mixing regime could be altered due to the combined effects of a shortened ice-cover period and warmer lake water (Woolway et al., 2020; Woolway & Merchant, 2019); one potential problem is that extended summer stratification could result in greater risks of oxygen depletion at the bottom of eutrophied lakes (Paerl & Huisman, 2008; Smucker et al., 2021). The shortened ice-covered season and higher air temperature could enhance lake surface evaporation (by up to 16%, as projected by W. Wang et al. (2018)), triggering more drought events (Williams et al., 2020). Furthermore, future alterations of the freezing cycle could potentially shift the ecological regimes when climate-related thresholds are exceeded (Dahlke et al., 2020; Shuter et al., 2012;

Smol et al., 2005), threatening freshwater biodiversity (Barbarossa et al., 2021), and causing fish die-offs (Till et al., 2019). Indeed, our GLIP database provides critical baseline information to assess these consequences of historical and future lake ice dynamics. For example, a previous prediction showed that 656 million people across 50 countries could be affected by future lake ice loss (Sharma et al., 2019). Our detailed ice phenology data for individual lakes can be potentially used to quantify the associated cultural and socioeconomic impacts. Overall, our analysis contributes the first comprehensive insight into how future global lake ice phenology changes might be mitigated through greenhouse gas emission control, further underscoring the critical nature of reducing emissions and limiting climate change to well under 2°C as per the Paris agreement.

Conflict of Interest

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

Data Availability Statement

The MODIS level-3 snow cover products (MOD10A1, Collection 6) are available through Google Earth Engine (data set link: https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD10A1), 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 ERA5-Land air temperature data sets were obtained from https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_HOURLY, and the projected temperature data sets are available from the Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b) (data set link: https://www.isimip.org/gettingstarted/details/27/). The entire global lake ice phenology (GLIP) data set generated in this study is available here: https://doi.org/10.6084/m9.figshare.19424801.

Acknowledgments
The authors thank Google Earth Engine for providing global-scale data sets and processing power. The authors thank two anonymous reviewers for their valuable comments to improve our manuscript. The National Natural Science Foundation of China (Grant no: 41971304), the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA20060402), Shenzhen Science and Technology Innovation Committee (No.JCYJ20190809155205559), Stable Support Plan Program of Shenzhen Natural Science Fund (No. 20200925155151006),and Shenzhen Science and Technology Program (No. KCXFZ20201221173007020)

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