water

Review

Seasonal Variations of Ice-Covered Lake Ecosystems in the Context of Climate Warming: A Review

Qianqian Wang [1], Fang Yang [1,*], Haiqing Liao [1,*], Weiying Feng [2], Meichen Ji [1], Zhiming Han [3], Ting Pan [1] and Dongxia Feng [1]

[1] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China; wangqianqian221@outlook.com (Q.W.); ji.meichen@craes.org.cn (M.J.); panting_2021@sina.com (T.P.); fengdx@craes.org.cn (D.F.)

[2] School of Materials Science and Engineering, Beihang University, Beijing 100191, China; fengweiying@buaa.edu.cn

[3] College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China; m15029258074@163.com

* Correspondence: yang.fang@craes.org.cn (F.Y.); liaohq@craes.org.cn (H.L.)

Abstract: The period of freezing is an important phenological characteristic of lakes in the Northern Hemisphere, exhibiting higher sensitivity to regional climate changes and aiding in the detection of Earth's response to climate change. This review systematically examines 1141 articles on seasonal frozen lakes from 1991 to 2021, aiming to understand the seasonal variations and control conditions of ice-covered lakes. For the former, we discussed the physical structure and growth characteristics of seasonal ice cover, changes in water environmental conditions and primary production, accumulation and transformation of CO_2 beneath the ice, and the role of winter lakes as carbon sources or sinks. We also proposed a concept of structural stratification based on the differences in physical properties of ice and solute content. The latter provided an overview of the ice-covered period (-1.2 d decade^{-1}), lake evaporation (+16% by the end of the 21st century), the response of planktonic organisms (earlier spring blooming: 2.17 d year^{-1}) to global climate change, the impact of greenhouse gas emissions on ice-free events, and the influence of individual characteristics such as depth, latitude, and elevation on the seasonal frozen lakes. Finally, future research directions for seasonally ice-covered lakes are discussed. Considering the limited and less systematic research conducted so far, this study aims to use bibliometric methods to synthesize and describe the trends and main research points of seasonal ice-covered lakes so as to lay an important foundation for scholars in this field to better understand the existing research progress and explore future research directions.

Keywords: ice-covered lakes; seasonal variability; climate change; bibliometrics

check for updates

Citation: Wang, Q.; Yang, F.; Liao, H.; Feng, W.; Ji, M.; Han, Z.; Pan, T.; Feng, D. Seasonal Variations of Ice-Covered Lake Ecosystems in the Context of Climate Warming: A Review. *Water* **2024**, *16*, 2727. https://doi.org/10.3390/w16192727

Academic Editors: Qiting Zuo, Fuqiang Wang, Jiaqi Zhai, Xiuyu Zhang, Dunxian She, Lei Zou, Rong Gan and Zengliang Luo

Received: 28 August 2024
Revised: 19 September 2024
Accepted: 23 September 2024
Published: 25 September 2024

1. Introduction

The ice-covered period is a significant phenological characteristic of Northern Hemisphere lakes, with nearly 50% of the 117 million lakes larger than 0.002 km^2 worldwide regularly freezing over. Seasonal ice cover exists in 14,800 lakes larger than 0.1 km^2 in the Northern Hemisphere [1,2], particularly in the mid-to-high latitudes (30–70° N) [3]. Lakes above 50° N in North America and Asia experience frequent ice cover occurrence (ICO = 100%). Within the latitude range of 50–60° N, the ICO values are almost twice as high as those in European lakes [4]. Under similar latitude conditions, seasonal lake ice is more common in high-altitude regions such as the Qinghai-Tibet Plateau (>4000 m, Asia) and the Rocky Mountains (>2700 m, North America) [3,5,6]. In the southern hemisphere (excluding Antarctica), lake ice cover occurs only at the southern end of the Andes. The lakes in this region have only thin ice cover and short ice duration, and the lake ice is continuing to shrink. By the end of the 21st century, the vast majority of lakes in the region will be virtually ice-free [7].

Seasonally frozen lakes respond uniquely to climate change, such as ice-on/off date, ice duration and spring blooms, and seasonal CO_2 flux [4,8,9], as highly sensitive indicators of regional watershed changes to detect the Earth's response to climate change to some extents [10]. Specifically, variations in lake morphology [11], geographical location [12], and local climatic factors [13] result in significant differences in ice duration, freeze-thaw processes, ice thickness, and spatial coverage in seasonally ice-covered lakes. These differences affect the nutrient status, material cycling, dominant species succession, and ecological conditions within the lakes [6,14,15]. During the frozen period, the trophic status of most lakes is regulated by the solute exclusion processes of ice and sediments [16,17]. Moreover, the CO_2 flux during freeze-thaw events is noteworthy, occasionally surpassing that of other seasons (Buffalo Pound Lake [18]: spring flux contribution: 64% ± 20%; summer: 43.6%; autumn: 23.3%). Ice phenology has social impacts. The centuries-long records of ice phenology indirectly indicate the social impacts of northern lake ice on human activities and livelihoods. Indigenous communities in northern Canada rely on ice cover for supplies and social interactions [19]. Ice fishing and skating competitions held on lake ice in the United States and Europe promote the development of local infrastructure and winter tourism [20]. Religious practices and ceremonies related to ice phenology are also observed in certain communities. In Japan, Shinto practitioners living near Lake Suwa have been recording ice phenology since 1443 and hold religious purification ceremonies in ice duration [21].

Traditional understanding and practical conditions have historically hindered the study of winter ice-covered lakes [10,22]. Due to the low water temperature and insufficient photosynthetically active radiation (PAR) during the frozen period, it was mistakenly believed that the metabolic and biological activities within the lakes were stagnant, leading to the perception of limited research value [17]. Previous studies on water environmental research and flux estimation often excluded the ice-covered period due to site selection and equipment limitations. However, it is now recognized that lake metabolism continues during the freezing period, with processes such as carbon cycling and nutrient accumulation sometimes exceeding those of the non-ice period. In Qinghai Lake [8], ice season draws large amounts of CO_2 from the atmosphere (-0.87 ± 0.38 g C m^{-2} d^{-1}), more than twice the CO_2 flux rate during the ice-free period (-0.41 ± 0.35 g C m^{-2} d^{-1}). In Lake Uliansuhai, the nutrient concentration ratio between the open water and the ice season was 5–10. TDS was 1050–2270 mg L^{-1} in summer and 2430–5230 mg L^{-1} in winter; TN was about 2 mg L^{-1} in summer and increased to 9 mg L^{-1} in winter [16]. There are still unexplained phenomena and unresolved issues in research on seasonally ice-covered lakes, including the specific mechanisms and processes of carbon sources and sinks in brackish lakes [8,14], the specific categories of solutes excluded and absorbed by lake ice [16,23], and the responsiveness of these lakes to climate change [24,25].

Despite extensive research by scholars from various countries, represented by Matti Leppäranta, Stephanie E. Hampton, Sapna Sharma, Blaize A. Denfeld et al. However, Hampton [26] stated in Eos Special Reports, "Although basic understanding about winter limnology has increased in the past decade, the pace of scientific progress has not kept pace with rates of ecological change". The research on ice season is relatively limited and scattered compared to the non-ice period. Therefore, we use the Web of Science Core Collection (WOSCC) as the data source and make a bibliometric analysis of internationally published literature related to seasonal freezing lakes. This study provides a comprehensive overview of research progress, highlighting hotspots and trends in this field, and aims to guide future global research on the environmental aspects of seasonally ice-covered lakes.

2. Research History and Frontier Hotspots of Seasonal Ice-Covered Lakes during 1991–2021

We searched the articles of the Web of Science Core Collection (WOSCC) database from 1991 to 2021, using the following search item: TS = ((lake OR reservoir) NOT (*glacial OR permafrost)) AND TS = (ice OR frozen OR freezing) AND TS = (seasonal). The total number of publications found was 1141. Overall, the number of papers on seasonal ice-covered lake research has been increasing year by year; the growth rate is significantly higher from 2011 to 2021 compared to 1991 to 2010 (Figure 1).

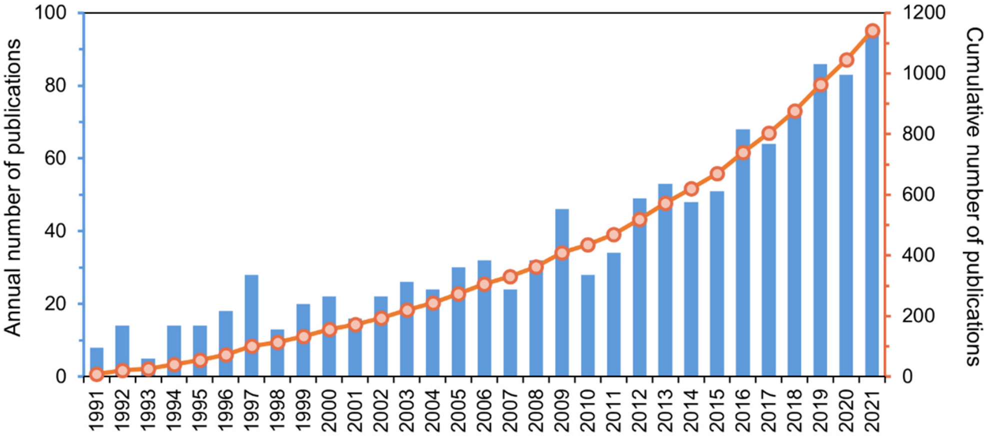

Figure 1. The annual publication volume and cumulative publication volume. A large amount of basic research found seasonal variations in the nutrient status and the dominance of planktonic species in the early stage of research (1991–1998). Starting from 1999, the impact of climate change on the water environment of seasonally frozen lakes has gradually attracted attention.

According to the statistics on the research locations of seasonally ice-covered lakes (Figure 2), 21 major research lakes are concentrated in North America (Lawrence Great Lakes), Europe (Lake Vanajanselkä, Lake Tovel), and China (Lake Uliansuhai, Lake Qinghai) between 30 and 70° N, consistent with the findings of Denfeld (2018). These studies have been conducted in 59 countries. The United States, Canada, and China are the top three countries contributing to publications, accounting for a total publication percentage of 67.69% by 2021 (Table S1). Among the 1285 institutions worldwide that focus on research in this field, the top three institutions with the most publications are the Chinese Academy of Sciences (75 papers), the Russian Academy of Sciences (55 papers), and the University of Helsinki in Finland (36 papers).

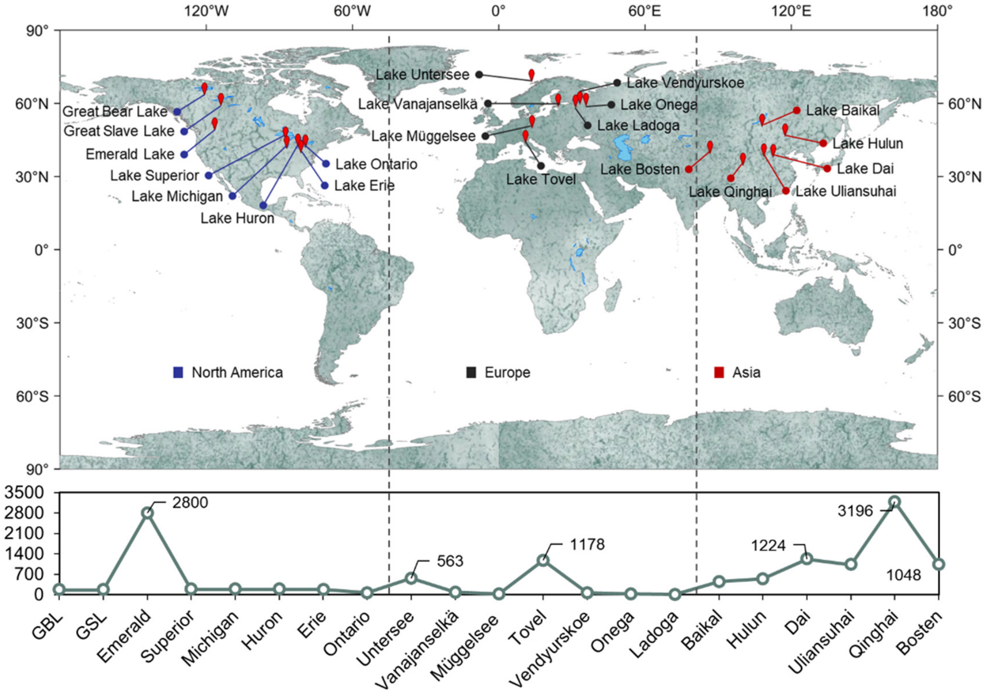

Figure 2. Major seasonally ice-covered lakes (N = 21) and their elevation.

Over the past few years, interdisciplinary studies in physics, chemistry, biology, and geology have intensified the environmental field of seasonally frozen lakes, leading to expanded study areas. This has made research in this field more comprehensive and specific. Under the background of climate warming, an in-depth study on the response of seasonally ice-covered lakes to climate change, combined with large-scale spatial and temporal data, has also promoted cooperation among research countries and institutions [4,11,27]. The exchange and cooperation between countries and institutions show different patterns (Figures S1 and S2). Perhaps the seasonally frozen lakes in Europe are mostly mountain lakes at high altitudes and high latitudes, and European countries tend to cooperate more internally, and the lakes are characterized by certain regional similarities [28].

The links between articles were analyzed by VOSviewer to identify the top 10 keywords as “climate change”, “sediments”, “lake”, “temperature”, “seasonality”, “variability” and “climate change”, “temperature”, “seasonality”, “variability”, “phytoplankton”, “water”, “climate”, “dynamics” (Figure 3). This implies the research focuses on the seasonal dynamics of sediments and water environment (nutrients and phytoplankton) during the ice period and the response of frozen lakes to climate change. This study also investigates the impact of “carbon” and “CO$_2$” in light of growing concerns about carbon emissions. The average appearance time (keyword link intensity) of these two topics in the four phases (Figure 4) indicates a continuous increase in attention toward “carbon” and “CO$_2$”, with respective values of 1995.33 (27), 2002.00 (21), 2010.27 (28), 2017.75 (91) and 1997.67 (25), 2001.80 (10), 2010.00 (19), 2018.38 (57).

The visual analysis of keyword activity (Figure 4) describes the research history of seasonally ice-covered lakes. Due to the continuous innovation of techniques and methods, research has evolved from the evolution of the dominant phytoplankton species [29,30] to the diversity of phytoplankton and planktonic microorganisms and their biological effects in winter [31]. It has also shifted from the dynamic changes in water substances [16,32,33] to the seasonal material cycle in the lake ecosystems [8,14,34]. This reveals a transition of indicators from single-factor to multi-factor research in the field of seasonally ice-covered lake water environments and an expansion of research content from the water environment to the integrated study of “hydrology” and “climate”.

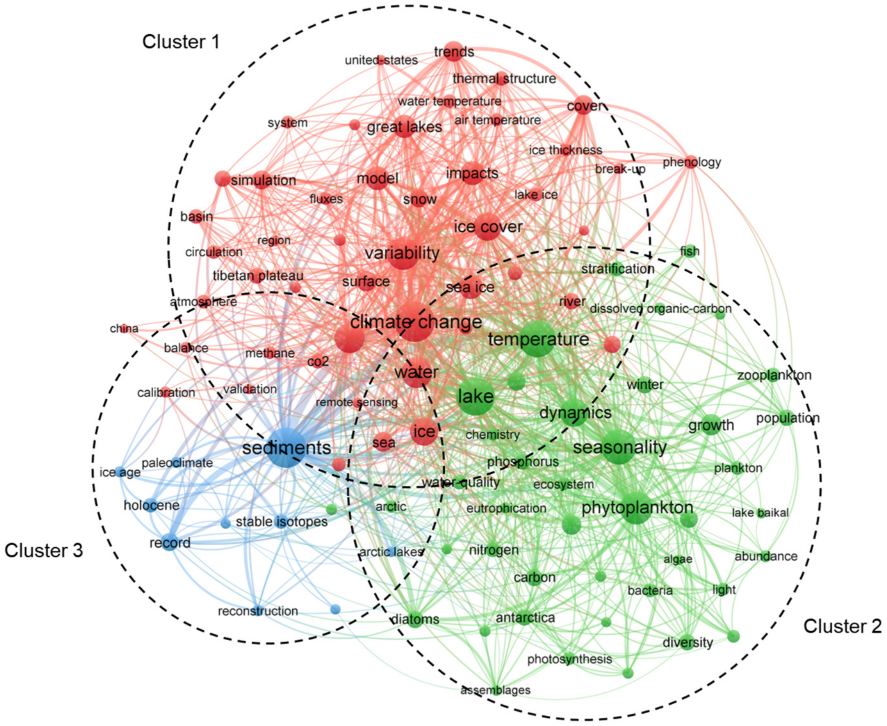

Figure 3. Cluster analysis of research keywords.

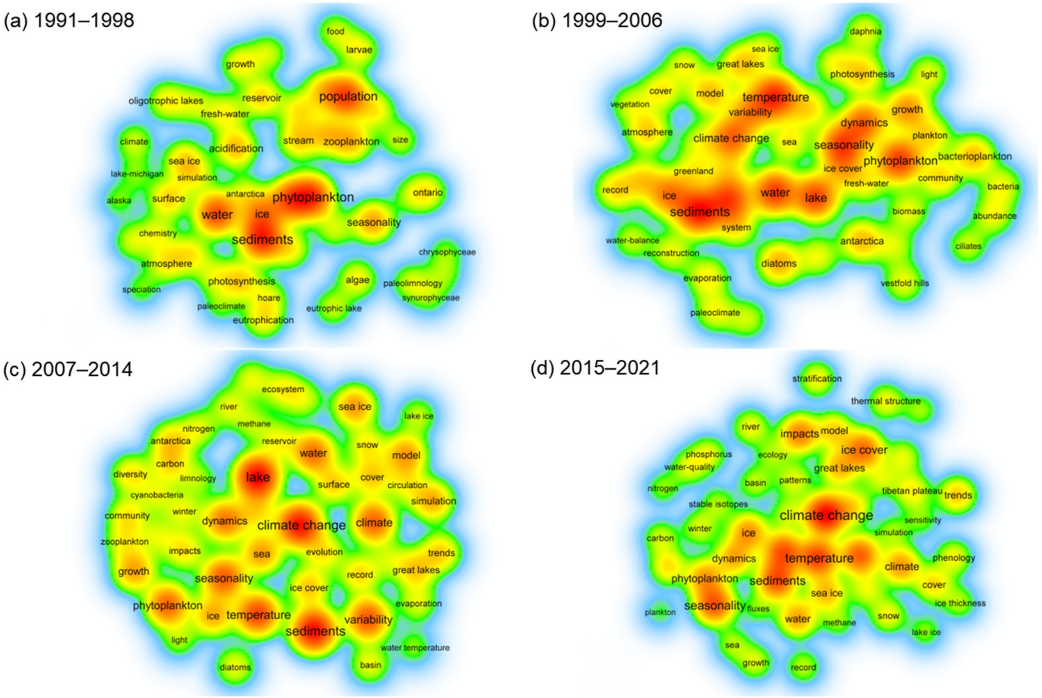

Figure 4. Keyword activity at different stages. The red indicates the keyword has the highest active degree (the research hotspot in this stage).

3. Seasonal Variability of Lakes during the Ice-Covered Period

3.1. Ice Structure and Growth Characteristics

The static lake ice of seasonally ice-covered lakes in the Northern Hemisphere consists of three main layers: primary ice, congelation ice, and superimposed ice (Figure 5). The texture of primary or superimposed ice depends on the meteorological and hydrodynamic conditions during formation. On calm water surfaces, primary ice forms as floating ice grown horizontally within the super-cooled layer, with a thickness of a few millimeters, larger horizontal crystal sizes, and a predominantly vertical c-axis orientation. Under disturbed conditions (turbulent water, windy conditions, or snowfall), primary ice forms from frazil ice crystals or condensed slush, with smaller crystal sizes (<1 mm) and a random orientation of the c-axis, which may be thicker than the former [35,36]. Superimposed ice forms above the primary ice and results from submerging the ice cover with any imaginable water source, such as liquid precipitation or meltwater. It is typically composed of condensed slush (a mixture of snow and liquid water) forming snow ice [35,37,38]. Congelation ice extends from the ice cover into the water column and is the predominant ice type in northern lakes. Its crystal structure is controlled by the primary ice, and the crystal size grows with increasing lake depth [35,39]. When the crystals in the primary ice are vertically oriented, the same pattern will be formed in the congelation ice, resulting in large macroscopic crystals. Otherwise, the congelation ice has a columnar crystal structure with a horizontal rotation of the optic axis [36,40].

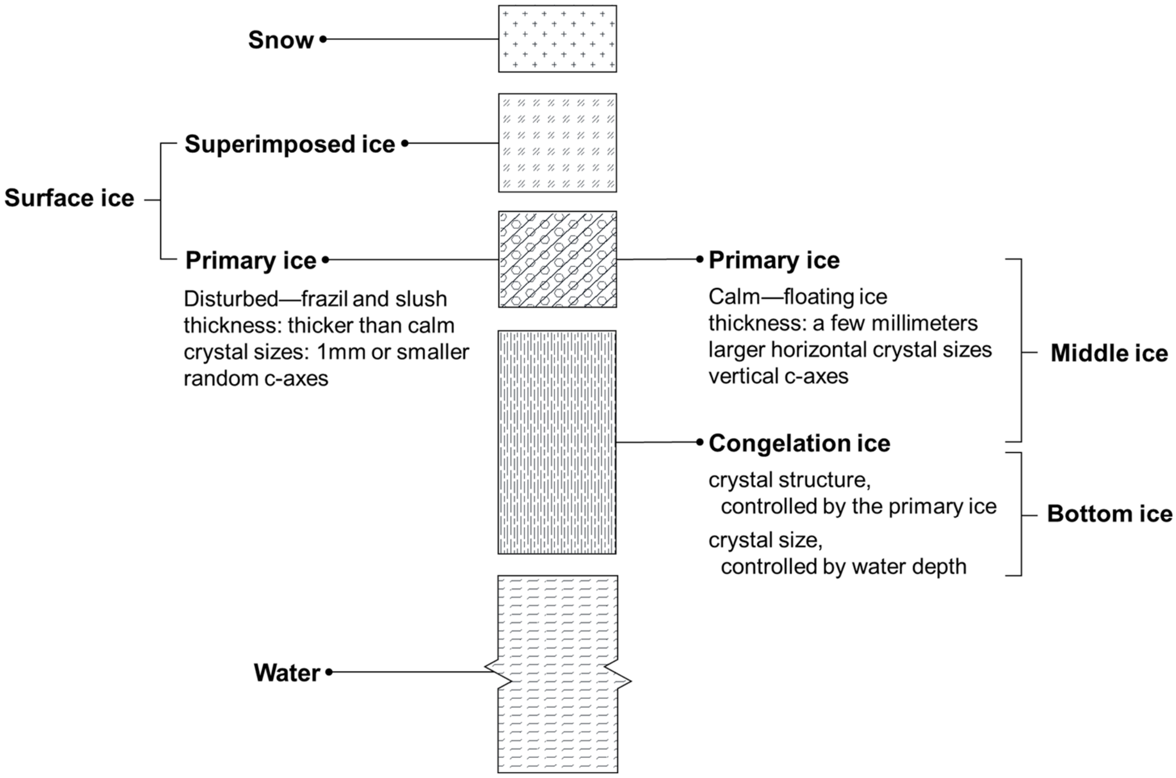

Figure 5. Lake ice structure conceptual diagram. Based on the traditional physical layering, further divisions of ice layers have been made based on the concentration of impurities.

Numerous studies have identified differences in impurity content, such as bubbles and particles in the seasonal lake ice, but they are not specifically stratified. Here, we roughly divide the lake ice into three layers based on the impurity content (Figure 5): surface ice, middle ice, and bottom ice. Surface ice generally contains snow slush and is composed of superimposed ice and primary ice under disturbed conditions, with most impurities likely resulting from water submerging the ice and atmospheric deposition [22,41]. Bottom ice (submerged congelation ice), in contact with the water layer beneath the ice and has a loose, chopsticks-like or horse-teeth shape (also known as horse teeth ice), which could accumulate substances such as chlorophyll-a, phytoplankton, algal fatty acids, and bacteria, regulating primary production by affecting light limitation and modulating dissolved oxygen (DO) and solute concentrations at the ice-water interface (excluding impurities in the ice) [42–44]. During thermodynamic growth, the latent heat released at the bottom of the ice is conducted through the ice to the atmosphere. When the latent heat flux exceeds the heat flux from water to ice, the continuous downward growth of the bottom ice increases the distance of conduction, gradually reducing its growth rate [38,40]. Middle ice mainly consists of primary ice on calm water surfaces and upper congelation ice. It has a higher purity crystal content, slower growth rate, and higher degree of solute exclusion compared to bottom ice. Therefore, the nutrient content in the ice often follows a similar C-shaped distribution pattern: surface > bottom > middle [16,23,44].

3.2. Characteristics of Water Environmental Conditions

The aquatic environment of lakes during the ice-covered period is primarily influenced by factors such as PAR, DO, and organic matter (OM) (Figure 6).

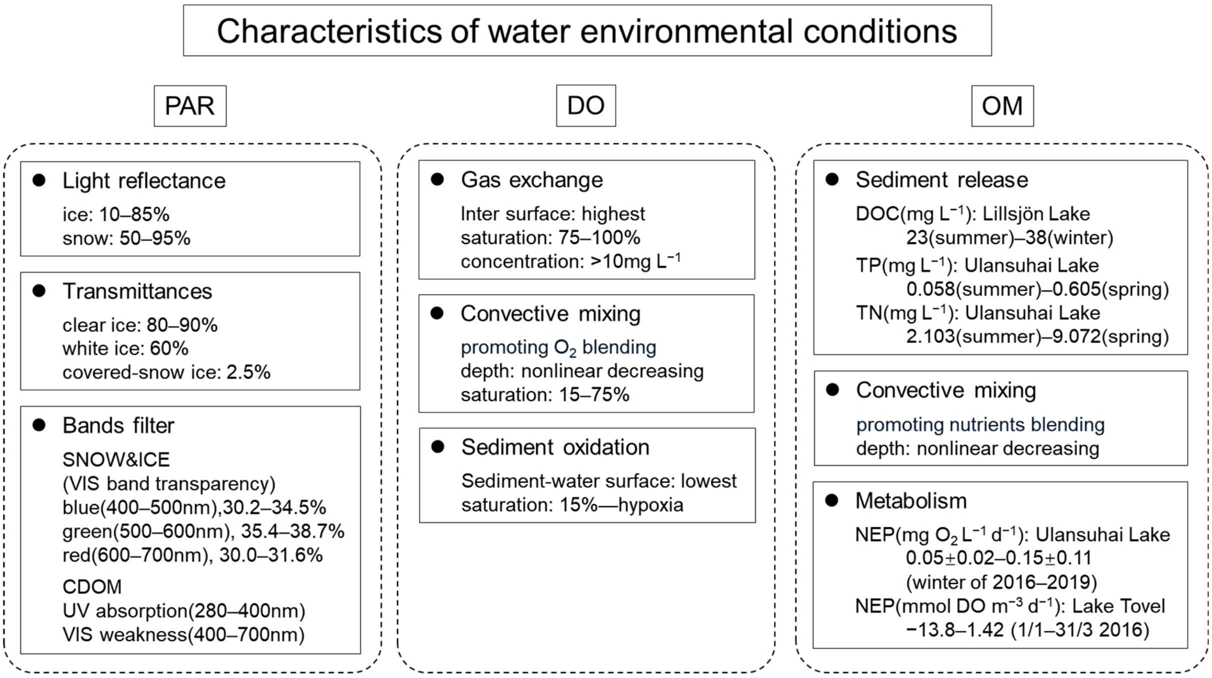

Figure 6. The main variation characteristics of water environmental conditions.

Increased lake ice coverage reduces PAR [20,45]. Light limitation occurs when PAR falls below the critical light intensity threshold for photosynthesis and biomass accumulation [46]. It is primarily caused by ice and snow albedo, ice transmittance coefficient, radiation bands filter, and colored dissolved organic matter (CDOM) in the water. Ice and snow albedo, determined by factors such as ice thickness, humic substances on the ice surface, snow grain size, and water content, affect light reflectance (lake ice: 0.10–0.85, snow: 0.50–0.95) and light attenuation coefficient, which together influence sub-ice radiation [47–49]. According to ice thickness and structure, clear ice transmittance contrasts sharply with snow-covered ice transmittance (clear ice: 80–90% range, white ice: 60%, covered-snow ice: 2.5%) [45]. Moreover, Bolsenga et al. [45] also found that covered snow and ice can filter out a significant portion of visible light, with the green band (500–600 nm) exhibiting the highest transparency (35.4–38.7%), followed by the blue band (400–500 nm, 30.2–34.5%) and the red band (600–700 nm, 30.0–31.6%). CDOM contributes to light limitation beneath the ice by ultraviolet radiation absorption (280–400 nm) and visual light weakness (400–700 nm), reducing the Secchi depth of water [49,50].

DO is another important factor influenced by lake ice during winter. The vertical stability of the water column is enhanced during the ice-covered period compared to the ice-free period, leading to distinct vertical gradients of temperature and DO concentration in the sub-ice water, as density gradient flows are generated due to heat flux from sediments [51]. The formation of ice cover restricts gas exchange and physical disturbance by wind. The exclusion of oxygen from the ice, greater primary production, and convective mixing in the upper water generally result in the highest DO saturation (75–100%) and concentration (>10 mg L^{-1}) near the surface throughout the entire lake [52–54]. As the lake depth increases, the water temperature rises continuously, and enhanced lake metabolism accelerates the consumption of DO, primarily due to biological respiration and chemical oxidation of reduced substances in the bottom sediments, leading to a different decrease in DO at the bottom layer and the lowest DO concentration around the sediment–water interface, creating an anoxic environment [53]. For example, in Eagle Lake of Canada (maximum depth ~31 m), the DO concentration remained relatively stable at all depths (~10 mg L^{-1}, 75% saturation) during pre-winter. At ~30 m depth, it depleted at 0.1 mg L^{-1} d^{-1} in winter and down to 4 mg L^{-1} (31% saturation) by the following spring turnover. Under the convective mixing and metabolism, the DO remained at ~78 mg L^{-1} (52% saturation) in the middle layer and ultimately approached hypoxia (15% saturation) at the bottom [54].

In Lake Tovel, a deep, oligotrophic lake at a high altitude in Italy (maximum depth ~39 m), the rate of O_2 consumption varies at different depths [32]. In March 2014–2016, the DO concentration at 5 m depth averaged ~11 mg L^{-1}, with an unstable seasonal pattern influenced by radiation infiltration. At a depth of 25 m, the DO concentration averaged ~8.5 mg L^{-1}, and the pattern of DO was consistently decreasing, with an average rate of decrease of 0.02 mg L^{-1} d^{-1}. In shallower lakes, solar radiation intensity can also affect DO by altering entire convective mixing. Transmitted radiation and heat released from sediments jointly influence thermal conduction in the water column, triggering convective turbulent mixing and promoting the uniform distribution of oxygen. In Lake Uliansuhai in Inner Mongolia, China [17], it was observed that during the growth and stable period of ice, local turbulence or turbulence–layer flow mixing can occur in the top or middle layers, promoting heat and oxygen mixing. After the ice melts, convection transports oxygen downward to the near-bottom layer, alleviating or preventing hypoxic conditions. In Lake Vanajanselkä in southern Finland [29], biological metabolism reduction decreases DO in winter. In spring, sunlight penetrates the ice and induces convection, resulting in a more even vertical distribution of DO.

The low-temperature environment and limited light availability result in lower net ecosystem production during the ice duration, such as Lake Ulansuhai, 2016–2019, 0.05 ± 0.02–0.15 ± 0.11 mg O_2 L^{-1} d^{-1} [17], and Lake Tovel, spring in 2016: -13.80–1.42 mmol DO m^{-3} d^{-1} [32]. Although most of DOM and 90% of the salt excluded in the ice growth process leads to an increase in nutrient concentration at the ice-water interface, the release from sediment is the main reason for increased eutrophication in the entire lake [16,17,49]. The cold anoxic conditions also facilitate the release of large amounts of other reduced substances (hydrogen, methane, acetate, ammonium, etc.) and oxidants (hydrogen peroxide, sulfates, carbon dioxide, etc.) and heavy metals, leading to significant changes in water conductivity and salinity during the ice-covered period and freeze–thaw cycles and altering the thermodynamic properties and convective mixing structure of lakes, thereby affecting their aquatic ecosystems [55–57]. In addition, some studies also proved the limitation of PAR under the ice and higher eutrophication levels could result in weaker convective mixing and a more stable density layer [46].

3.3. The Growth Changes of Primary Producers

Changes in environmental conditions can strongly limit the growth of certain species and remove growth restrictions for others. Light availability is a primary limiting factor, leading to a decrease in overall primary production during the frozen period. In Gossenköllesee Lake, the primary production during the freezing period is 56% lower than in the ice-free season [58]. Although the community structure is influenced by factors such as light conditions and nutrient concentrations of lakes, biodiversity is still present in the ice duration [30,59].

The light conditions in the lake affect the composition of dominant species and community structure of planktonic plants during the ice-covered period. In Lake Balkan, a shallow, large, and nutrient-rich lake [59], the most abundant planktonic plants under the ice layer are *Cyclotella meneghiniana* and *S. uvella* before and after snowfall. In Lake Erie [30], the dominant species of planktonic plants is *Aulacoseira islandica*, with *Cyclotella* spp. as the subdominant species. In Lake Vanajanselkä [29], which is shallow and eutrophic, the most abundant planktonic plant communities consist of cryptophytes (44%), chrysophytes (23%), and chlorophytes (6%) in mid-winter. In comparison, cyanobacteria (39%), cryptophytes (29%), and diatoms (13%) become dominant in late winter. The main reason for the dominance of the former in winter was their ability to adapt to low temperatures and low light conditions, while later, cyanobacteria became the main dominant species due to rapid blooms prompted by warmer temperatures and enhanced light conditions [29]. The ability of these dominant species to continue to flourish under the ice can be attributed to their unique adaptations under low-light and low-temperature conditions (efficient light energy utilization, buoyancy regulation, ability to move, and tolerance to low temperatures and nutrients) [30,59]. For example, *Cyclotella meneghiniana* has some cold tolerance and is able to maintain metabolic activity at lower temperatures. The species also benefits from its small cell size and ability to regulate buoyancy through changes in lipid content to move through the water column to the optimal light level and utilize the low light through the ice more efficiently.

Furthermore, effective PAR also influences the distribution of planktonic plants in seasonally ice-covered lakes. Studies on lake ice have found that planktonic plants tend to aggregate at the ice-water interface, such as the filamentous diatom community suspended under the ice in Lake Baikal [60] and algal aggregations at the ice-water interface in Lake Saint-Pierre in southern Canada [61]. Lake ice can also absorb some planktonic plant cells. In the freezing Laurentian Great Lakes [42], filamentous diatoms were found to be adsorbed onto the overlying ice through frazil ice. In Simoncouche Lake [44], planktonic plants (*Peridinium* sp., *Cryptomonas* sp., *Synechococcus* sp., etc.) were excluded from lake ice water, while certain populations (*Botryococcus* sp., *Chromulina* sp., *Gymnodinium* sp., etc.) exhibited aggregation within the ice, with their numbers remaining constant or increasing in winter. This proves lake ice can provide stable and potentially beneficial winter habitats for some planktonic plants. When ice cracks, the release of planktonic plant cells promotes spring blooms [44,61]. At this time, the rising of PAR and temperature trigger convective mixing in the water, accelerating the growth of planktonic plants and providing the foundation for spring blooms [29,59]. For some lakes with thicker ice cover and longer ice periods, phytoplankton biomass was correlated with certain nutrient contents. In 28 ice-covered lakes in the Songnen Plain of northeastern China during winter, phytoplankton growth was mainly related to the total nitrogen concentration in the water column and the difference in total phosphorus concentration at the ice–water interface, with contribution rates being, respectively, 25.5–35.0% and 9.2–11.3% [62].

Convective mixing induced by solar radiation has a notable impact on the growth of planktonic plants in freshwater lakes with a low coefficient of expansion ($<3.98\ ^\circ$C) [63]. It was found that when there was no convective mixing layer, light conditions were sufficient to support the growth of 50.0% of planktonic plants in four mesotrophic lakes in the northern temperate zone [46]. However, in the presence of convective mixing, only 37.5% of planktonic plants had enough light to increase biomass. This is likely due to the fact that a convective mixing layer can significantly affect the vertical position of non-motile planktonic plants in the upper water column and influence the light intensity they experience during the day. For instance, buoyant planktonic plants can be cycled through the convective mixing layer, providing them with improved light conditions and enhancing their growth and photosynthetic rates [63,64]. Conversely, if positively buoyant or motile planktonic plants are directly beneath the ice, they may have increased opportunities to acquire light, while those within the convective mixing layer may cycle deeper within the water column, reducing their access to light [51].

3.4. Material Circulation

With climate warming, carbon emissions and carbon neutrality have become hot topics of discussion. The carbon cycling process during the freezing period of lakes and its response to climate warming are gradually receiving attention.

During the ice-covered period, the decrease in hydrological inputs (such as surrounding soil, rivers, and groundwater) and hindered gas exchange at the water-air interface constrains the external input of greenhouse gases [65]. Due to higher light limitation and OM, respiration, mineralization, and microbial activity dominate the primary productivity in most lakes, leading to the accumulation of CO_2 [66,67]. At the same time, changes in DO gradients under the ice create environmental conditions for the transformation of CO_2 and CH_4. Under anoxic conditions, archaea utilize CO_2 and other carbon-containing compounds to produce CH_4 in the bottom layer [68,69], which exists in large amounts at the sediment-water interface and ice-water interface through diffusion or ebullition (bubble-mediated transport) [70]. The produced CH_4 is then consumed by methane-oxidizing bacteria in the surface sediment or upper layer, with CO_2 as a typical byproduct [71,72]. Furthermore, in terms of lake morphology, sediment metabolism, diffusion, and transformation of CO_2 often result in the highest CO_2 concentrations in the bottom water of most frozen lakes. The overall CO_2 concentration beneath the ice in large, deep lakes may be lower than that in small, shallow lakes [3]. Denfeld et al. [73] divided 506 lakes located in Finland and Sweden into four depth groups and found the average pCO_2 near the surface decreased from ~5000 µatm (mean depth < 2.5 m) to ~2000 µatm (mean depth > 4.5 m). This may be due to incomplete mixing in autumn and faster ice development, which leads to lower oxygen levels and more accumulation of CO_2 and CH_4 during the freezing period. Additionally, small lakes can cool down quickly and are less affected by wind disturbances [74].

Most seasonal frozen lakes have a certain carbon sink effect in winter. It is well-known that the solubility of gases in water increases as temperature decreases. Before the freezing period, the lake can absorb CO_2 from the atmosphere through the water-air interface. Once the freezing period begins, the lake ice blocks most of the gas exchange, and CO_2 mainly accumulates within the lake [8,18]. Changes in ice phenology caused by climate warming reduce the accumulation of CO_2 produced by winter lake metabolism and increase the pH value of the water in spring and summer, diminishing the carbon sink effect [14]. Differences in salinity lead to varying source-sink processes in freshwater lakes and saline lakes in winter. Freshwater lakes mainly achieve CO_2 supersaturation through metabolism and release CO_2 into the atmosphere [75]. With climate warming, the CO_2 emissions decrease because of reduced CO_2 accumulation under the ice.

In contrast, the alkaline conditions (pH 8–11) of saline lakes are influenced by carbonate precipitation or dissolution reactions and the chemical enhancement of the air-water interface CO_2 exchange rate [34,76], primarily determined by the average water pH [14]. When the pH of water exceeds 9.0, CO_2 is converted to HCO_3^- and CO_3^{2-}, promoting carbonate precipitation reactions [76], and CO_2 becomes undersaturated. Consequently, as the water temperature decreases during the freezing process, the salinity and pH of saline lakes increase, pCO_2 decreases, and the total absorption of CO_2 continues to increase [8,14]. During the frozen period, weaker gas exchange at the water-air interface and higher lake metabolism lead to continuous accumulation of CO_2 in the water. As lake ice breaks, the increased gas exchange leads to a decrease in the solubility of gases in water and a reduction in CO_2 flux (depending on the pH of the water at that time, it may be released into the atmosphere). When the temperature rises in spring and solar radiation increases, saline lakes gradually regain their higher primary productivity, fixing a large amount of inorganic carbon stored in the lake from the freezing process and the accumulation during the freezing period, showing a stronger ability to store inorganic carbon than freshwater lakes [34,77,78]. For saline lakes, the reduction in lake water volume caused by climate warming increases water salinity. A shorter ice-covered period results in less accumulation of CO_2 under the ice and higher pH values during spring and summer, which means the seasonal freezing saline lakes emit less CO_2 [14]. Furthermore, studies have shown that high temperatures can lead to autogenic carbonate precipitation, reducing the concentration of Ca^{2+}, which favors CO_2 emissions. That means rising temperatures may cause saline lakes to transition from a carbon sink to a carbon source again [79].

4. Investigation of Factors Affecting Seasonal Ice Duration

4.1. Global Climate Change

Recently, studies comparing time series data have revealed a trend of shorter ice cover duration and thinner ice thickness in lakes across the Northern Hemisphere [11]. Lopez et al. [27] studied 152 lakes located in the Northern Hemisphere and found that 97% of the lakes were shrinking ice cover duration, and the ice breakup dates advanced at a rate of 1.2 d decade^{-1} during 1951–2014. The ice duration and thickness of five temperate lakes located in northern Poland decreased at rates of 5.4 d decade^{-1} and 2.5 cm decade^{-1} from 1961 to 2017 and are predicted to lose their ice season at a rate between 4.5 and 10.0 d decade^{-1}, and ice thickness will decrease by between 3.0 and 5.0 cm decade^{-1} during the 21st century (ice thickness $0.12 < R^2 < 0.24$, $p < 0.001$; ice duration $0.14 < R^2 < 0.18$, $p < 0.001$) [80]. The fraction of maximum ice thickness for 402 shallow lakes of the North Slope of Alaska decreased from 51% to 26% during 2000–2011, while their ice cover was thinner by 21–38 cm, and the ice season was shorter by about 24 days in 1950–2011 [81]. A large number of lakes are completely losing their ice cover. Under the background of climate warming, winter surface water temperature plays a crucial role in influencing lake ice phenology, along with factors such as precipitation, solar radiation, and wind. The increase in winter precipitation (snowfall) can control the physical structure and transparency of lake ice cover by suppressing black ice growth and promoting white ice growth, thereby regulating the amount of radiation entering the lake [9]. At the same time, the rise in surface water temperature leads to shorter ice cover duration and thinner lake ice, intensifying the influence of solar radiation and wind on winter lake mixing, resulting in accelerated ice formation in autumn and hastens melting in spring [53,80]. The lack of lake ice coverage (23%) also led to higher evaporation rates (58% increase) and more water loss (natural lakes: 2.1% decade^{-1}, artificial reservoirs: 5.4% decade^{-1}) from 1985 to 2018 [82] and the global annual lake evaporation increase by 16% ($R^2 = 0.82$) by the end of the 21st century [83], which can affect regional air humidity and hydrological processes [84]. It is worth noting that higher ice coverage often experiences high autumn evaporation rates (water temperature cooling), but increased evaporation rates in late winter and the following summer and early autumn may also cause lower lake ice coverage (depleting from 90% in 2008–2009 to 31% in 2009–2010), which reflects the complexity and necessity of studies on the interannual climate-seasonal ice phenology-evaporation feedback process [85].

The warming seasonal pattern will also impact the response of planktonic organisms in lake ecosystems to climate change. Due to shorter ice cover duration and higher surface water temperature, the physical conditions and nutrient status of the water have changed (Section 3.2). This inhibits the growth of planktonic organisms adapted to winter's low temperature and hypoxic conditions, while some rapidly growing spring species, such as diatoms and copepods, exhibit a pronounced trend of earlier (2.17 d year^{-1}, 2000–2020) and synchronized blooming [86]. Although some slow-growing, long-living, and more complex summer planktonic species are more affected during crucial developmental stages (e.g., resting stage hatching in cladocerans, *Dreissena* spawning [87], the combined effects of predator–prey relationships and shortened ice cover duration result in a gradual reduction and disappearance of winter phytoplankton blooms in seasonally frozen lakes, with maximum biomass shifting towards summer [88].

In addition, seasonally frozen lakes will gradually lose their lakes in the future, regardless of GHG emissions. Under a climate scenario with substantially lower GHG emissions (RCP 2.6), winter ice thickness and ice period will decrease by 0.1 m and ~15 d, respectively, by 2100, while under a higher emissions scenario (RCP 8.5), ice thickness and ice duration are projected to decrease by 0.17 m and 40 days (RCT, $p > 0.1$) [89]. Therefore, reducing greenhouse gas emissions is crucial for minimizing the loss of seasonally ice-covered lakes and mitigating the associated ecological, cultural, and societal impacts [25].

4.2. Individual Characteristics of Lakes

In recent years, Sharma et al. [2] and Warne et al. [11] analyzed datasets and found that lower altitude, western longitude, and lower latitude deep lakes are more influenced by climate in terms of their ice phenology, which suggests, besides surface temperature trends, individual characteristics of seasonally ice-covered lakes such as surface area, depth, and geographical location can also have an impact on ice phenology.

In winter, as the lake ice forms and temperatures decrease, the lake undergoes vertical density-driven cooling from the water surface downwards. Deeper lakes often have greater heat storage capacity and require a longer cooling period below the freezing point to freeze [90].

Dimictic lakes undergo complete vertical mixing from top to bottom when they cool or warm and through the maximum density temperature (T_{MD}, 3.984 °C at zero salinity) at the surface pressure [91]. In shallow freshwater lakes during the ice-covered period, stable inverse thermal stratification forms and persists beneath the ice when the water temperature is below the T_{MD} [92]. When the lake ice begins to melt, solar radiation penetrates the ice cover and drives turbulent convection [49] until the overall temperature reaches or exceeds the T_{MD}. For example, in Lake Onega (mean depth: 15 m, max depth: 30 m), higher solar radiation passing through the ice intensifies the daytime activity of the convective mixing layer (reaching depths of 20 m), resulting in a slow overall temperature increase until the end of the ice-covered period [93], promoting the breakup and melting of the ice layer in spring [94]. However, complete sub-ice convective mixing may not occur because of the stratification of salinity in the water. Some of the shallower mid-latitude salt lakes during the freezing period may have a warm intermediate layer formed by salinity stratification, separating the overlying inverse thermal stratification from the underlying positive thermal stratification. For example, in a shallow thermokarst lake in the central part of the Qinghai-Tibet Plateau (mean depth: 120 m, max depth: 150 m), the vertical thermal structure beneath the ice consists of stable, strong inverse thermal stratification and a lower convective layer reaching the lake bottom. The stronger inverse thermal stratification induces horizontal and vertical advection, accelerating ice melting. Meanwhile, a warm layer with gradually increasing thickness and temperature has been present between the two since the middle equilibrium period, accumulating more heat during the ice-covered period, with temperatures rising to 7–9 °C at the end of the frozen period [95].

In deeper seasonally ice-covered lakes, lake ice phenology is typically associated with the upper water column. Since the T_{MD} decreases with increasing pressure in the deeper lake, once the ~4 °C water begins to sink, the interface at the bottom of the upper mixed layer falls below the depth corresponding to the temperature of the T_{MD} at that water depth, resulting in the thermobaric instability being activated and free convection until colder water closer to the T_{MD} curve is encountered at greater depth [96]. Therefore, the upper and lower water masses exhibit distinct temperature profiles and convective mixing patterns with a fuzzy boundary at a certain depth. For example, based on the difference between water temperature and T_{MD} decreases with depth, the Great Slave Lake (max depth: 614 m) in the Mackenzie River Basin of Canada is divided into inverse thermal stratification (<200 m), thermobaric horizon (~200 m), and weakly permanent stratification (>200 m). At the end of the ice duration, solar radiation penetrates the ice, driving convective mixing in the upper layers, deepening the mixed layer, promoting ice breakup and melting, and influencing the timing of spring phytoplankton production [92].

Elevation and latitude have a significant impact on the ice phenology of lakes. Leppäranta and Wen [12] demonstrated through ice phenology time series from 10 Eurasian sites that local temperature (determined by elevation, latitude, and longitude) and solar radiation (determined by latitude) can influence the dates of freezing, thawing, and ice duration. Lakes at higher elevations may also be cooler and less influenced by climate change compared to lakes at lower elevations. For example, during 2000–2016, Qinghai Lake, located on the Tibetan Plateau (3196 m elevation), experienced relatively small fluctuations in freezing, thawing, and ice duration, with values of 20 days, 10 days, and 108 days, respectively [97]. Of the seven alpine lakes (3126–3620 m elevation) in the same region of Colorado, USA, 1981–2014, those at higher elevations demonstrated more consistent freezing and thawing times [98]. Compared to the historical rates of change in northern hemisphere water bodies (1846–1995), the average rate of change for freeze-up and breakup dates in the Great Lakes region was 5.8 times faster and 3.3 times faster, respectively. The average ice duration decreased by 5.3 d decade^{-1}, with the southwest lakes experiencing even faster rates of change in breakup dates and ice duration [99].

Additionally, a clear negative correlation between lake surface area and the start of ice cover, as well as a potential negative correlation with ice duration (Figure 7). Theoretically, larger lakes with greater surface areas often absorb more radiation and have a larger gas exchange interface, facilitating more efficient heat exchange, leading to faster temperature changes in the water during winter and spring, accelerating the freezing and thawing of ice and resulting in earlier ice formation and breakup. However, it should be noted that this could not determine whether the lake area directly influences ice duration or the direction of its impact. Currently, there is a lack of research exploring the relationship and mechanisms between winter lake ice phenology and lake area. Future studies could potentially investigate the response of different types of seasonally ice-covered lakes to climate change by using it as a starting point.

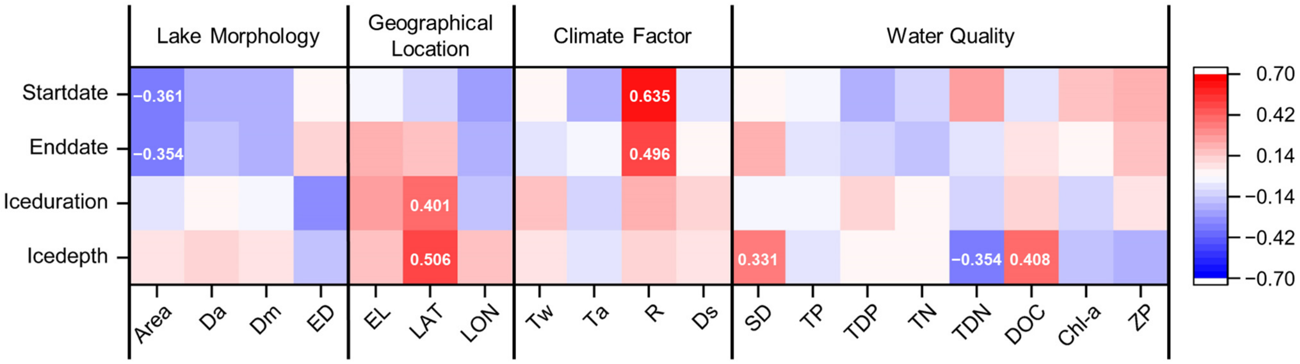

Figure 7. The heat map shows the relationship between ice phenology parameters and influencing factors of seasonally frozen lakes (N = 73). The numbers within the boxes represent Pearson correlation coefficients. The labels on the X-axis represent specific influencing factors, including surface area (Area), lake average depth (Da), lake max depth (Dm), euphotic depth (ED), elevation (EL), station latitude (LAT), station longitude (LON), water temperature (Tw), air temperature (Ta), radiation intensity (R), snow depth (Ds), Secchi depth (SD), total phosphorus (TP), total dissolved phosphorus (TDP), total nitrogen (TN), total dissolved nitrogen (TDN), dissolved organic carbon (DOC), Chlorophylla (Chl-a), zooplankton biomass (ZP).

5. Conclusions and Future Trends

In this study, we discuss the growth characteristics of seasonal ice cover, changes in hydric environmental conditions and primary production, and the accumulation and transformation of carbon dioxide by winter lakes. We also provide an overview of winter lake ice cover periods, evapotranspiration, planktonic responses to global climate change, the effects of greenhouse gas emissions on ice-free events, and the effects of individual characteristics on seasonally frozen lakes. We found that most current studies focus on analyzing water phytoplankton succession, quality changes, and ice phenology in individual seasonal frozen lakes. This existing work provides an important foundation for our continued exploration and study of ice-covered lake ecosystems in the future. In addition, the development of remote sensing has led to the emergence of joint research on multiple lakes with similar or different characteristics at various spatial scales. To comprehensively understand the response of global seasonal frozen lakes to climate change and predict local climate, regression analysis, R, machine learning, and other methods are combined with large datasets containing time series data on lake morphology, geographical location, and climate factors. This helps explore and simulate the impacts of various factors on winter lakes and establish a global-scale frozen lake data model. In addition, the following aspects still need further exploration: future impacts of meteorological/climatic parameters on ice-covered ecosystems, solute changes and carbon emissions in high-altitude lakes and salt lakes in winter, chemical composition and distribution patterns at the ice–water interface, differences in phytoplankton responses among species characteristics, lake types, and regional climates, and rapid stratification methods for measuring solute content or ice physical properties, the use of sensitivity analyses, and/or multi-criteria methods to determine the impact of analyzed parameters on ice thickness.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16192727/s1, Table S1. TOP 10 most productive countries on seasonal ice-covered lakes research during 1991–2021. Figure S1. Research Collaboration between Countries. Figure S2. Global Institutional Collaboration.

Author Contributions: Q.W.: investigation, visualization, writing—original draft. F.Y.: conceptualization, writing—review and editing. W.F., M.J., T.P., D.F. and Z.H.: investigation, data curation, writing—review and editing; H.L.: writing review and editing, funding acquisition, project administration, supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key Research and Development Program (grant ID: 2021YFC3201001) and the Foundation of Important Science & Technology Specific Projects of Ordos (grant ID: ZD20232301).

Data Availability Statement: No new data were created or analyzed in this study.

Acknowledgments: We thank the editors and anonymous reviewers for their excellent comments on the manuscript.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Verpoorter, C.; Kutser, T.; Seekell, D.A.; Tranvik, L.J. A Global Inventory of Lakes Based on High-Resolution Satellite Imagery. *Geophys. Res. Lett.* **2014**, *41*, 6396–6402. [CrossRef]
2. Sharma, S.; Blagrave, K.; Magnuson, J.J.; O'Reilly, C.M.; Oliver, S.; Batt, R.D.; Magee, M.R.; Straile, D.; Weyhenmeyer, G.A.; Winslow, L.; et al. Widespread Loss of Lake Ice around the Northern Hemisphere in a Warming World. *Nat. Clim. Change* **2019**, *9*, 227–231. [CrossRef]
3. Denfeld, B.A.; Baulch, H.M.; del Giorgio, P.A.; Hampton, S.E.; Karlsson, J. A Synthesis of Carbon Dioxide and Methane Dynamics during the Ice-Covered Period of Northern Lakes. *Limnol. Oceanogr. Lett.* **2018**, *3*, 117–131. [CrossRef]
4. Wang, X.; Feng, L.; Gibson, L.; Qi, W.; Liu, J.; Zheng, Y.; Tang, J.; Zeng, Z.; Zheng, C. High-Resolution Mapping of Ice Cover Changes in over 33,000 Lakes across the North Temperate Zone. *Geophys. Res. Lett.* **2021**, *48*, e2021GL095614. [CrossRef]
5. Yan, F.; Sillanpää, M.; Kang, S.; Aho, K.S.; Qu, B.; Wei, D.; Li, X.; Li, C.; Raymond, P.A. Lakes on the Tibetan Plateau as Conduits of Greenhouse Gases to the Atmosphere. *J. Geophys. Res. Biogeosci.* **2018**, *123*, 2091–2103. [CrossRef]
6. Cohen, A.P.; Mélack, J.M. Carbon Dioxide Supersaturation in High-Elevation Oligotrophic Lakes and Reservoirs in the Sierra Nevada, California. *Limnol. Oceanogr.* **2020**, *65*, 612–626. [CrossRef]
7. Huang, L.; Timmermann, A.; Lee, S.-S.; Rodgers, K.B.; Yamaguchi, R.; Chung, E.-S. Emerging Unprecedented Lake Ice Loss in Climate Change Projections. *Nat. Commun.* **2022**, *13*, 5798. [CrossRef]
8. Li, X.; Shi, F.; Ma, Y.; Zhao, S.; Wei, J. Significant Winter CO_2 Uptake by Saline Lakes on the Qinghai-Tibet Plateau. *Glob. Change Biol.* **2022**, *28*, 2041–2052. [CrossRef]
9. Zdorovennova, G.; Palshin, N.; Golosov, S.; Efremova, T.; Belashev, B.; Bogdanov, S.; Fedorova, I.; Zverev, I.; Zdorovennov, R.; Terzhevik, A. Dissolved Oxygen in a Shallow Ice-Covered Lake in Winter: Effect of Changes in Light, Thermal and Ice Regimes. *Water* **2021**, *13*, 2435. [CrossRef]
10. Murfitt, J.; Duguay, C.R. 50 Years of Lake Ice Research from Active Microwave Remote Sensing: Progress and Prospects. *Remote Sens. Environ.* **2021**, *264*, 112616. [CrossRef]
11. Warne, C.P.K.; McCann, K.S.; Rooney, N.; Cazelles, K.; Guzzo, M.M. Geography and Morphology Affect the Ice Duration Dynamics of Northern Hemisphere Lakes Worldwide. *Geophys. Res. Lett.* **2020**, *47*, e2020GL087953. [CrossRef]
12. Leppäranta, M.; Wen, L. Ice Phenology in Eurasian Lakes over Spatial Location and Altitude. *Water* **2022**, *14*, 1037. [CrossRef]
13. Wright, D.M.; Posselt, D.J.; Steiner, A.L. Sensitivity of Lake-Effect Snowfall to Lake Ice Cover and Temperature in the Great Lakes Region. *Mon. Weather Rev.* **2013**, *141*, 670–689. [CrossRef]
14. Finlay, K.; Vogt, R.J.; Bogard, M.J.; Wissel, B.; Tutolo, B.M.; Simpson, G.L.; Leavitt, P.R. Decrease in CO_2 Efflux from Northern Hardwater Lakes with Increasing Atmospheric Warming. *Nature* **2015**, *519*, 215–218. [CrossRef]
15. Sadro, S.; Sickman, J.O.; Mélack, J.M.; Skeen, K. Effects of Climate Variability on Snowmelt and Implications for Organic Matter in a High-Elevation Lake. *Water Resour. Res.* **2018**, *54*, 4563–4578. [CrossRef]
16. Yang, F.; Li, C.; Leppäranta, M.; Shi, X.; Zhao, S.; Zhang, C. Notable Increases in Nutrient Concentrations in a Shallow Lake during Seasonal Ice Growth. *Water Sci. Technol.* **2016**, *74*, 2773–2783. [CrossRef]
17. Huang, W.; Zhang, Z.; Li, Z.; Leppäranta, M.; Arvola, L.; Song, S.; Huotari, J.; Lin, Z. Under-Ice Dissolved Oxygen and Metabolism Dynamics in a Shallow Lake: The Critical Role of Ice and Snow. *Water Resour. Res.* **2021**, *57*, e2020WR027990. [CrossRef]

18. Finlay, K.; Vogt, R.J.; Simpson, G.L.; Leavitt, P.R. Seasonality of PCO_2 in a Hard-Water Lake of the Northern Great Plains: The Legacy Effects of Climate and Limnological Conditions over 36 Years. *Limnol. Oceanogr.* **2019**, *64*, S118–S129. [CrossRef]
19. Hori, Y.; Cheng, V.Y.S.; Gough, W.A.; Jien, J.Y.; Tsuji, L.J.S. Implications of Projected Climate Change on Winter Road Systems in Ontario's Far North, Canada. *Clim. Change* **2018**, *148*, 109–122. [CrossRef]
20. Leppäranta, M. *Freezing of Lakes and the Evolution of Their Ice Cover*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2014; ISBN 9783642290817.
21. Knoll, L.B.; Sharma, S.; Denfeld, B.A.; Flaim, G.; Hori, Y.; Magnuson, J.J.; Straile, D.; Weyhenmeyer, G.A. Consequences of Lake and River Ice Loss on Cultural Ecosystem Services. *Limnol. Oceanogr. Lett.* **2019**, *4*, 119–131. [CrossRef]
22. Salonen, K.; Leppäranta, M.; Viljanen, M.; Gulati, R.D. Perspectives in Winter Limnology: Closing the Annual Cycle of Freezing Lakes. *Aquat. Ecol.* **2009**, *43*, 609–616. [CrossRef]
23. Han, Z.M.; Jia, K.L.; Zhao, S.N.; Sun, B.; Wang, X.Y. Distribution Characteristics of the Nutrients and Ion of Hulun Lake in Frozen and Unfrozen Period. *Ecol. Environ. Sci.* **2017**, *26*, 1201–1209.
24. Woolway, R.I.; Kraemer, B.M.; Lenters, J.D.; Merchant, C.J.; O'Reilly, C.M.; Sharma, S. Global Lake Responses to Climate Change. *Nat. Rev. Earth Environ.* **2020**, *1*, 388–403. [CrossRef]
25. Woolway, R.I.; Sharma, S.; Smol, J.P. Lakes in Hot Water: The Impacts of a Changing Climate on Aquatic Ecosystems. *BioScience* **2022**, *72*, 1050–1061. [CrossRef]
26. Hampton, S.E.; Powers, S.; Devlin, S.; McKnight, D. Big Questions, Few Answers about What Happens under Lake Ice. *EOS* **2020**, *101*. [CrossRef]
27. Lopez, L.S.; Hewitt, B.A.; Sharma, S. Reaching a Breaking Point: How Is Climate Change Influencing the Timing of Ice Breakup in Lakes across the Northern Hemisphere? *Limnol. Oceanogr.* **2019**, *64*, 2621–2631. [CrossRef]
28. George, D.G. (Ed.) *The Impact of Climate Change on European Lakes*; Aquatic Ecology Series; Springer: Dordrecht, The Netherlands, 2010; Volume 4, pp. 1–13.
29. Leppäranta, M.; Heini, A.; Jaatinen, E.; Arvola, L. The Influence of Ice Season on the Physical and Ecological Conditions in Lake Vanajanselkä, Southern Finland. *Water Qual. Res. J.* **2012**, *47*, 287–299. [CrossRef]
30. Twiss, M.R.; McKay, R.M.L.; Bourbonniere, R.A.; Bullerjahn, G.S.; Carrick, H.J.; Smith, R.E.H.; Winter, J.G.; D'souza, N.A.; Furey, P.C.; Lashaway, A.R.; et al. Diatoms Abound in Ice-Covered Lake Erie: An Investigation of Offshore Winter Limnology in Lake Erie over the Period 2007 to 2010. *J. Great Lakes Res.* **2012**, *38*, 18–30. [CrossRef]
31. Butler, T.M.; Wilhelm, A.-C.; Dwyer, A.C.; Webb, P.N.; Baldwin, A.L.; Techtmann, S.M. Microbial Community Dynamics during Lake Ice Freezing. *Sci. Rep.* **2019**, *9*, 6231. [CrossRef]
32. Obertegger, U.; Obrador, B.; Flaim, G. Dissolved Oxygen Dynamics under Ice: Three Winters of High-Frequency Data from Lake Tovel, Italy. *Water Resour. Res.* **2017**, *53*, 7234–7246. [CrossRef]
33. Yang, F.; Cen, R.; Feng, W.; Zhu, Q.; Leppäranta, M.; Yang, Y.; Wang, X.; Liao, H. Dynamic Simulation of Nutrient Distribution in Lakes during Ice Cover Growth and Ablation. *Chemosphere* **2021**, *281*, 130781. [CrossRef] [PubMed]
34. Duarte, C.M.; Prairie, Y.T.; Montes, C.; Cole, J.J.; Striegl, R.; Melack, J.; Downing, J.A. CO_2 Emissions from Saline Lakes: A Global Estimate of a Surprisingly Large Flux. *J. Geophys. Res. Biogeosci.* **2008**, *113*, G4. [CrossRef]
35. Michel, B.; Ramseier, R.O. Classification of River and Lake Ice. *Can. Geotech. J.* **1971**, *8*, 36–45. [CrossRef]
36. Bengtsson, L. Spatial Variability of Lake Ice Covers. *Geogr. Ann. Ser. A-Phys. Geogr.* **1986**, *68*, 113–121. [CrossRef]
37. Michel, B. *Properties and Processes of River and Lake Ice*; Université Laval, Laboratoire de mécanique des glaces: Québec, QC, Canada, 1972.
38. Leppäranta, M. Modelling the Formation and Decay of Lake Ice. In *The Impact of Climate Change on European Lakes*; Aquatic Ecology Series; George, G., Ed.; Springer: Dordrecht, The Netherlands, 2010; pp. 63–83.
39. Gow, A.J. Orientation Textures in Ice Sheets of Quietly Frozen Lakes. *J. Cryst. Growth* **1986**, *74*, 247–258. [CrossRef]
40. Gow, A.J.; Langston, D. *Growth History of Lake Ice in Relation to Its Stratigraphic, Crystalline and Mechanical Structure*; Department of Defense, Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory: Hanover, NH, USA, 1977.
41. Leppäranta, M.; Tikkanen, M.; Virkanen, J. Observations of Ice Impurities in Some Finnish Lakes. *Proc. Est. Acad. Sci.* **2003**, *52*, 59–75. [CrossRef]
42. D'souza, N.A.; Kawarasaki, Y.; Gantz, J.D.; Lee Jr, R.E.; Beall, B.F.N.; Shtarkman, Y.M.; Koçer, Z.A.; Rogers, S.O.; Wildschutte, H.; Bullerjahn, G.S.; et al. Diatom Assemblages Promote Ice Formation in Large Lakes. *ISME J.* **2013**, *7*, 1632–1640. [CrossRef]
43. Santibáñez, P.A.; Michaud, A.B.; Vick-Majors, T.J.; D'Andrilli, J.; Chiuchiolo, A.; Hand, K.P.; Priscu, J.C. Differential Incorporation of Bacteria, Organic Matter, and Inorganic Ions into Lake Ice during Ice Formation. *J. Geophys. Res. Biogeosci.* **2019**, *124*, 585–600. [CrossRef]
44. Imbeau, E.; Vincent, W.F.; Wauthy, M.; Cusson, M.; Rautio, M. Hidden Stores of Organic Matter in Northern Lake Ice: Selective Retention of Terrestrial Particles, Phytoplankton and Labile Carbon. *J. Geophys. Res. Biogeosci.* **2021**, *126*, e2020JG006233. [CrossRef]
45. Bolsenga, S.J.; Herdendorf, C.E.; Norton, D.C. Spectral Transmittance of Lake Ice from 400–850 Nm. *Hydrobiologia* **1991**, *218*, 15–25. [CrossRef]
46. Pernica, P.; North, R.L.; Baulch, H.M. In the Cold Light of Day: The Potential Importance of Under-Ice Convective Mixed Layers to Primary Producers. *Inland Waters* **2017**, *7*, 138–150. [CrossRef]
47. Warren, S.G. Optical Properties of Snow. *Rev. Geophys.* **1982**, *20*, 67. [CrossRef]

48. Leppäranta, M.; Terzhevik, A.; Shirasawa, K. Solar Radiation and Ice Melting in Lake Vendyurskoe, Russian Karelia. *Hydrol. Res.* **2010**, *41*, 50–62. [CrossRef]
49. Pulkkanen, M. Under-Ice Temperature and Oxygen Conditions in Boreal Lakes. In *Jyväskylä Studies in Biological and Environmental Science*; University of Jyväskylä: Jyväskylä, Finland, 2013.
50. Belzile, C.; Gibson, J.A.E.; Vincent, W.F. Colored Dissolved Organic Matter and Dissolved Organic Carbon Exclusion from Lake Ice: Implications for Irradiance Transmission and Carbon Cycling. *Limnol. Oceanogr.* **2002**, *47*, 1283–1293. [CrossRef]
51. Vehmaa, A.; Salonen, K. Development of Phytoplankton in Lake Pääjärvi (Finland) during Under-Ice Convective Mixing Period. *Aquat. Ecol.* **2009**, *43*, 693–705. [CrossRef]
52. Yang, B.; Wells, M.G.; Li, J.; Young, J. Mixing, Stratification, and Plankton under Lake-Ice during Winter in a Large Lake: Implications for Spring Dissolved Oxygen Levels. *Limnol. Oceanogr.* **2020**, *65*, 2713–2729. [CrossRef]
53. Cavaliere, E.; Fournier, I.B.; Hazuková, V.; Rue, G.P.; Sadro, S.; Berger, S.A.; Cotner, J.B.; Dugan, H.A.; Hampton, S.E.; Lottig, N.R.; et al. The Lake Ice Continuum Concept: Influence of Winter Conditions on Energy and Ecosystem Dynamics. *J. Geophys. Res. Biogeosci.* **2021**, *126*, e2020JG006165. [CrossRef]
54. Ghane, A.; Boegman, L. The Dissolved Oxygen Budget of a Small Canadian Shield Lake during Winter. *Limnol. Oceanogr.* **2023**, *68*, 265–283. [CrossRef]
55. Sabbe, K.; Hodgson, D.A.; Verleyen, E.; Taton, A.; Wilmotte, A.; Vanhoutte, K.; Vyverman, W. Salinity, Depth and the Structure and Composition of Microbial Mats in Continental Antarctic Lakes. *Freshw. Biol.* **2004**, *49*, 296–319. [CrossRef]
56. Pieters, R.; Lawrence, G.A. Effect of Salt Exclusion from Lake Ice on Seasonal Circulation. *Limnol. Oceanogr.* **2009**, *54*, 401–412. [CrossRef]
57. Boetius, A.; Anesio, A.M.; Deming, J.W.; Mikucki, J.A.; Rapp, J.Z. Microbial Ecology of the Cryosphere: Sea Ice and Glacial Habitats. *Nat. Rev. Microbiol.* **2015**, *13*, 677–690. [CrossRef] [PubMed]
58. Panzenböck, M. Effect of Solar Radiation on Photosynthetic Extracellular Carbon Release and Its Microbial Utilization in Alpine and Arctic Lakes. *Aquat. Microb. Ecol.* **2007**, *48*, 155–168. [CrossRef]
59. Öterler, B. Winter Phytoplankton Composition Occurring in a Temporarily Ice-Covered Lake: A Case Study. *Pol. J. Environ. Stud.* **2017**, *26*, 2677–2688. [CrossRef] [PubMed]
60. Obolkina, L.; Bondarenko, N.A.; Doroshchenko, L.F.; Gorbunova, L.A.; Molozhavaya, O.A. On Finding of Cryophilic Community of Lake Baikal. *Dokl. Akad. Nauk* **2000**, *371*, 815–817.
61. Frenette, J.; Thibeault, P.; Lapierre, J.; Hamilton, P.B. Presence of Algae in Freshwater Ice Cover of Fluvial Lac Saint-Pierre (St. Lawrence River, Canada). *J. Phycol.* **2008**, *44*, 284–291. [CrossRef]
62. Wen, Z.; Song, K.; Shang, Y.; Lyu, L.; Yang, Q.; Fang, C.; Du, J.; Li, S.; Liu, G.; Zhang, B.; et al. Variability of Chlorophyll and the Influence Factors during Winter in Seasonally Ice-Covered Lakes. *J. Environ. Manag.* **2020**, *276*, 111338. [CrossRef]
63. Kelley, D.E. Convection in Ice-Covered Lakes: Effects on Algal Suspension. *J. Plankton Res.* **1997**, *19*, 1859–1880. [CrossRef]
64. Matthews, P.C.; Heaney, S.I. Solar Heating and Its Influence on Mixing in Ice-Covered Lakes. *Freshw. Biol.* **1987**, *18*, 135–149. [CrossRef]
65. Denfeld, B.A.; Klaus, M.; Laudon, H.; Sponseller, R.A.; Karlsson, J. Carbon Dioxide and Methane Dynamics in a Small Boreal Lake during Winter and Spring Melt Events. *J. Geophys. Res. Biogeosci.* **2018**, *123*, 2527–2540. [CrossRef]
66. Larsen, S.; Andersen, T.; Hessen, D.O. The PCO_2 in Boreal Lakes: Organic Carbon as a Universal Predictor? *Glob. Biogeochem. Cycles* **2011**, *25*. [CrossRef]
67. Peter, S.; Isidorova, A.; Sobek, S. Enhanced Carbon Loss from Anoxic Lake Sediment through Diffusion of Dissolved Organic Carbon. *J. Geophys. Res. Biogeosci.* **2016**, *121*, 1959–1977. [CrossRef]
68. Berg, I.A.; Kockelkorn, D.; Ramos-Vera, W.H.; Say, R.F.; Zarzycki, J.; Hügler, M.; Alber, B.E.; Fuchs, G. Autotrophic Carbon Fixation in Archaea. *Nat. Rev. Microbiol.* **2010**, *8*, 447–460. [CrossRef] [PubMed]
69. Saini, R.; Kapoor, R.; Kumar, R.; Siddiqi, T.O.; Kumar, A. CO_2 Utilizing Microbes—A Comprehensive Review. *Biotechnol. Adv.* **2011**, *29*, 949–960. [CrossRef] [PubMed]
70. Sepulveda-Jauregui, A.; Walter Anthony, K.M.; Martinez-Cruz, K.; Greene, S.; Thalasso, F. Methane and Carbon Dioxide Emissions from 40 Lakes along a North–South Latitudinal Transect in Alaska. *Biogeosciences* **2015**, *12*, 3197–3223. [CrossRef]
71. Denfeld, B.A.; Canelhas, M.R.; Weyhenmeyer, G.A.; Bertilsson, S.; Eiler, A.; Bastviken, D. Constraints on Methane Oxidation in Ice-Covered Boreal Lakes. *J. Geophys. Res. Biogeosci.* **2016**, *121*, 1924–1933. [CrossRef]
72. Kalyuzhnaya, M.G.; Gomez, O.A.; Murrell, J.C. The Methane-Oxidizing Bacteria (Methanotrophs). In *Taxonomy, Genomics and Ecophysiology of Hydrocarbon-Degrading Microbes*; Springer: Cham, Switzerland, 2019; pp. 245–278. [CrossRef]
73. Denfeld, B.A.; Kortelainen, P.; Rantakari, M.; Sobek, S.; Weyhenmeyer, G.A. Regional Variability and Drivers of below Ice CO_2 in Boreal and Subarctic Lakes. *Ecosystems* **2015**, *19*, 461–476. [CrossRef]
74. Huotari, J.; Ojala, A.; Peltomaa, E.; Nordbo, A.; Launiainen, S.; Pumpanen, J.; Rasilo, T.; Hari, P.; Vesala, T. Long-Term Direct CO_2 flux Measurements over a Boreal Lake: Five Years of Eddy Covariance Data. *Geophys. Res. Lett.* **2011**, *38*. [CrossRef]
75. Cole, J.J.; Caraco, N.F.; Kling, G.W.; Kratz, T.K. Carbon Dioxide Supersaturation in the Surface Waters of Lakes. *Science* **1994**, *265*, 1568–1570. [CrossRef]
76. Anderson, L.G. Enhanced Uptake of Atmospheric CO2during Freezing of Seawater: A Field Study in Storfjorden, Svalbard. *J. Geophys. Res.* **2004**, 109. [CrossRef]

77. Hammer, U.T. Primary Production in Saline Lakes. In *Salt Lakes*; Williams, W.D., Ed.; Springer: Dordrecht, The Netherlands, 1981; Volume 5, pp. 47–57, ISBN 9789400986671.
78. Shadrin, N. Peculiarities of Structure, Functioning and Dynamics of the Salt Lake Ecosystems. In *Introduction to Salt Lake Sciences*; Science Press: Beijing, China, 2017; pp. 179–188.
79. Jin, Z.; You, C.-F.; Wang, Y.; Shi, Y. Hydrological and Solute Budgets of Lake Qinghai, the Largest Lake on the Tibetan Plateau. *Quat. Int.* **2010**, *218*, 151–156. [CrossRef]
80. Bartosiewicz, M.; Ptak, M.; Iestyn Woolway, R.; Sojka, M. On Thinning Ice: Effects of Atmospheric Warming, Changes in Wind Speed and Rainfall on Ice Conditions in Temperate Lakes (Northern Poland). *J. Hydrol.* **2020**, *597*, 125724. [CrossRef]
81. Surdu, C.M.; Duguay, C.R.; Brown, L.C.; Fernández Prieto, D. Response of Ice Cover on Shallow Lakes of the North Slope of Alaska to Contemporary Climate Conditions (1950–2011): Radar Remote-Sensing and Numerical Modeling Data Analysis. *Cryosphere* **2014**, *8*, 167–180. [CrossRef]
82. Zhao, G.; Li, Y.; Zhou, L.; Gao, H. Evaporative Water Loss of 1.42 Million Global Lakes. *Nat. Commun.* **2022**, *13*, 3686. [CrossRef] [PubMed]
83. Wang, W.; Lee, X.; Xiao, W.; Liu, S.; Schultz, N.; Wang, Y.; Zhang, M.; Zhao, L. Global Lake Evaporation Accelerated by Changes in Surface Energy Allocation in a Warmer Climate. *Nat. Geosci.* **2018**, *11*, 410–414. [CrossRef]
84. Xiao, K.; Griffis, T.J.; Baker, J.M.; Bolstad, P.V.; Erickson, M.; Lee, X.; Wood, J.J.; Hu, C.; Nieber, J.L. Evaporation from a Temperate Closed-Basin Lake and Its Impact on Present, Past, and Future Water Level. *J. Hydrol.* **2018**, *561*, 59–75. [CrossRef]
85. Blanken, P.D.; Spence, C.; Hedstrom, N.; Lenters, J.D. Evaporation from Lake Superior: 1. Physical Controls and Processes. *J. Great Lakes Res.* **2011**, *37*, 707–716. [CrossRef]
86. Ma, J.; Loiselle, S.; Cao, Z.; Qi, T.; Shen, M.; Luo, J.; Song, K.; Duan, H. Unbalanced Impacts of Nature and Nurture Factors on the Phenology, Area and Intensity of Algal Blooms in Global Large Lakes: MODIS Observations. *Sci. Total Environ.* **2023**, *880*, 163376. [CrossRef] [PubMed]
87. Adrian, R.; Wilhelm, S.; Gerten, D. Life-History Traits of Lake Plankton Species May Govern Their Phenological Response to Climate Warming. *Glob. Change Biol.* **2006**, *12*, 652–661. [CrossRef]
88. Wollrab, S.; Izmest'yeva, L.; Hampton, S.E.; Silow, E.A.; Litchman, E.; Klausmeier, C.A. Climate Change-Driven Regime Shifts in a Planktonic Food Web. *Am. Nat.* **2020**, *197*, 281–295. [CrossRef]
89. Grant, L.; Vanderkelen, I.; Gudmundsson, L.; Tan, Z.; Perroud, M.; Stepanenko, V.M.; Debolskiy, A.V.; Droppers, B.; Janssen, A.B.G.; Woolway, R.I.; et al. Attribution of Global Lake Systems Change to Anthropogenic Forcing. *Nat. Geosci.* **2021**, *14*, 849–854. [CrossRef]
90. Benson, B.J.; Magnuson, J.J.; Jensen, O.P.; Card, V.M.; Hodgkins, G.; Korhonen, J.; Livingstone, D.M.; Stewart, K.M.; Weyhenmeyer, G.A.; Granin, N.G. Extreme Events, Trends, and Variability in Northern Hemisphere Lake-Ice Phenology (1855–2005). *Clim. Change* **2011**, *112*, 299–323. [CrossRef]
91. Vincent, W.F. Effects of Climate Change on Lakes. *Encycl. Inland Waters* **2009**, 55–60. [CrossRef]
92. Carmack, E.; Vagle, S. Thermobaric Processes Both Drive and Constrain Seasonal Ventilation in Deep Great Slave Lake, Canada. *J. Geophys. Res. Earth Surf.* **2021**, *126*, e2021JF006288. [CrossRef]
93. Bouffard, D.; Zdorovennov, R.E.; Zdorovennova, G.E.; Pasche, N.; Wüest, A.; Terzhevik, A.Y. Ice-Covered Lake Onega: Effects of Radiation on Convection and Internal Waves. *Hydrobiologia* **2016**, *780*, 21–36. [CrossRef]
94. Yang, B.; Wells, M.G.; McMeans, B.; Dugan, H.A.; Rusak, J.A.; Weyhenmeyer, G.A.; Brentrup, J.A.; Hrycik, A.R.; Laas, A.; Pilla, R.M.; et al. A New Thermal Categorization of Ice-Covered Lakes. *Geophys. Res. Lett.* **2021**, *48*, e2020GL091374. [CrossRef]
95. Huang, W.; Zhang, J.; Leppäranta, M.; Li, Z.; Cheng, B.; Lin, Z. Thermal Structure and Water-Ice Heat Transfer in a Shallow Ice-Covered Thermokarst Lake in Central Qinghai-Tibet Plateau. *J. Hydrol.* **2019**, *578*, 124122. [CrossRef]
96. Farmer, D.M.; Carmack, E.C. Wind Mixing and Restratification in a Lake near the Temperature of Maximum Density. *J. Phys. Oceanogr.* **1981**, *11*, 1516–1533. [CrossRef]
97. Qi, M.; Yao, X.; Li, X.; Duan, H.; Gao, Y.; Liu, J. Spatiotemporal Characteristics of Qinghai Lake Ice Phenology between 2000 and 2016. *J. Geogr. Sci.* **2019**, *29*, 115–130. [CrossRef]
98. Preston, D.L.; Caine, N.; McKnight, D.M.; Williams, M.W.; Hell, K.; Miller, M.P.; Hart, S.J.; Johnson, P.T.J. Climate Regulates Alpine Lake Ice Cover Phenology and Aquatic Ecosystem Structure. *Geophys. Res. Lett.* **2016**, *43*, 5353–5360. [CrossRef]
99. Jensen, O.P.; Benson, B.J.; Magnuson, J.J.; Card, V.M.; Futter, M.N.; Soranno, P.A.; Stewart, K.M. Spatial Analysis of Ice Phenology Trends across the Laurentian Great Lakes Region during a Recent Warming Period. *Limnol. Oceanogr.* **2007**, *52*, 2013–2026. [CrossRef]