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Contrasting Changes in Lake Ice Thickness and Quality Due to Global Warming in the Arctic, Temperate, and Arid Zones and Highlands of Eurasia

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Abstract: Lake ice has a major impact on the functioning of lake ecosystems, the thermal and gas regimes of lakes, habitat conditions, socio-economic aspects of human life, local climate, etc. The multifaceted influence of lake ice makes it important to study its changes associated with global warming, including lake ice phenology, ice thickness, and the snow–ice fraction. This article presents a study of lake ice changes in different regions of Eurasia: the Arctic (Lake Imandra in the Murmansk region and Lake Kilpisjärvi in Finland), the temperate zone (six small and medium lakes in Karelia, Mozhaysk Reservoir in the Moscow region, and Lake Pääjärvi in Finland), the arid zone (Lake Ulansuhai in China), and the highlands (lakes Arpi and Sevan in Armenia). In the study regions, a statistically significant increase in winter air temperature has been recorded over the past few decades. The number of days with thaw (air temperature above 0 °C) has increased, while the number of days with severe frost (air temperature below −10 °C and −20 °C) has decreased. The share of liquid or mixed precipitation in winter increases most rapidly in the temperate zone. For two Finnish lakes, lakes Vendyurskoe and Vedlozero in Karelia, and Mozhaysk Reservoir, a decrease in the duration of the ice period was revealed, with later ice-on and earlier ice-off. The most dramatic change occurred in the large high-mountain Lake Sevan, where the water area has no longer been completely covered with ice every winter. In contrast, the small high-mountain Lake Arpi showed no significant changes in ice phenology over a 50-year period. Changes in the ice composition with an increase in the proportion of white ice and a decrease in the proportion of black ice have occurred in some lakes. In the temperate lakes Pääjärvi and Vendyurskoe, inverse dependences of the thickness of black ice on the number of days with thaw and frost in December–March for the first lake and on the amount of precipitation in the first month of ice for the second were observed. In the arid study region of China, due to the very little winter precipitation (usually less than

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10 mm) only black ice occurs, and significant interannual variability in its thickness has been identified.

Keywords: lake; Arctic; temperate zone; arid zone; highlands; ice phenology; snow; ice cover composition; black ice; white ice; regional climatic variability

1. Introduction

Changes in lake ice cover affect many aspects of nature and society, from the functioning of lake ecosystems to human activities and safety, local climate, economy, etc. [1–6]. Snow and ice cover limits the mass and energy fluxes between lakes and the atmosphere, affecting the light conditions, temperature, circulation, and gas content of the water body. Ice cover also changes the factors that shape the habitat of aquatic organisms [1,4,6–10]. Despite the increased interest in winter limnology, changes in lake ice due to climate variability have only been studied in a limited number of lakes; large blank spots still remain in vast areas of the Arctic and temperate zones, highlands, and arid regions.

Ice phenology is of critical importance for lake–atmosphere interactions and the socio-economic use of lakes. The main focus of lake researchers was, until recently, on the dates of ice-on and ice-off, as well as the duration of the ice period. To date, long data series of these dates in lakes in different regions of the world have been accumulated; their analyses have made it possible to find significant evidence of the relationship between climate change and ice phenology [11–20]. The use of remote sensing methods has greatly expanded the possibilities of obtaining ice phenology information in vast territories that are often difficult to access [21–24]. Remote sensing, together with field data, has revealed many patterns of changes in the ice regime of lakes, related, among other things, to local physical and geographical features of the territories [24,25].

Lake ice grows primarily via two mechanisms [8]. Black ice or congelation ice crystals grow down from the bottom of the ice, and the released latent heat is conducted through the ice cover to the atmosphere. White ice or snow–ice forms in a slush layer on top of the ice where the slush is a mixture of snow and liquid water from the lake, from melting, or from rain. Also, in this case, latent heat is conducted to the atmosphere. Frazil ice which is common in rivers may form in lakes only when there is open water present, and its contribution to the ice volume is small [8]. Thus, lake ice growth needs cold air (temperature below the freezing point), and white ice growth also needs snow accumulation on ice that is large enough (at least 1/3 of ice thickness) to cause flooding, the main factor in the production of slush on ice. For white ice, the timing of snowfall, in addition to the amount, is critical and makes ice thickness and composition a difficult climate problem.

Along with changes in the duration of the ice period, there are also long-term changes in the total ice thickness and composition of snow and ice cover; however, these changes have been studied much less. The publications in [5,26–32] provide references to several datasets on lake snow and ice cover composition in different regions of the world. A temperate lake ice cover usually includes black and white ice [8,33], while lake ice in the arid zone consists predominantly of black ice [10,34]. Black ice has a greater bearing capacity than white ice, which must be taken into account when calculating safe loads [5,32]. White ice is noticeably less transparent than black ice [35], and thus an increase in its thickness affects biological (development of phytoplankton) and thermo-hydrodynamic (radiation-driven convection) processes due to a decrease in sunlight under ice [5,7,36].

The study of ice cover thickness and composition requires visiting each specific lake and making on-site measurements. This is why the structure of ice cover remains virtually unstudied in lakes located in hard-to-reach places. In this regard, the development of methods for calculating the thickness of white and black ice based on weather data, such as air temperature and precipitation (snow, rain, sleet), is becoming relevant [36]. All surface heat balance factors, such as temperature, solar radiation, cloudiness, snow thickness on ice, and wind, should be taken into account, as they affect the formation and melting of ice.

The traditional method of studying the composition of lake ice cover requires an ice core to be cut out. Along with the traditional method, special devices such as an ice-penetrating radar [37] or a ground-penetrating radar [38] can be used to study the thickness and composition of snow-covered ice and its spatial heterogeneity. These devices are attached to a drone that flies over the lake [37] or on a sledge towed on the ice [38]. More recently, the ice profiling sonar has been a recognized high-tech tool for studying the evolution of ice in marine and freshwater bodies [39].

Autonomous measurement complexes with temperature sensors distributed vertically at intervals of 2–10 cm in the snow, ice, and water have been used successfully to study the seasonal evolution of snow and ice cover [28,40–43]. The advantage of these complexes is the capacity to obtain long time series of water and ice temperature with a small timestep (minutes-hours), allowing us to study the seasonal evolution of snow and ice cover thickness and composition.

The interest in changing lake ice cover composition under global warming sharply increased after the year 2000. A field campaign IceBlitz was carried out as part of the Global Lake Ecological Observatory Network (GLEON) in the winter season of 2020–2021 [5]. The total ice thickness and the thickness of white and black ice layers were measured several times during the winter in 31 lakes in the Northern Hemisphere. It was found that during the abnormally warm winter of 2020–2021, the proportion of white ice increased throughout the winter in most of the lakes. For some lakes, a predominant proportion of white ice was noted. The authors emphasized that during warm winters, when air temperature fluctuates around the freezing point (0 °C for fresh water), conditions are favorable for an increase in the proportion of white ice [5]. Attention was paid to an important consequence of the increasing proportion of white ice: the bearing capacity of ice decreases, requiring a review of ice safety regulations. In addition, the researchers emphasized the important role of white ice as a regulator of physical, chemical, and biological processes in lakes [5].

An analysis of ice structure changes in 21 Swedish lakes over five decades has shown a statistically significant correlation between the number of thaw days during the winter season and the thickness of both black and white ice [32]. These authors considered the number of thaw days to be an important parameter determining the thickness of ice in winter and showed that as the number of thaw days increases, the thickness of black and white ice decreases. Along with air temperature, precipitation plays a decisive role in the stratification of black and white ice [8].

Despite the research conducted, there are still many gaps in our knowledge of how the duration of the ice period and the thickness and composition of ice cover of lakes in different regions of the world change in the long term and seasonally. The connection of these changes with regional climate variability makes the task of accumulating and analyzing in situ and remote data very relevant, given the important role of snow and ice cover in the functioning of lake ecosystems and socio-economic aspects.

This paper presents the results of studying the ice regime (ice phenology, snow and ice cover thickness, and ice composition) of lakes of the Arctic zone (Lake Imandra, Murmansk region; Lake Kilpisjärvi, Finland), temperate zone (six small and medium lakes in Karelia, Mozhaysk Reservoir in Moscow region, and Lake Pääjärvi in southern Finland), highlands (lakes Arpi and Sevan, Republic of Armenia), and Central Asian arid zone (Lake Ulansuhai, Inner Mongolia, People's Republic of China) under current climatic conditions. The goal of this study was to identify the features of recent changes in lake ice against the background of regional climatic variability.

2. Materials and Methods

2.1. Study Sites and Weather Data Analysis

The locations of the studied lakes and the weather stations closest to them are shown in Figure 1. Table 1 provides the main information for each lake and the type/years of measurements, and information for the weather stations is provided in Table S1. The weather data for the Karelian lakes, Lake Imandra, Mozhaysk Reservoir, and the lakes of Armenia were obtained from websites [44–46], for Lake Ulansuhai from the website of the National Weather Data Center of China [47], and for the Finnish lakes Kilpisjärvi and Pääjärvi from the local FMI (Finnish Meteorological Institute) weather stations [48]. The distance from the weather stations to the lakes did not exceed 100 km; that is, changes in weather conditions that could affect the ice regime of the lakes in the long term were estimated with acceptable accuracy.

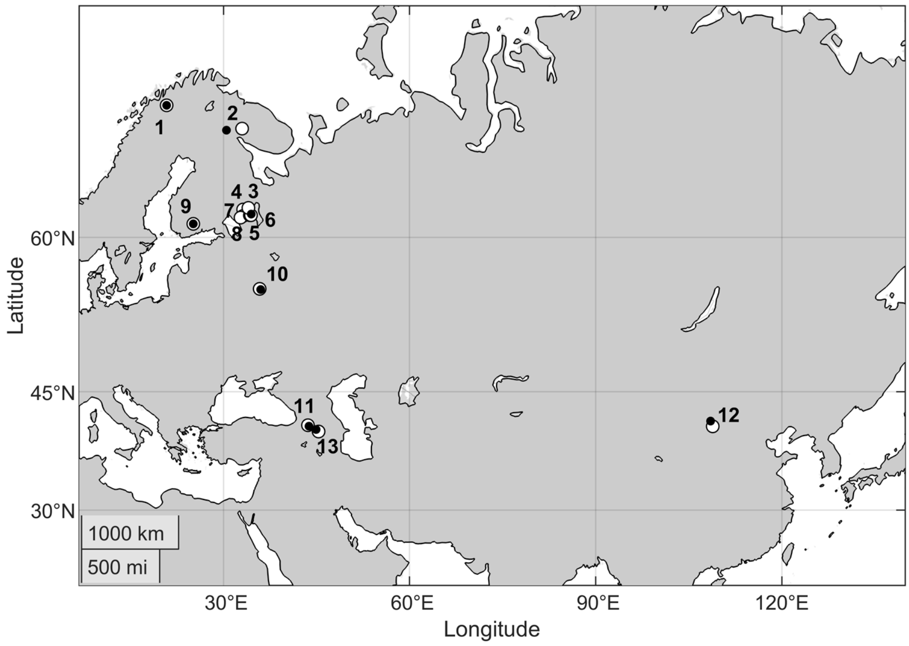

Figure 1. The position of the studied lakes (white circles) and weather stations (black dots): 1—Lake Kilpisjärvi, Finnish Arctic; 2—Lake Imandra, Murmansk region; 3—Forest pond no. 1, Karelia; 4—Lake Vendyurskoe, Karelia; 5—Forest pond no. 2, Karelia; 6—City lake, Karelia; 7—Lake Kroshnozero, Karelia; 8—Lake Vedlozero, Karelia; 9—Lake Pääjärvi, southern Finland; 10—Mozhaysk Reservoir, Moscow region; 11—Lake Arpi, Armenia; 12—Lake Ulansuhai, Inner Mongolia; 13—Lake Sevan, Armenia. The lake number increases as the latitude decreases.

To identify the climatic features of each study area, the average air temperature and precipitation were calculated for the whole year and for the four seasons (winter, spring, summer, and autumn) at each weather station for the period from 1991 to 2020 based on the open data [44–48]. The average air temperatures for December–March and November–April were calculated for all years/weather stations to identify long-term changes in winter weather conditions. To characterize the "severity" of winter, the accumulated freezing degree days (FDDs) for each year/weather station were also calculated (based on the average daily data).

In order to characterize how the conditions varied for the formation of white and black ice in different winter seasons, the number of days with a thaw (average daily air temperature is above 0 °C) and with frost (average daily air temperature below −10 °C and −20 °C) for each winter/meteorological station were counted. For the Arctic stations Kovdor and Kilpisjärvi, the counting period was from November to April, and for the other stations, it was from December to March. Precipitation was calculated for all stations from November to April, and liquid/mixed precipitation was calculated from December to March. The latter was estimated using the following method: if the average daily air temperature was above 0 °C, then the day's precipitation was assumed to be liquid/mixed. For the Amasia and Sevan weather stations, FDDs, the number of days with thaw and frost, and liquid precipitation were calculated only for 2005, when daily data [45] were available. Statistical analysis of the data series was carried out using STATISTICA 8.0 software. Statistical significance of linear trends was determined at the 5% significance level using Student's *t*-test ($p < 0.05$).

Table 1. The characteristics of the studied lakes and the type/years of measurements. The lakes are listed in order of decreasing latitude.

Lake, Region	Coordinates	A.s.l., m	Area, km^2	Volume, km^3	Average/Max Depth, m	Type of Measurements—Years of Measurements
Lake Kilpisjärvi, Finnish Arctic	N 69°03′ E 20°50′	473	37.3	0.727	19.5/57	IT, IC, IPh—1993–2022
Lake Imandra, Murmansk region	N 67°40′ E 33°00′	127	876	11.2	16/67	[1] IT, [2] IC—2021, 2023, 2024
Forest pond no. 1, Karelia	N 62°17′ E 34°01′	67	0.0069	No data	4.9/8.9	IT, IC—2024
Lake Vendyurskoe, Karelia	N 62°10′ E 33°10′	143	10.1	0.061	6.1/12.1	IT—1995–2000, 2002–2018, 2020–2024 IC—1997, 1999, 2000, 2002–2018, 2020–2024 [3] IPh—1994–2024
Forest pond no. 2, Karelia	N 61°44′, E 34°15′	157	0.012	No data	No data	IT, IC—2023, 2024
City lake, Karelia	N 61°44′ E 34°26′	102.2	0.118	0.000373	3.2/4.6	IT, IC—2023, 2024
Lake Kroshnozero, Karelia	N 61°40′ E 33°07′	94	8.9	0.0505	5.7/12.6	IT, IC—2021–2024
Lake Vedlozero, Karelia	N 61°33′ E 32°45′	76.6	57	0.407	7.0/14.8	IT, IC—2021–2024 IPh—1950–2021
Lake Pääjärvi, southern Finland	N 61°04′ E 25°08′	103	13.4	0.193	14.4/87	IT, IC, IPh—1993–2022
Mozhaysk Reservoir, Moscow region	N 55°35′ E 35°50′	183	30.7	0.221	22.5	IT—1971–2024 IC—1972, 1983, 1984, 2010, 2011, 2013, 2016, 2019–2024, IPh—1962–2022
Lake Arpi, Armenia	N 41°03′ E 43°37′	2022	20	0.1	4.2/8.0	IPh—1953–1975 (data averaged over the period), 1979, 1982
Lake Ulansuhai, Inner Mongolia	N 40°56′ E 108°52′	1019	233 (306)	0.328	1.12/2.5	IC—2021–2023
Lake Sevan, Armenia	N 40°18′ E 45°20′	1898	1240	36.088	26.8/79.7	IPh—1965–1975 (data averaged over the period), 1979, 1982

Note: [1] IT—ice thickness; [2] IC—ice composition; [3] IPh—ice phenology.

2.2. Ice Phenology Data Analysis

Ice phenology was studied in lakes Vendyurskoe and Vedlozero in Karelia, Lake Pääjärvi in southern Finland, Lake Kilpisjärvi in the Finnish Arctic, and Mozhaysk Reservoir in Moscow region. The duration of ice was taken as equal to the period between the dates of ice-on and ice-off. In Mozhaysk Reservoir, Lake Vedlozero, and lakes in Finland, the dates of ice-on and ice-off were determined visually by an observer. The lake ice data for Finnish lakes are open data from the Finnish Environment Institute [48]. In Lake Vendyurskoe, these dates were determined based on year-round water temperature measurements at an autonomous station (a chain equipped with temperature sensors TR-1060 RBR Ltd., Ottawa, ON, Canada) in the center of the lake [49]. Due to the fact that in some years water temperature measurements at the autonomous station were not carried out or began after ice-on and ended before ice-off, there are many gaps in the ice phenology of Lake Vendyurskoe. Linear trends in ice-on and ice-off dates and ice duration were analyzed using STATISTICA 8.0 software. Statistical significance of linear trends was determined at the 5% significance level using Student's *t*-test ($p < 0.05$).

Archived data from the middle of the last century on ice phenology of high-mountain lakes Arpi and Sevan [50,51] were compared with modern satellite imagery data to identify changes in the duration of ice cover of these lakes [52]. This comparison was carried out at a qualitative level.

2.3. Field Ice Thickness and Ice Cover Composition Research Methods

Measurements of ice thickness and ice cover composition were carried out in all lakes except the high-mountain lakes of Armenia. The most frequent measurements of ice thickness (once every 7–10 days during the whole winter) were made in certain years in Mozhaysk Reservoir (the years of these measurements are given in Table 1). In Lake Imandra, ice measurements were taken in April for three years before intensive melting began; therefore, these thickness values (total, black ice, and white ice) were taken as the maximums over winter. In the Karelian lakes, measurements were carried out for 1–22 years at a frequency of 1–3 times during the winter until intensive melting began. In the Finnish lakes, the frequency of measurements of ice thickness and structure was 2–3 times per each winter month for 30 years. The lake ice data are open data from the Finnish Environment Institute [48]. In Lake Ulansuhai, measurements were taken 2–3 times in winter and spring before intensive melting began for two years.

A cylindrical ice corer was used to extract an ice core sample in Mozhaysk Reservoir. In Lake Imandra and the lakes of Karelia and Finland, the following technique was used: 3–4 holes were drilled in the ice cover with an ice drill, cuts were made between the holes using an ice saw, and then the ice sample was lifted. Sometimes, the sample broke up into separate layers already in the hole. In this case, each layer of ice was extracted separately from the hole, and then the thickness of each ice layer was measured using a hydrological ruler. The measurement accuracy was 0.5 cm. Technologies similar to those used in Lake Imandra and the Karelian lakes were used in Lake Ulansuhai, where intact ice blocks were harvested due the lack of a slush layer. In the Finnish lakes, a snow–ice stake was deployed in new black ice cover when this was thick enough to walk on. The stake had a scale from which the thickness of accumulated snow–ice could be detected. The accumulated data on ice structure were used to analyze its interannual variability in each lake, as well as to identify similarities and differences in the ice structure of lakes in different climatic zones.

In studying changes in lake ice cover composition under the influence of regional climate variability, the focus was on black ice thickness and its limiting factors. The working hypothesis was that black ice growth decreases sharply after snowfall in early winter, and if the winter is fairly warm, black ice thickness does not increase much further. Thus, two decisive factors for the thickness of black ice at the end of winter were accepted: (1) precipitation at the beginning of winter, and (2) air temperature throughout the winter. The precipitation and the cumulative FDDs during the first month of the ice period and the number of days with thaw and frost in the first month of the ice period and from December to March were analyzed as the factors determining black ice thickness at the end of winter. The correlation between these parameters was studied using the STATISTICA 8.0 software.

3. Results

3.1. Weather Conditions

The Kilpisjärvi Lake area in the Finnish Arctic (Kilpisjärvi kyläkeskus weather station) has the lowest air temperature among the studied regions: the average annual air temperature for the period 1991–2020 was −1.4 °C, and the average air temperature for the calendar winter (December–February) was −11.5 °C (Table S2). Winter in this area is long (7 months a year) but not severe, the air temperature is rarely below −30 °C, and summer is short and cool with an average air temperature of 9.8 °C. In the Imandra Lake area (Kovdor weather station), the climate is warmer compared to the Kilpisjärvi Lake area: The average annual air temperature is 0.5 °C, the average winter temperature is −10.2 °C, and the average summer temperature is 12.4 °C. Winter lasts for 6 months.

In southern Karelia (Petrozavodsk weather station), Lake Pääjärvi (Lammi Pappila, southern Finland), and Mozhaysk Reservoir (Mozhaysk weather station, Moscow region), the average annual air temperature in 1991–2020 was 3.6 °C, 4.8 °C, and 5.5 °C, respectively. Winter in these areas lasts 4–5 months. The average air temperature in the winter months in 1991–2020 was −7.4 °C, −5.0 °C, and −6.1 °C, respectively, and the average temperature in summer was 15.4 °C, 15.5 °C, and 17.3 °C, respectively.

The average annual precipitation in 1991–2020 in these regions was 606–657 mm, except for in Lake Kilpisjärvi where it was 515 mm. The precipitation is distributed unevenly throughout the year. The highest level is in summer (33–36%); in autumn, it is 22–28%; in spring, it is 18–20%; and in winter, it is 18–22% (in Lake Kilpisjärvi it is 27%). In winter, the greatest monthly precipitation falls in December—42–53 mm.

At the high-mountain lakes Sevan and Arpi (weather stations of Sevan and Amasia in Armenia), the average annual air temperature in 1991–2020 was 6.2 °C and 5.1 °C, respectively. The temperature differed mainly in the winter period, when it was 2.9 °C higher at the Sevan station than at the Amasia station and averaged at −3.8 °C. The winter period with negative air temperature lasts four months from December to March. This region is characterized by a long and warm autumn. Almost the same annual precipitation falls at these stations: 607 and 608 mm. The greatest seasonal fraction falls in spring (34–35%) and summer (28–30%), and there is noticeably less precipitation in autumn (19%) and winter (16–18%).

The area of the Mid Urad weather station (Inner Mongolia) is characterized by a sharply continental climate with a hot summer (the average air temperature in 1991–2020 was 21.7 °C), a warm spring (8.2 °C) and autumn (6.0 °C), and a cold winter (−10.2 °C). The climate is dry. The average annual precipitation was 212 mm in 1991–2020. The greatest monthly precipitation fell in July (50 mm) and August (56 mm), and from November to February, the monthly values were extremely small, averaging at 2.6 mm in November, 2.7 mm in December, 1.2 mm in January, and 1.6 mm in February. Winter precipitation accounted for 2.5% of the annual precipitation, while the summer fraction represented 64%.

Thus, winters are becoming warmer in all study regions, as evidenced by an increase in the average air temperature for the periods December–March and November–April, as well as a decrease in cumulative FDDs for the entire winter season (Figure 2). The trend parameters are shown in Table 2. There is an increase in the number of days with thaw (Tair > 0 °C) and a decrease in the number of days with severe frost (Tair < −10 °C and Tair < −20 °C). A change in the amount of liquid/mixed precipitation (December–March) over several decades was also found (Figure 3), and the most pronounced increase occurred in the temperate zone in recent decades.

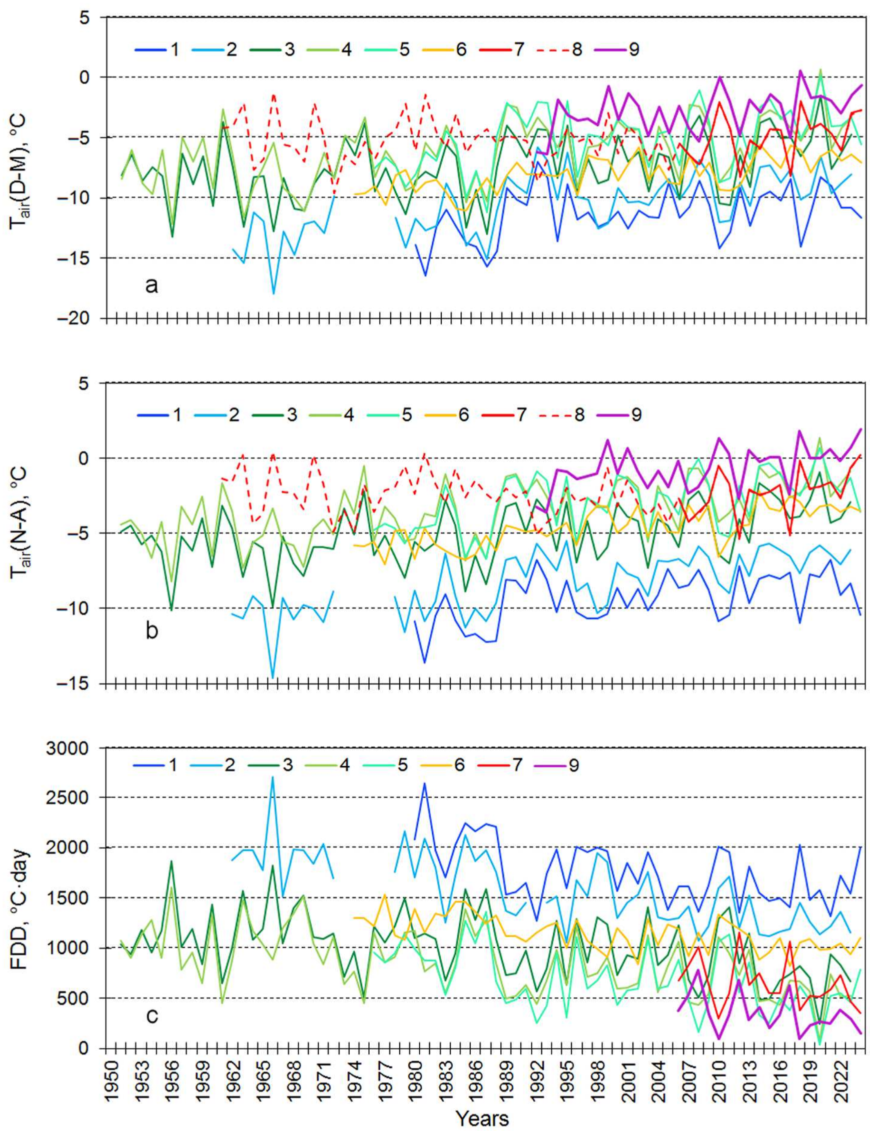

Figure 2. Air temperature during December–March (**a**) and November–April (**b**) and FDDs during winter (**c**) in different years/for different meteorological stations. Here and in Figure 3, 1—Kilpisjärvi kyläkeskus (Lake Kilpisjärvi) [48]; 2—WMO 22204 Kovdor (Lake Imandra) [44,45]; 3—WMO 22820 Petrozavodsk (Karelian lakes) [44,45]; 4—27509 WMO Mozhaysk (Mozhaysk Reservoir) [44,45]; 5—Lammi Pappila (Lake Pääjärvi) [48]; 6—Mid Urad (Lake Ulansuhai) [47]; 7 and 8—Amasia (Lake Arpi) [45] and [46] respectively; and 9—WMO 37717 Sevan (Lake Sevan) [46].

In order to detect the present changes in regional climates, meteorological data series of comparable duration, starting from 1976 to 1979, were analyzed. A statistically significant increase in air temperature in winter months of 0.6–0.8 °C/10 years was found at all stations in the Arctic, temperate and arid zones, and highlands (Table 2). The number of days with thaw (T_{air} > 0 °C) increased significantly at all stations (excluding Amasia and Sevan from the analysis), and the increase was the greatest at the Mid Urad station in Inner Mongolia (6.3 days/10 years), gradually decreasing to the minimum values in the Arctic (2.0 days/10 years). The number of days with severe frost (T_{air} < −10 °C) decreased significantly at all stations (excluding Amasia and Sevan from the analysis), with a minimum rate of change at the Mid Urad station (−3.1 days/10 years) and a maximum in the Arctic (−5 to −7 days/10 years). The number of days with highly severe frost (T_{air} < −20 °C) decreased most rapidly in the Arctic (−2 to −3 days/10 years); in the temperate zone, this rate was −1 day/10 years, and in the arid zone of China, it was −0.5 days/10 years. The trends were significant only for the Arctic stations and Mozhaysk.

A significant decrease in cumulative FDDs was found at all stations, with the maximum in the Arctic (−11.5 to −14.8 °C·day/year). In Kovdor, the average air temperature in winter months increased (0.8 °C/10 years) and the sum of FDDs decreased (−14.81 °C· day/year) most rapidly. The rate of warming in the Finnish Arctic was somewhat lower than in the Murmansk region but still significant: an increase in winter air temperature of 0.6 °C/10 years and a decrease in cumulative FDDs of −11.5 °C·day/year.

Table 2. The characteristics of the linear trends of indicators reflecting changes in regional climates over the past several decades. Statistical significance of linear trends was determined at the 5% significance level using Student's *t*-test ($p < 0.05$).

Weather Station, Lake	Years	Parameter	b	r^2	p
Kilpisjärvi kyläkeskus Lake Kilpisjärvi	1979–2024	T_{air} December–March	+0.06 °C/year	$r^2 = 0.14$	$p = 0.0108$
	1979–2024	T_{air} November–April	+0.06 °C/year	$r^2 = 0.24$	$p = 0.0007$
	1979–2024	FDD	–11.5 °C·day/year	$r^2 = 0.25$	$p = 0.0004$
	1979–2024	Thaw	+0.20 day/year	$r^2 = 0.13$	$p = 0.0153$
	1979–2024	$T_{air} < -10$ °C	–0.69 day/year	$r^2 = 0.28$	$p = 0.0002$
	1979–2024	$T_{air} < -20$ °C	–0.25 day/year	$r^2 = 0.13$	$p = 0.0180$
22204 Kovdor Lake Imandra	1976–2023	T_{air} December–March	+0.08 °C/year	$r^2 = 0.25$	$p = 0.0003$
	1976–2023	T_{air} November–April	+0.08 °C/year	$r^2 = 0.39$	$p = 0.0000$
	1976–2023	FDD	–14.8 °C·day/year	$r^2 = 0.43$	$p = 0.0000$
	1976–2023	Thaw	+0.29 day/year	$r^2 = 0.16$	$p = 0.0037$
	1976–2023	$T_{air} < -10$ °C	–0.55 day/year	$r^2 = 0.19$	$p = 0.0018$
	1976–2023	$T_{air} < -20$ °C	–0.32 day/year	$r^2 = 0.24$	$p = 0.0004$
22820 Petrozavodsk Karelian lakes	1976–2023	T_{air} December–March	+0.07 °C/year	$r^2 = 0.17$	$p = 0.0037$
	1976–2023	T_{air} November–April	+0.07 °C/year	$r^2 = 0.24$	$p = 0.0004$
	1976–2023	FDD	–10.4 °C·day/year	$r^2 = 0.22$	$p = 0.0008$
	1976–2023	$T_{air} < -10$ °C	–0.44 day/year	$r^2 = 0.16$	$p = 0.0055$
	1976–2023	Total precipitation	+0.75 mm/year	$r^2 = 0.10$	$p = 0.0256$
	1950–2023	Liquid precipitation	+0.30 mm/year	$r^2 = 0.12$	$p = 0.0023$
27509 Mozhaysk Mozhaysk Reservoir	1976–2023	T_{air} December–March	+0.07 °C/year	$r^2 = 0.18$	$p = 0.0029$
	1976–2023	T_{air} November–April	+0.06 °C/year	$r^2 = 0.25$	$p = 0.0003$
	1976–2023	FDD	–9.ºC·day/year	$r^2 = 0.22$	$p = 0.0006$
	1976–2023	Thaw	+0.38 day/year	$r^2 = 0.11$	$p = 0.0191$
	1976–2023	$T_{air} < -10$ °C	–0.40 day/year	$r^2 = 0.16$	$p = 0.0046$
	1976–2023	$T_{air} < -20$ °C	–0.10 day/year	$r^2 = 0.08$	$p = 0.0457$
	1976–2023	Liquid precipitation	+0.65 mm/year	$r^2 = 0.10$	$p = 0.0260$
	1950–2023	Liquid precipitation	+0.57 mm/year	$r^2 = 0.20$	$p = 0.0000$
Lammi Pappila Lake Pääjärvi	1976–2024	T_{air} December–March	+0.08 °C/year	$r^2 = 0.19$	$p = 0.0016$
	1976–2024	T_{air} November–April	+0.07 °C/year	$r^2 = 0.26$	$p = 0.0002$
	1976–2024	FDD	–9.5 °C·day/year	$r^2 = 0.20$	$p = 0.0016$
	1976–2024	Thaw	+0.37 day/year	$r^2 = 0.11$	$p = 0.0223$
	1976–2024	$T_{air} < -10$ °C	−0.42 day/year	$r^2 = 0.18$	$p = 0.0029$
	1976–2024	Liquid precipitation	+0.87 mm/year	$r^2 = 0.13$	$p = 0.0097$
Mid Urad Lake Ulansuhai	1976–2024	T_{air} December–March	+0.06 °C/year	$r^2 = 0.37$	$p = 0.0000$
	1976–2024	T_{air} November–April	+0.06 °C/year	$r^2 = 0.48$	$p = 0.0000$
	1976–2024	FDD	–6.7 °C·day/year	$r^2 = 0.33$	$p = 0.0000$
	1976–2024	Thaw	+0.63 day/year	$r^2 = 0.41$	$p = 0.0000$
	1976–2024	$T_{air} < -10$ °C	–0.31 day/year	$r^2 = 0.17$	$p = 0.0040$
Amasia Lake Arpi	1992–2024	T_{air} December–March	+0.06 °C/year	$r^2 = 0.13$	$p = 0.0422$
	1992–2024	T_{air} November–April	+0.06 °C/year	$r^2 = 0.18$	$p = 0.0139$
	2006–2024	T_{air} November–April	+0.12 °C/year	$r^2 = 0.22$	$p = 0.0446$
37717 Sevan Lake Sevan	1992–2024	T_{air} December–March	+0.08 °C/year	$r^2 = 0.21$	$p = 0.0081$
	1992–2024	T_{air} November–April	+0.07 °C/year	$r^2 = 0.27$	$p = 0.0017$
	2006–2024	T_{air} November–April	+0.14 °C/year	$r^2 = 0.25$	$p = 0.0422$

High warming rates were also found for the high-mountain stations of Amasia and Sevan in Armenia. The length of the daily air temperature time series that we had for them—about 20 years—is too short to identify statistically significant trends. However, we have established that warming in their area is also proceeding quite rapidly. The number of thaw days is increasing (6–8 days/10 years), the number of days with frost is decreasing (−5 to −11 days/10 years), and the accumulated FDD is decreasing (−13.7–15.4 °C·day/year).

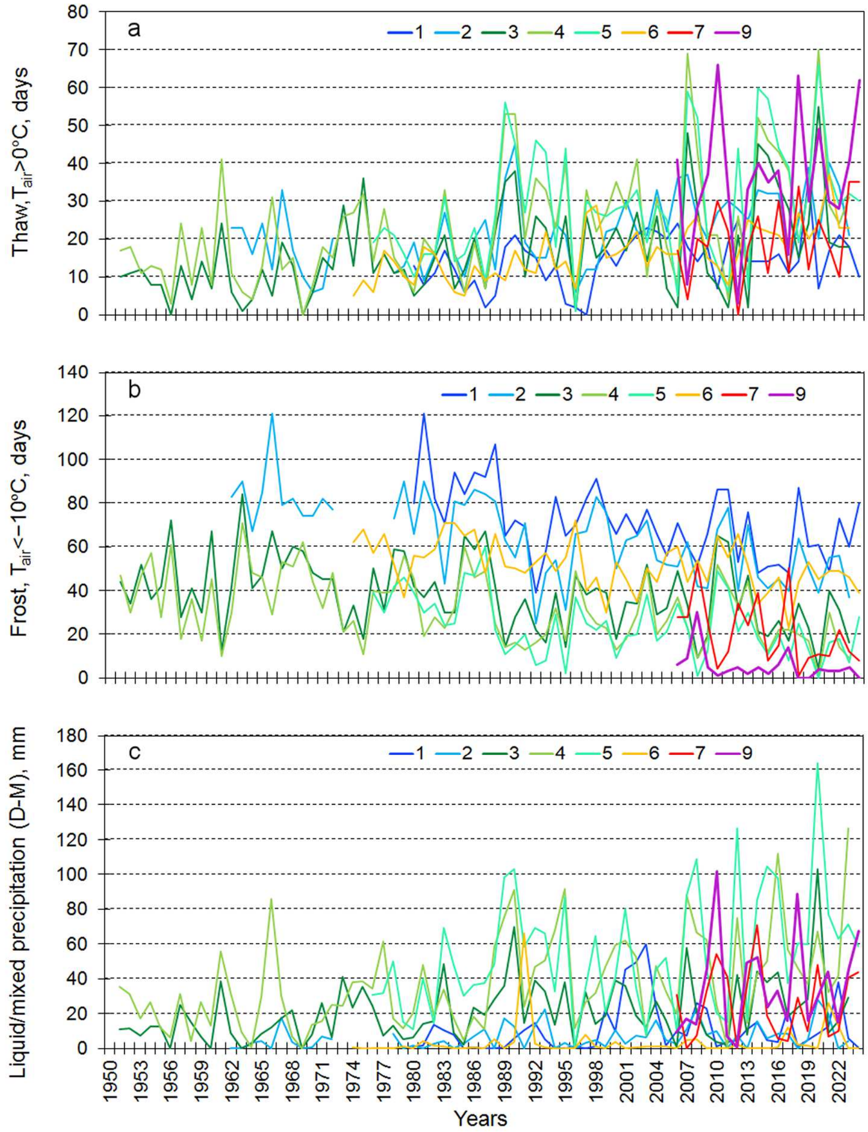

Figure 3. The number of days with thaw (**a**), the number of days with frost (**b**), and the liquid/mixed precipitation (**c**) for the period December–March in different years/for different weather stations.

In 1976–2024, winter precipitation increased significantly only at one meteorological station, Petrozavodsk (7.5 mm/10 years) (Table 2). During this period, winter precipitation also increased at other stations, but not significantly (8–10 mm/10 years at Arctic stations, 7.5 mm/10 years in southern Finland, 3.5 mm/10 years at Mozhaysk station, 3.0 mm/10 years in Inner Mongolia). For the highlands of Armenia, total precipitation in winter has not changed over the past 20 years.

The share of liquid precipitation in winter has increased most significantly in southern Finland (8.7 mm/10 years, significant trend) and in the Moscow region (6.5 mm/10 years, significant trend) over the past 50 years. A comparison of data for the past 50 and 70 years in these regions shows that the rate of increase in liquid precipitation has accelerated in recent years. The increasing liquid precipitation in the Arctic reached 1–2 mm/10 years (the trends are not significant) and 3 mm/10 years in Karelia (the trend is significant). In the highlands of Armenia and in the arid zone of Inner Mongolia, liquid precipitation slightly increased (+2 mm/10 years, but the trends are not significant).

3.2. Ice Phenology and Maximum Ice Thickness

The highest rate of decrease in the ice cover period over the past 30 years was found in Mozhaysk Reservoir (−10.5 days/10 years) and in the Karelian lake Vedlozero (−9.3 days/10 years) (trends are significant) (Table 3). In Lake Pääjärvi, southern Finland, the reduction in ice cover was −10.4 days/10 years, but the trend was not significant. In the Finnish Arctic lake Kilpisjärvi, the reduction (−5.8 days/10 years) was half of the temperate zone value but the trend was statistically significant. Observations of the duration of the ice period in Lake Vendyurskoe have been conducted for 30 years. In some years, the dates of ice-on and/or ice-off are unknown, and therefore, large gaps exist in the series of ice duration. There is a tendency toward a reduction in the ice period at Lake Vendyurskoe, although it is not statistically significant. Comparing the rate of ice cover reduction in Mozhaysk Reservoir and the Karelian lake Vedlozero over a long period of 60–70 years, we can see that the rate of reduction in both lakes has increased by 2–3 times over the last 30 years (Table 3).

Table 3. Parameters of linear trends of ice duration, ice-on and ice-off dates, maximum ice thickness, and black ice thickness in different lakes. Statistical significance of linear trends was determined at 5% significance level using Student's *t*-test ($p < 0.05$).

Lake	Parameter	Years	b	r^2	p
Lake Kilpisjärvi	Ice duration	1993–2022	−0.58 day/year	$r^2 = 0.14$	$p = 0.0422$
	Ice-off	1994–2022	−0.36 day/year	$r^2 = 0.14$	$p = 0.0403$
Lake Vendyurskoe	Total ice	1995–2000, 2002–2018, 2020–2024	−0.52 cm/year	$r^2 = 0.24$	$p = 0.0083$
	Black ice	1997, 1999–2000, 2002–2018, 2020–2024	−0.83 cm/year	$r^2 = 0.36$	$p = 0.0015$
	White ice	1997, 1999–2000, 2002–2018, 2020–2024	+0.65 cm/year	$r^2 = 0.18$	$p = 0.0266$
Lake Vedlozero	Ice duration	1950–2021	−0.33 day/year	$r^2 = 0.20$	$p = 0.0001$
		1993–2021	−0.93 day/year	$r^2 = 0.24$	$p = 0.0061$
	Ice-on	1950–2020	+0.22 day/year	$r^2 = 0.13$	$p = 0.0027$
		1993–2021	+0.54 day/year	$r^2 = 0.13$	$p = 0.0485$
	Ice-off	1951–2021	−0.15 day/year	$r^2 = 0.19$	$p = 0.0002$
		1993–2021	−0.40 day/year	$r^2 = 0.24$	$p = 0.0067$
Mozhaysk Reservoir	Ice duration	1961–2021	−0.50 day/year	$r^2 = 0.20$	$p = 0.0003$
		1993–2020	−1.05 day/year	$r^2 = 0.22$	$p = 0.0110$
	Ice-on	1961–2020	+0.36 day/year	$r^2 = 0.17$	$p = 0.0011$
	Ice-off	1962–2023	−0.14 day/year	$r^2 = 0.08$	$p = 0.0316$
	Total ice	1972–1999, 2003–2017, 2019–2021	−0.38 cm/year	$r^2 = 0.24$	$p = 0.0006$
Lake Pääjärvi	Ice-on	1993–2021	+0.94 day/year	$r^2 = 0.14$	$p = 0.0417$
	Total ice	1994–2022	−0.58 cm/year	$r^2 = 0.17$	$p = 0.0230$
	Black ice	1994–2022	−0.70 cm/year	$r^2 = 0.33$	$p = 0.0009$

Over the last thirty years, freezing dates have shifted later in all lakes, but the trends are significant only in the Karelian lake Vedlozero and Lake Pääjärvi in southern Finland. The largest delay in the ice-on date has been found in Lake Pääjärvi: 12.5 days/10 years (trend is statistically significant) (Table 3). In Mozhaysk Reservoir and Lake Vedlozero, ice also forms later, but the rate of delay is less, 6 days/10 years and 5.4 days/10 years, respectively (trend is statistically significant only for Lake Vedlozero). In Lake Kilpisjärvi in the Finnish Arctic, the ice-on date has so far been delayed by only 2.4 days/10 years (the trend is not significant).

Ice breakup date trends were significant only in lakes Kilpisjärvi (−3.6 days/10 years) and Vedlozero (−4.0 days/10 years) over the last thirty years. In Mozhaysk Reservoir and lakes Vedlozero and Kilpisjärvi, the rate of shift to earlier ice-off dates is 3–4 times greater than in Lake Pääjärvi (−1.1 days/10 years, the trend is not significant). The rate of shift to earlier dates has increased by a factor of 2–2.5 over the past 30 years compared to the past 70-year period in Lake

Vedlozero (1.5 days/10 years) and Mozhaysk Reservoir (1.4 days/10 years). The shift in the dates of ice-on and ice-off for Lake Vendyurskoe is complicated due to the large number of gaps in the data, but a tendency toward later ice-on and earlier ice-off is also observed.

A significant decreasing trend in total ice thickness (−5.8 cm/10 years) was found in Lake Pääjärvi, southern Finland (Table 3). In the Karelian lake Vendyurskoe, the trend is slightly lower (−5.2 cm/10 years) and noticeably lower in Mozhaysk Reservoir (−3.8 cm/10 years), but each trend was significant. In Lake Kilpisjärvi in the Finnish Arctic, overall ice thickness, as well as the thickness of black and white ice, has remained virtually unchanged for 30 years.

The change in the thickness of black and white ice was estimated only for two lakes: Lake Pääjärvi in southern Finland and the Karelian lake Vendyurskoe. A significant decrease in black ice thickness (−7 to −8 cm/10 years) was found for both lakes over the past 30 years. An increase in white ice thickness was found for both lakes, but in Pääjärvi the trend was not significant. In Lake Vendyurskoe (6.5 cm/10 years), it was much greater than in Lake Pääjärvi (1.2 cm/10 years). Interestingly, the white ice trend in Lake Vendyurskoe was negative, excluding the last three years [6], when significant amounts of snow fell and the thickness of white ice was more than 50% of the total ice thickness. This conclusion shows that observation series that are too short (less than 30 years) do not allow us to obtain reliable trends.

Changes in ice phenology in the high-mountain lakes of Armenia—the large lake Sevan and the small lake Arpi—were assessed based on published data from the middle of the last century and modern satellite images (Table 4 and Figures 4–7). The duration of the ice period in the middle of the XX century was about 150 days in Lake Arpi and 27–70 days for different parts of Lake Sevan (Table 4, Figure 6).

Table 4. Ice phenology dates (day.month) for Arpi and Sevan lakes in middle of XX century [50,51].

Lake—Station	Years	Date of Autumn Ice Events *	Date of Ice-On	Date of Ice-Off
Arpi—Shurabad	1953–1975 average date	17 November	23 November	23 April
	1953–1975 earliest date	25 October 1965	25 October 1965	8 April 1955
	1953–1975 latest date	9 December 1968	24 December 1971	7 May 1954
	1978–1979	3 November	13 November	15 April
	1981–1982	5 November	14 November	20 April
Sevan peninsula	1978–1979	9 December	no data	9 March
	1981–1982	10 January	24 February	24 March
Sevan—Shorzha	1978–1979	10 January	no data	26 March
	1981–1982	5 February	21 February	18 March
Sevan—Dara	1978–1979	13 January	no data	8 March
	1981–1982	20 January	19 February	20 March
Sevan—Karchaghbyur	1978–1979	8 January	no data	6 March
	1981–1982	no data	16 February	21 March
Sevan—Noraduz	1978–1979	1 January	no data	12 February
	1981–1982	21 January	19 February	26 March

Notes: * ice events—the period from the first appearance of ice near the coast until the water area is completely covered with ice.

In the period from 1953 to 1975, the longest ice period in Lake Arpi was 171 days in the winter of 1973–1974 and the longest ice event period was 236 days in 1970–1971 (Figure 6b). The shortest ice period was in 1971–1972 (112 days). The earliest date of autumn ice events in Lake Arpi and the ice-on date were 25 October 1965, and the latest ice event and ice-on dates were 9 December 1968 and 24 December 1971, respectively (Table 4). The latest date of ice-off was 7 May 1954, and the earliest one was 8 April 1955. Ice periods in 1978–1979 and 1981–1982 were 153 and 158 days long, and ice event durations were 174 and 172 days long, respectively, which are roughly consistent with the data for 1953–1975. In 1995 and 2022–2024, the duration of the ice period in Lake Arpi did not change significantly compared to the mid-XX century (according to satellite images, see Figures S1–S13 and Figure 4). For example, Figure 4 shows satellite images from late December 2022 and mid-March 2023, when the lake was completely covered with ice. In the period 1954–1970, the average ice thickness in Lake Arpi reached 63 cm in March, and its maximum occurred in April 1968 (88 cm) (Figure 5).

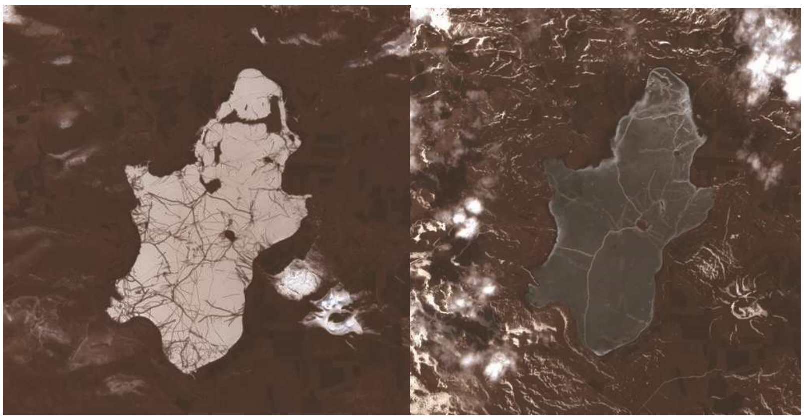

Figure 4. Satellite images of the surface of Lake Arpi on 25 December 2022 (**left**) and 15 March 2023 (**right**) from Sentinel-2 L2A.

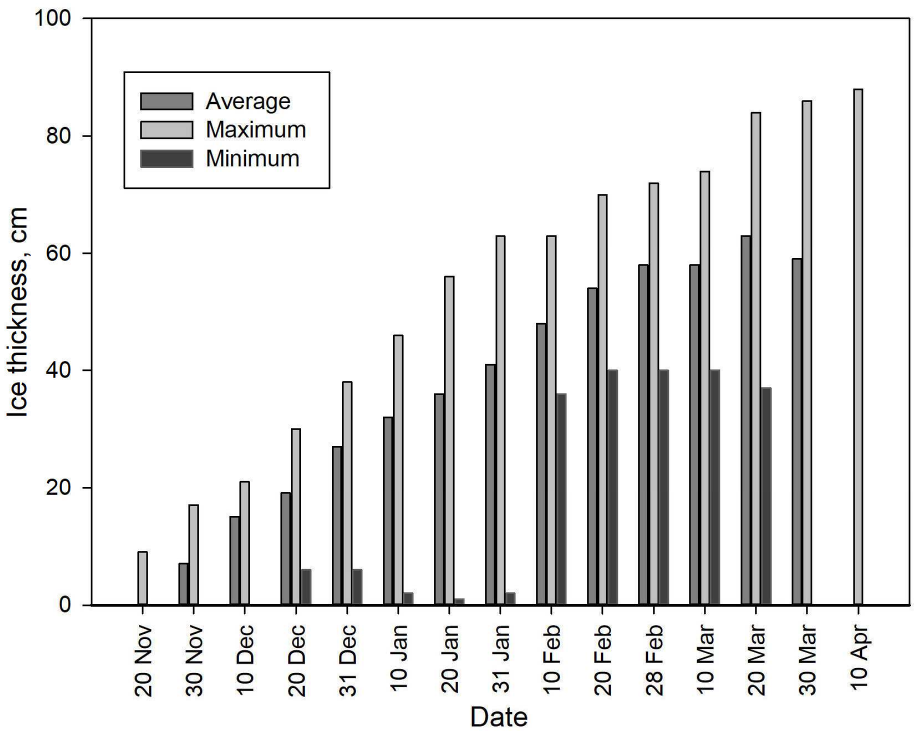

Figure 5. Average, maximum, and minimum ice thickness of Lake Arpi (Shurabad) in period 1954–1970.

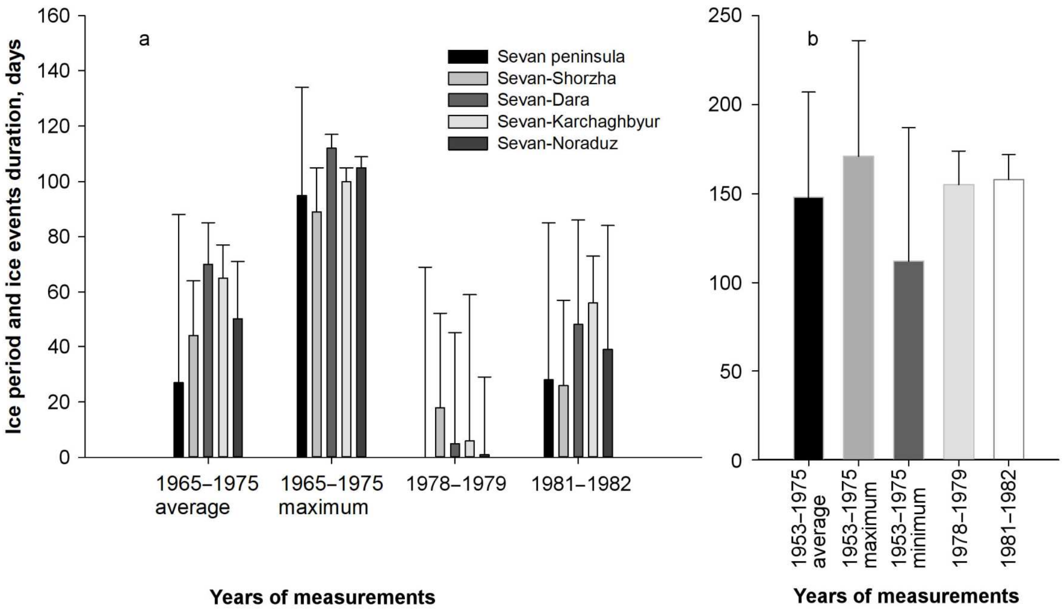

Figure 6. Average and maximum ice period (bars) and ice event (lines) duration at different stations in Lake Sevan (**a**) for 1965–1975 and two winters, 1978–1979 and 1981–1982, and for Lake Arpi (**b**) for 1953–1975 and two winters, 1978–1979 and 1981–1982.

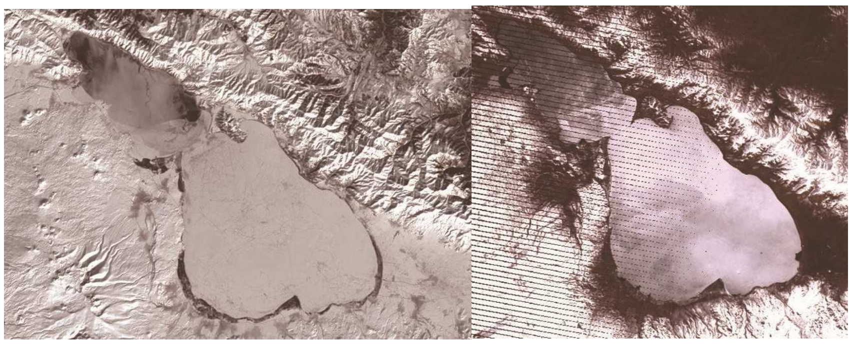

Figure 7. Satellite images of Lake Sevan on 18 February 2017 from Landsat_8L (**left**) and on 30 March 2017 from Landsat-7 (**right**).

The ice regime has been unstable in Lake Sevan for last 100 years and there have been significant ice cover changes due to anthropogenic impacts and climate change. In 1930–1980, there was a man-made decrease in the water level of Lake Sevan, the peak of which occurred in 1940–1950. As a result, by the 1980s, the lake level had dropped by 19 m. Before the decrease in the water level, the lake was completely covered with ice only once every 15–20 years, but after the decrease the lake was completely ice-covered almost every year. Currently, complete freeze-up occurs approximately every seven years [53].

The dates of ice events at different stations in Lake Sevan in 1965–1975, 1978–1979, and 1981–1982 are shown in Table 4. The average ice duration during 1965–1975 was 27–70 days (Figure 6a), and moreover, the maximum duration at different stations reached 105–134 days. A noticeably short ice duration was observed in the winter of 1978–1979: 1–18 days at different stations. The ice period of 26–56 days were observed at different stations in 1981–1982. The duration of ice events was 29–69 days in 1978–1979 and 57–86 days in 1981–1982. The thickness of Lake Sevan ice has decreased by 5 cm/year this century, rarely reaching 30 cm [54]. According to HYDROLARE data on water temperature in Lake Sevan for 1938–2013, a positive trend is observed for all winter months, which is especially significant in December, and this is the reason for the reduction in the duration of ice cover.

Satellite images of Lake Sevan are given in Figure 7, Figures S14 and S15. During the cold winter of 2016–2017, the entire water area was covered with ice and this persisted to the end of March 2017.

3.3. Ice Cover Composition

The thickness of snow, white and black ice, and slush measured in the Karelian lakes, Lake Imandra, Mozhaysk Reservoir, and Lake Ulansuhai in 2021–2024 are shown in Figure 8 and Table S3. Annual data on the composition of ice in Lake Pääjärvi are given in Table S4, and data on Lake Kilpisjärvi are given in Table S5. The thickness of black and white ice in Finnish lakes at the end of winter in different years is shown in Figure 9. Photos of ice from some lakes are shown in Figures 10 and 11. Data on the structure and thickness of ice in the lakes of Karelia and Mozhaysk Reservoir in different years given in Table 1 are also provided in [5].

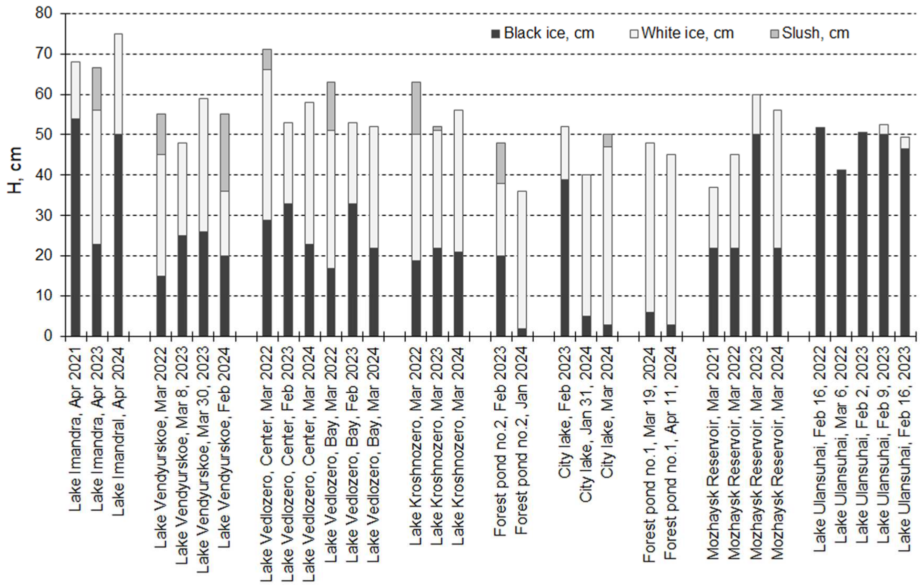

Figure 8. Thickness of black ice, white ice, and slush in lakes in Arctic, temperate, and arid zones in 2021–2024.

In Lake Imandra in April 2021 and 2024, the ice core consisted of black and white ice, with no layer of slush between them; in April 2023, the ice was multi-layered, and the sample disintegrated into separate layers, since black ice and three layers of white ice had a layer of wet snow (slush) between them (Figure 10d). Black ice thickness accounted for 66–79% of the total ice thickness in April 2021 and 2024, and only 34% in April 2023, when the proportion of white ice and slush combined exceeded 66% (Figure 8).

In all of the studied lakes of Karelia across all of the years of measurements given in Table 1, in the middle and at the end of winter before melting (January, February, March, and April), the ice cover included layers of black and white ice; a layer of slush was observed in some years. White ice was multi-layered in March 2022 in all lakes (see Table S3 and Figures 8 and 10a) with three to four layers. This ice structure was formed as a result of alternating heavy snowfall and thaw/freeze cycles during the winter of 2021–2022. The total ice thickness of the Karelian lakes varied between 36 and 71 cm in the years given in Table 1 and Table S3. The thickness of black ice (15–39 cm) accounted for 22–75% (on average 43%) of the total ice thickness in the middle and at the end of winter. The minimum thickness of black ice (2–6 cm which corresponded to 5.5–12.5% of the total ice thickness) was observed in the winter of 2023–2024 in small Karelian lakes—two forest ponds and a small city lake in Petrozavodsk (Figure 8 and Table S3). During this winter, the thickness of white ice and slush on small lakes increased to 93–94%. In other studied lakes of Karelia (Vendyurskoe, Vedlozero, Kroshnozero) in 2023–2024, the share of black ice was noticeably higher, amounting to 32–42%. The very small proportion of black ice in small lakes is explained by the fact that snow fell almost immediately after ice had formed. But in mid-sized lakes, ice formed later, and no snow fell during the initial period of ice. A model [36] confirms the important role of snow in the formation of white ice and the limitation of black ice when there is a large amount of snow on the ice.

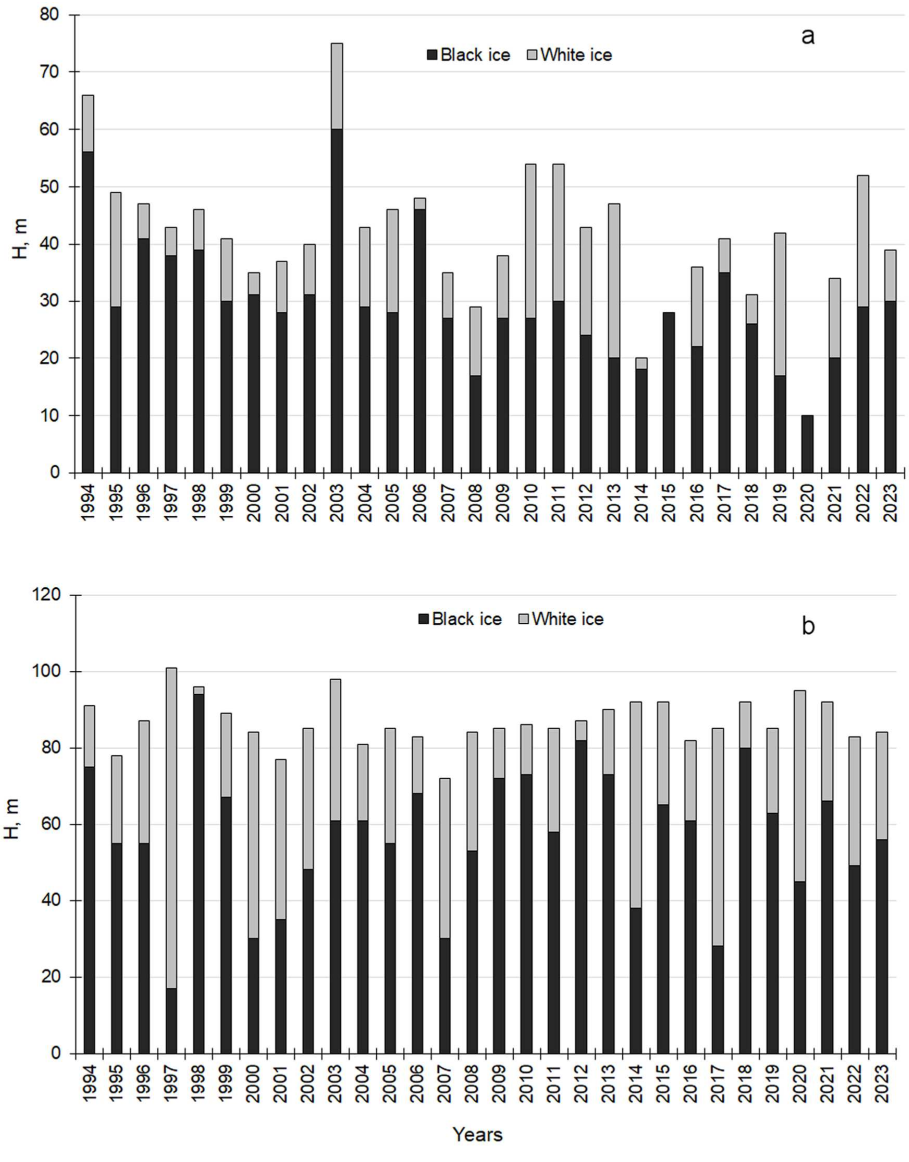

Figure 9. The thickness of black ice and white ice in lakes Pääjärvi (**a**) and Kilpisjärvi (**b**) at the end of winter in 1994–2023.

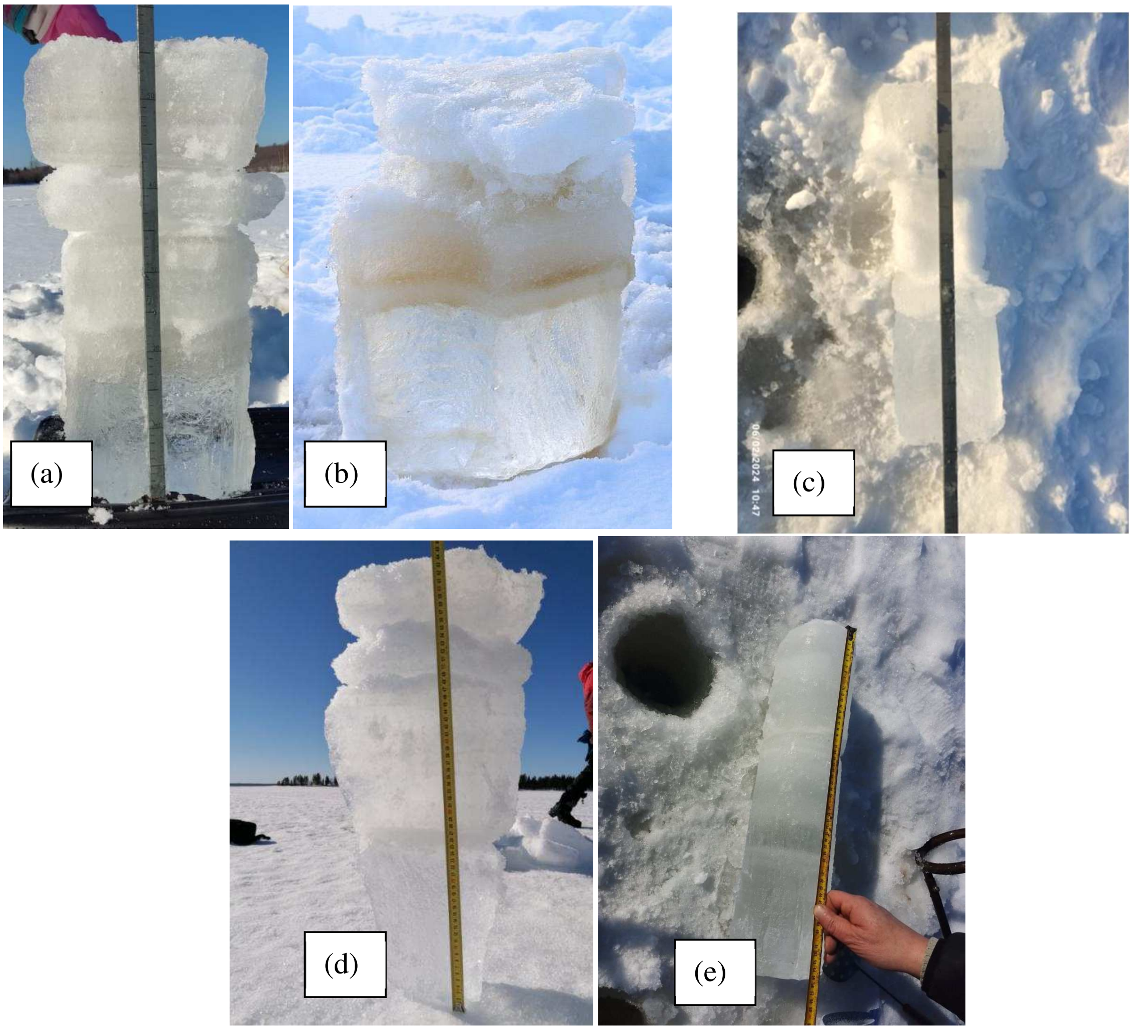

Figure 10. Ice samples from the lakes of southern Karelia, Murmansk, and Moscow regions: (**a**) Lake Vedlozero, Karelia, 18 March 2022. Total ice thickness, measured from the hole, is 64 cm. At the bottom of the ice sample, there is 17 cm of black ice and 6 cm of white ice combined into one block; above, there are three layers of white ice, 11, 5, and 12 cm thick, separated by layers of wet snow 1, 8, and 3 cm thick. (**b**) Forest pond no. 2, Karelia, 2 February 2023. Total ice thickness measured from the hole is 48 cm; below is 20 cm of black ice and 10 cm of white ice, above is a 10 cm layer of wet snow, and on the top is 8 cm of white ice. (**c**) Lake Vendyurskoe, 6 February 2024. Total ice thickness is 55 cm, black ice is 20 cm thick, slush is 1 cm thick, lower white ice is 4 cm thick, wet snow is 18 cm thick, and upper white ice is 12 cm thick. (**d**) Lake Imandra, 14 April 2023. Total ice thickness is 66.5, snow on ice is 9 cm thick, black ice is 23 cm thick, and three white ice layers are 20, 6, and 7 cm thick, separated by two layers of wet snow 3.5 and 4 cm thick. (**e**) Mozhaysk Reservoir, 3 March 2024. Total ice thickness is 56 cm, black ice is 22 cm thick, and white ice 34 cm thick.

In Mozhaysk Reservoir, the thickness of black ice (18–77 cm) accounted for 44–88% (on average 74%) of the total ice thickness (for the measurement years given in Table 1). In March 2024, white ice clearly predominated (Figures 8 and 10e).

In Lake Ulansuhai, the ice was almost totally composed of black ice due to little snowfall (Figures 8 and 11, Table S3). Light snowfall could not submerge the ice surface, and snow drift cleaned the lake surface after snowfall. But the long-lasting thin snow layer melted gradually due to solar heating during the daytime or warm air during spring, leading to wet snow or slush just over the ice surface. This slush or snowmelt refroze during night or cold spells to form a snow–ice layer of 1–3 cm thickness (e.g., February of 2023 in Table S3 and Figures 8 and 11a).

In all measurement years, the ice of the Finnish lake Pääjärvi included black ice (Figure 9a), and the percentage was 40–100% (average 73%) (Table S4). White ice was present in almost all measurement years (except for 2015 and 2020) and ranged from 0 to 60% (average 27%) (Table S4). The ice of the Arctic lake Kilpisjärvi contained black ice every winter at 17–98% (average 66%), while the rest was white ice (Figure 9b and Table S5).

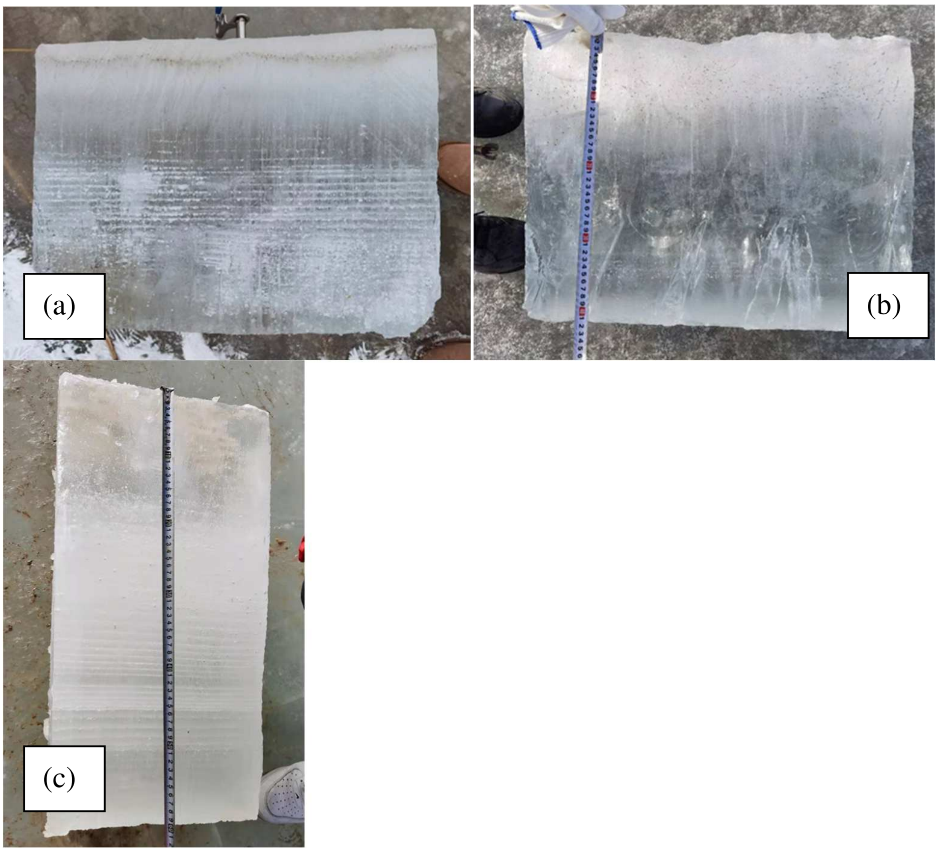

Figure 11. Ice samples from Lake Ulansuhai in Inner Mongolia, north China: (**a**) 9 February 2023, total thickness: 52.5 cm, white ice: 2–3 cm; (**b**) 6 March 2022, total thickness: 41.3 cm, no white ice; (**c**) 15 January 2021, total thickness: 59.5 cm, no white ice.

We looked into various factors that can determine the thickness of black ice at the end of winter: precipitation, FDDs, and the number of days with thaws and frost over different periods of time (the first month of the ice period and from December to March). Based on the data from Lake Vendyurskoe, a significant correlation between precipitation in the first month of ice period and the thickness of black ice at the end of winter was found (Figure 12a). The dependence of the thickness of black ice on the cumulative FDDs during the first month of the ice period was noticeably weaker (Figure 12b). No dependence was found between the thickness of black ice on Lake Vendyurskoe and the number of days with thaws and with frost the first month of the ice period and from December to March.

As for Lake Pääjärvi, the most significant factors determining the thickness of black ice at the end of winter are the number of days with thaws and frost in the period from December to March (Figure 13). No significant correlations were found with the amount of precipitation and the number of days with thaws and frosts in the first month of ice.

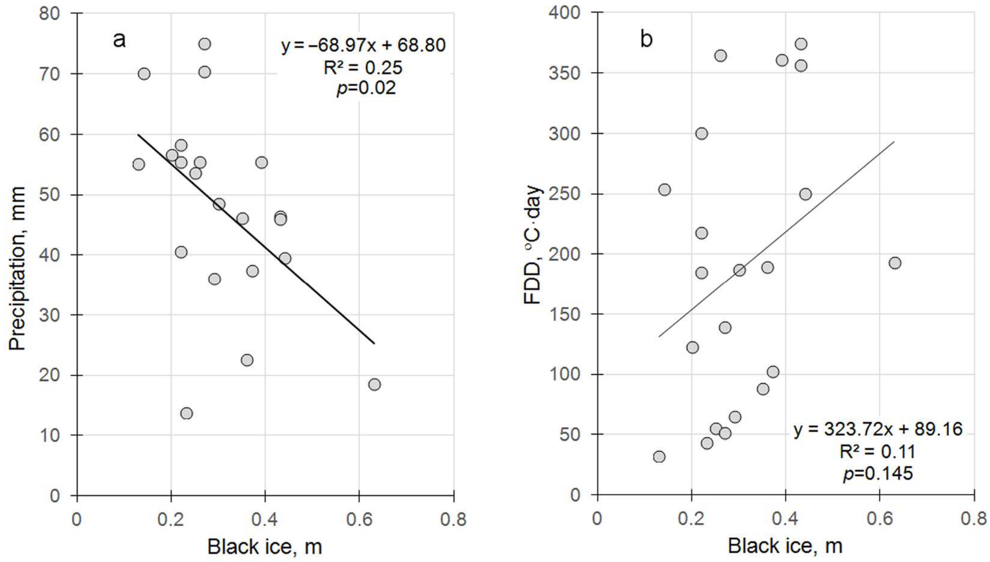

Figure 12. The dependence of the thickness of black ice in Lake Vendyurskoe on the precipitation (**a**) and cumulative FDDs (**b**) during the first month of the ice period. The years of measurements are given in Table 1.

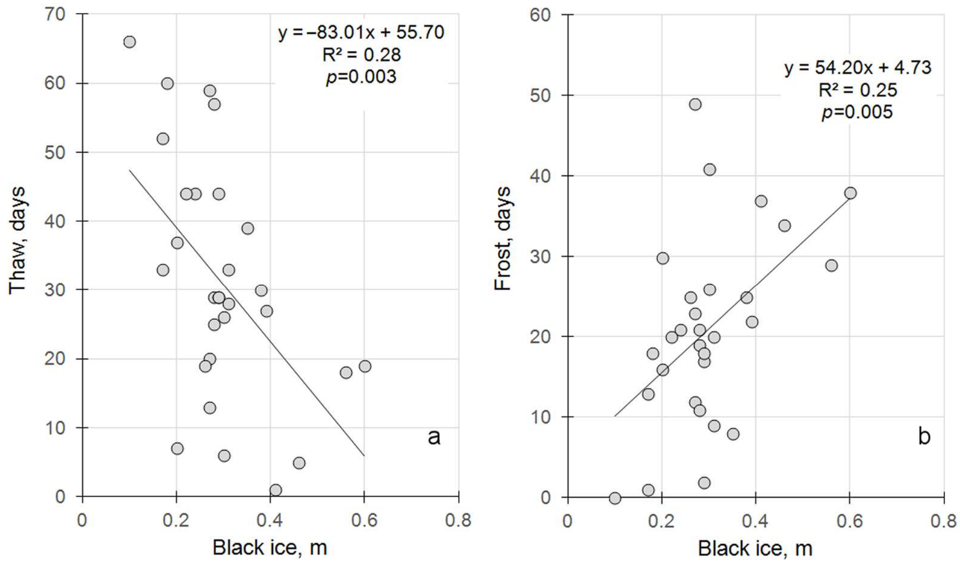

Figure 13. The dependence of the thickness of black ice at the end of winter in Lake Pääjärvi on the number days with thaws (**a**) and frost (**b**) from December to March. The years of measurements are given in Table 1.

4. Discussion

4.1. Regional Climate Variability and Ice Phenology

Many factors determine the characteristics of the ice regime of lakes, such as latitude, altitude, features of atmospheric circulation, precipitation regime, air temperature, surface area, depth, the influence of river runoff, wind action, and others [8,11,13,16,54–57]. Often, it is the climatological, physical, and geographical features of a particular area that have a decisive influence on the ice regime of lakes [58].

We studied changes in the ice regime of lakes in different regions of Eurasia, from the Arctic and temperate zones to highlands and arid zones. The climatic conditions of the areas of the studied lakes are extremely heterogeneous, as they are formed under the influence of different atmospheric patterns, such as the Quasi-Biennial Oscillation (QBO), the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the North

Atlantic Oscillation (NAO), and others. The Eurasian teleconnection pattern (ETP) is the dominant low-frequency variability mode in the Northern Hemisphere winter, exerting a significant influence on temperature and precipitation anomalies across the Eurasian region [59].

The climate conditions of the European territory are formed mainly under the influence of large-scale westerly circulation, which ensures the transfer of heat and moisture from the Atlantic Ocean. Episodic intrusions of arctic air also have an effect, which ensures excessive moisture and unstable weather conditions in all seasons. One of the most important global factors influencing the winter weather in Europe is the NAO [60]. For example, in Karelia, the NAO index accounts for 36–40% of air temperature variation in the winter months (December–March) ($r > 0.6$, $p < 0.001$) [15]. A positive NAO index is associated with strong westerly winds and mild, wet conditions in northern Europe [61]. The meridionally oriented circulation pattern favors intrusions of warm and moist air from mid-latitudes into the Finnish Arctic [62].

Dynamic links between the weather in the Moscow region and the variability in storm trajectories in the North Atlantic and Mediterranean, as well as the synoptic activity over the Barents and Kara Seas, are found [63]. Lagrangian analysis shows associations of winter extreme warm events with air masses originating over the North Atlantic and Mediterranean regions. The air masses involved in extreme cold events are mainly of Siberian and Arctic origin. On interannual time scales, the frequency of cold events in Moscow depends on the negative phase of the NAO, while the frequency of warm events depends on the positive phase of the NAO and the negative phase of the Scandinavian Teleconnection [63].

The climate of the highlands of Armenia is characterized by the presence of regional features of atmospheric circulation associated with the significant influence of the Caucasus Range. Armenia is under the influence of tropical and arctic (rarely) air masses, which can be of both continental and maritime origin, modified by continental influence [64]. In winter, weather changes are associated with the penetration of meridional cold air flows from the northwest to the southeast; the prevailing air masses are from mid-latitude anticyclones formed in the European part of Russia and Siberia. Southwestern flows penetrating in winter bring moisture and warm air masses. Heavy precipitation in Armenia may be caused by cyclonic activity over the South Caucasus and Armenia when Mediterranean cyclones move from the southwest, cyclones move from the south, or frontal waves spread over Armenia and the South Caucasus [64]. Patterns of increasing air temperature have been observed since the 1990s in most of the territory of Armenia. As in other mountainous regions, the expansion of mountains, river valleys, slopes, and slope orientation have a significant impact on atmospheric circulation.

Inner Mongolia's weather conditions are influenced by large-scale monsoon circulation patterns. In particular, the pressure of the Siberian High is responsible for the severe, cold winter and the accompanying dry conditions with little snow in Asian Russia, Mongolia, and China. A marked weakening of the Siberian High has been detected over the last $\sim$20 years, which is a manifestation of climate warming in the region [65]. The Eurasian teleconnection pattern is a major mode of low-frequency variability in the Northern Hemisphere winter, with notable impacts on the temperature and precipitation anomalies in China [59].

The existing differences in the weather conditions of the study regions determine the differences in changes in the ice regime of lakes. Situated quite close within the temperate zone, Karelia and Moscow show differences, with greater warming in Moscow but a faster increase in precipitation in Karelia. A more rapid increase in air temperature in the Moscow region and southern Finland entails a slightly more rapid decrease in the duration of ice cover of Mozhaysk Reservoir and Lake Pääjärvi (10 days/10 years), compared to Lake

Vedlozero in Karelia (9 days/10 years). It has also been found that the ice period has been declining more rapidly in temperate zone lakes, such as Lake Vedlozero and Mozhaysk Reservoir, over the past 30 years. Despite the fact that the rate of air temperature increase in the Arctic is the same, the reduction in the duration of ice cover in the Arctic lake Kilpisjärvi (5.8 days/10 years) is still half of that in lakes in the temperate zone.

The rate of delay of ice-on dates in Lake Pääjärvi, southern Finland (12.5 days/10 years), is more than twice as high as in the Karelian lake Vedlozero (5.4 days/10 years) and in Mozhaysk Reservoir (6.0 days/10 years) and more than four times as high as in the Finnish Arctic lake Kilpisjärvi (2.4 days/10 years). This reflects not only the impact of rising air temperatures, which is comparable in the regions of southern Finland, Karelia, and the Moscow region, but also other factors which may play an important role. At the same time, the dates of ice-off in the lakes of the Arctic and temperate zones change at approximately the same rate. This may be due to the same change in weather conditions in the spring in different regions, the strong role of solar radiation, and other factors that have not yet been studied. The rates of shortening of the ice period that we have identified in lakes in southern Finland, Karelia, and the Moscow region (−5 to −10 days/10 years) are very close and sometimes exceed the results identified in lakes in different regions of the world [11,13,14,66–72].

The highland region of Armenia (1800–1900 m a.s.l.) has shown very rapid warming over the past two decades, but not a significant trend in precipitation. Such changes may also lead to changes in both ice phenology and ice structure. As for the duration of ice cover on high-mountain lakes in Armenia, we did not find an abrupt shortening in ice cover on the small Arpi lake, while for the large Sevan lake, incomplete freezing in warm winters has been observed in recent years. Unfortunately, due to the lack of available measurement data, we were unable to obtain quantitative estimates of changes in the ice regime of high-mountain lakes in Armenia, but the changes in the regional climate that we discovered suggest that the ice regime of lakes would be changing.

The analysis of seasonal and annual temperature anomalies based on the observed data of 36 meteorological stations in Armenia for 1961–2014 showed that there is large inter-seasonal variation in terms of warming. The most noticeable increase in seasonal average temperature can be observed in summer, with a statistically significant trend of 0.29 °C/10 years. A significant increase was obtained also in spring, autumn, and annual average temperature, with trends varying from 0.18 to 0.19 °C/10 years. On the other hand, the temperature increase in winter is much weaker and statistically insignificant, with a trend of 0.08 °C/10 years [73]. However, we found that the air temperature increased in the winter months by 0.6–0.8 °C/10 years. The differences may be due to the fact that we included the last 20 years in the analysis, while the trends obtained in [73] refer to the period 1961–2014.

Clear changes in the ice regime have been established for mountain lakes in other regions in recent years. In particular, it was shown that over the past 40 years, there has been a decrease in the ice duration of mountain lakes by 9 days per decade [69] and in the maximum ice thickness by 2.0–2.5 cm per decade [66]. Over the past 50 years (from 1963), a decline in ice period and ice thickness has been noted for the mountain lake Morskie Oko (1392.8 m a.s.l., the Tatra Mountains, the highest mountain range of the Carpathians). The onset of ice phenomena occurs 11 days later and the ice-off date occurs 25 days early [69]. The number of days with ice phenomena has declined at a rate of 9 days/10 years (with a significant trend, $p < 0.001$), while ice cover duration decreased at a rate of 10.4 days/10 years in Lake Morskie Oko in 1971–2020 [71]. Weather conditions (air temperature and precipitation) have a major influence on the dates of ice-on, although the morphometry and characteristics of the catchment area are also important [57]. Modeling ice phenology of high-mountain lakes in the Pyrenees shows higher variability in ice-off dates with altitude compared to ice-on dates [74].

Many researchers have noted a slower response rate of the ice regime of high-mountain lakes to climate change compared to lowland lakes. Pawlowski (2018) [69] notes that for the glacial lake Morskie Oko, the effect of climate warming is noticeable but weaker than in European lowland lakes, and Livingstone (1997) [11] notes minor changes for mountainous European lakes as well. Long-term measurements in 85 mountain lakes of the Pyrenees showed a reduction in ice cover, which Sabas et al. (2024) [74] associate with an increase in summer temperatures, i.e., an increase in the summer heat content of the lakes. Only for lakes located above 3000 m a.s.l. has winter ice formation been characteristic over the past 20 years.

Sevan and Arpi lakes are situated at the same altitude but have different types of local climate. The landscapes around Lake Arpi are periglacial grassland with a cold climate and a cold summer without a dry season (Dfc [75]), and a temperate relatively cool wet climate exists in the Sevan catchment (Dfb, cold, no dry season, warm summer, [75]). Nonetheless, dramatic warming of Sevan and other small alpine Caucasus lakes has been predicted in future decades due to different climatic scenarios [54].

A more significant decrease in the ice formation period and changes in ice phenology can be noticed in large mountain lakes, such as Lake Sevan, because of the presence of a large heat flux due to an increase in water temperature and long autumn cooling of huge water volumes. Small alpine lakes, having greater resistance to climatic fluctuations due to their high altitude in the mountains, largely change only due to their internal parameters (hydrochemical and hydroecological), which largely depend on winter precipitation. Ice, its structure and its duration are a manifestation of external influences on lakes.

4.2. Regional Climate Variability and Ice Cover Thickness and Composition

The rapid warming of the Arctic is mainly manifested in the reduction in frosts (trends are statistically significant for the Murmansk region and the Finnish Arctic). Thus, the conditions for the growth of black ice are becoming less favorable. Increased overall precipitation in winter helps to insulate the ice from the atmosphere, reducing the growth of black ice. Observations of the thickness and composition of ice in Lake Kilpisjärvi in the Finnish Arctic have not yet revealed any significant changes in ice thickness or changes in the ratio of white to black ice. However, the wide variability in snow depth on ice in spring (from 9 to 36 cm) and the proportion of white ice (from 2 to 83%) is an indicator of the rapid response of the ice regime to weather conditions. The increase in thaws and liquid precipitation (trends are not statistically significant) will probably create favorable conditions for the growth of white ice in the future due to the wetting or melting of snow on the ice and its subsequent freezing.

Three years of measurements (2021, 2023, and 2024) showed significant interannual variability in the ice cover composition of Lake Imandra, with an increase in the proportion of black ice to 60–80% in 2021 and 2024 and a sharp decrease to 34% in 2023. That is, in this arctic lake, the range of variability in the thickness of white ice in successive years was also quite wide—from 20 to 66%. Significant interannual variability in winter precipitation in the Lake Imandra region was detected in 1985–2020 [76], suggesting that conditions for white ice formation vary from year to year. As current trends of increasing thaws and precipitation continue, we can expect an increasing share of white ice and slush and a decreasing share of black ice in Arctic lakes in the future.

In the temperate zone, severe frosts are decreasing (trends are statistically significant), i.e., as in the Arctic, the conditions for the growth of black ice are becoming unfavorable. Warming in the temperate zone is also manifested by a significant increase in thaws and an increase in the proportion of liquid precipitation, i.e., conditions for the melting and wetting of snow and the subsequent formation of white ice are favorable. In Karelia and southern Finland, there is a tendency for the total amount of precipitation to increase in winter, but in southern Finland the proportion of liquid precipitation is growing three times faster than in Karelia, i.e., in Karelia, one can expect a greater accumulation of snow on ice and, consequently, a greater increase in white ice than in southern Finland due to the flooding of black ice under the weight of snow. We found a higher rate of white ice growth in the Karelian lake Vendyurskoe than in Lake Pääjärvi in southern Finland, which coincides with the weather change. In the area of Mozhaysk Reservoir, a significant increase in liquid precipitation is also observed, which, with a rapid increase in thaws, will most likely contribute to a decrease in both black and white ice, as in southern Finland. Unfortunately, gaps in the data series did not allow us to establish the exact rate of change in white and black ice in Mozhaysk Reservoir.

In the high-mountain regions of Armenia, a sharp increase in thaws and a decrease in frosts will contribute to a decrease in ice, and a slight increase in precipitation (not significant) is unlikely to be favorable for the formation of white ice. However, short weather data series do not allow us to obtain significant trends. An increase in the proportion of liquid precipitation is unlikely to contribute to an increase in the proportion of white ice in high-mountain lakes in Armenia, but field observations are needed.

Relatively rapid warming in the arid Inner Mongolia region (the trends of increasing air temperature, and the number of days with thaws and decreasing days with frost are statistically significant) will contribute to a decrease in the thickness of black ice. An increased number of thaw days (6.3 days/10 years) and a slight increase in precipitation (3.9 mm/10 years) could contribute to the production of the white ice. However, a very small increase in the proportion of liquid precipitation is unlikely to contribute to the wetting of snow and its subsequent transformation into white ice. In arid regions, such as northern and northwestern China, the lake ice surface is consistently free of snow or is covered by sparse and banded thin snow due to little winter precipitation and winds. White ice is thus usually absent. But occasionally in some winters, a snowfall at the very beginning of freezing when the ice cover is very thin can lead to a thin snow–ice layer (less than 3–5 cm) [77]. This layer is prone to sublimate due to the dry air and strong winds. Sometimes, when snowfall occurs during calm conditions, the snow layer on top of the ice cover can melt due to intensive solar radiation, and then the wet snow refreezes to form a thin white ice layer of several centimeters. The absence of persistent white ice allows more sunlight to penetrate into the under-ice water column, which helps to maintain a higher water temperature, high dissolved oxygen level, and large phytoplankton biomass in the top water layer [10].

A joint analysis of the thickness of black ice and weather conditions in the first month of the ice period and in the period from December to March for two temperate lakes—Pääjärvi and Vendyurskoe—showed that the thickness of black ice in the Karelian lake is determined by the amount of precipitation at the beginning of winter, and in Lake Pääjärvi in southern Finland, it is determined by the number of days with thaws and frost during all winter. This is understandable, given that warming is weaker in Karelia, and the amount of precipitation increases more than in southern Finland. Thus, in Karelia, the factor determining the thickness of black ice is precipitation in the early winter, and in southern Finland it is air temperature. A study of Swedish lakes emphasized the role of thaws during winter in reducing the thickness of black ice [32] but did not consider the role of precipitation.

5. Conclusions

A study of weather trends and ice regimes of several lakes in different regions of Eurasia was conducted. The influence of weather changes on both the duration of the ice period and the thickness and composition of the ice cover of lakes from the Arctic to the temperate zone, high-mountain zone, and arid zones was revealed.

In all of the studied regions, conditions for a decrease in the thickness of black ice under the influence of global warming were found. The conditions for the formation of white ice vary in different regions. In the more northern regions of the temperate zone and in the Arctic, conditions for the increase in white ice are enhanced, while in the more southern regions of the temperate zone, where thaws are more frequent and the proportion of liquid precipitation is higher, the conditions for the formation of white ice worsen. In highland regions and in the arid zone, the increase in liquid precipitation is insignificant, and it is unlikely to contribute to the formation of white ice.

Changes in winter air temperature, total precipitation, and liquid precipitation, as well as days with thaws and frosts, were assessed, and the impact that these changes can have on the composition of ice cover is shown at a qualitative level for all of the studied regions. Long time series of observations for two temperate lakes, which revealed noticeable changes in the thickness of black ice, made it possible to quantitatively assess the impact of precipitation and air temperature on the thickness of black ice.

However, it is clear that the data are still insufficient to develop a model describing the change in ice composition depending on weather conditions. The development of such a model is part of our future research plans.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w17030365/s1: Table S1. The weather stations closest to the studied lakes; Table S2. Average annual and seasonal air temperature (°C) and average annual and seasonal precipitation for period 1991–2020; Table S3. Thickness of snow, ice, and slush layers in lakes in 2021–2024. Table S4. Thickness of snow, total ice, black ice, and white ice in Lake Pääjärvi in 1994–2023; Table S5. Thickness of snow, total ice, black ice, and white ice in Lake Kilpisjärvi in 1994–2023; Figure S1: Data from 27 October 1995 Landsat 5_ for Arpi lake; Figure S2: Data from 19 November 1995 Landsat 5_ for Arpi lake; Figure S3: Data from 5 December 1995 Landsat 5_ for Arpi lake; Figure S4: Data from 30 December 1995 Landsat 5_ for Arpi lake; Figure S5: Data from 17 December 2022 Sentinel-2 L2A_ for Arpi lake; Figure S6: Data from 25 December 2022 Sentinel-2 L2A_ for Arpi lake; Figure S7: Data from 15 March 2023 Sentinel-2 L2A_ for Arpi lake; Figure S8: Data from 4 April 2023 Sentinel-2 L2A_ for Arpi lake; Figure S9: Data from 3 December 2023 Landsat 9_ for Arpi lake; Figure S10: Data from 19 December 2023 Landsat 9_ for Arpi lake; Figure S11: Data from 27 December 2023 Landsat 8_ for Arpi lake; Figure S12: Data from 13 April 2024 Sentinel-2 L2A_ for Arpi lake; Figure S13: Data from 23 April 2024 Sentinel-2 L2A_ for Arpi lake; Figure S14: Data from 30 March 2017 Landsat-7_ for Lake Sevan; Figure S15: Data from 18 February 2017 Landsat-8_ for Lake Sevan. References [44–48] are cited in the Supplementary Materials.

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