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Manifestation of climatic change in the ice phenology of Lake Ladoga over the past 55 years

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Проявление климатических изменений в ледовом режиме Ладожского озера за последние 55 лет

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Summary

The article presents results of monitoring changes in some phenological characteristics of the ice cover of Lake Ladoga over the past 55 years. A steady tendency has been observed for a decrease in the duration of ice formation and the area of fast ice since the beginning of the 90s. A comparison is made of the average spatial patterns of ice formation dynamics between the periods 1964–1994 and 1993–2019. Since the beginning of the 90s, there has been a change in the ice characteristics of Lake Ladoga, directly related to a reduction in the duration of the cold period. The duration of ice events averaged over the past 30 years has decreased by about a month compared with the previous thirty-year period. Fast ice began to cover only 30% of the lake surface compared to 80% in previous years. The frequency of winters with incomplete freeze-up (remaining ice free areas) increased from two to six years per decade. The warming effect is most clearly seen in the central part of the lake. Such significant changes in the dynamics of ice phenology cannot but affect the functioning of the entire ecosystem of Lake Ladoga.

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Ключевые слова: ***Ладожское озеро, покрытость льдом, пространственное распределение льда, продолжительность ледового покрытия, изменение климата, температура воздуха.***

Представлены изменения некоторых фенологических характеристик ледяного покрова Ладожского озера за последние 55 лет. Установлена устойчивая тенденция уменьшения продолжительности ледообразования и площади припая с начала 1990-х годов, что связано с сокращением продолжительности холодного периода. Выполненное сравнение осреднённых пространственных закономерностей динамики ледообразования за периоды 1964–1994 и 1993–2019 гг. с перекрытием в один год позволило выявить уменьшение во второй период примерно на месяц по сравнению с первым 30-летним периодом средней продолжительности сплошного ледостава.

Introduction

Lakes and their shores are the habitat of aquatic organisms, fish, wildlife and humans. Each lake differs in terms of such characteristics as geographical location, the influence of the catchment basin, the morphology of the basin, the chemical composition of the water and the biota inhabiting it, hydrological parameters, including thermal and ice regimes. Depending on the size of the lake, there is a limited range of external influences which allows its ecological state to remain stable. Noticeable changes in the environment to varying degrees can lead to a change in limnic characteristics. Such characteristics include the ice regime of large lakes. Over the past 30 years, significant changes in ice characteristics for lakes in the Northern Hemisphere have been recorded [1], in particular, a decrease in the total duration of ice formation [2].

The consequences of these ongoing changes due to winter warming in the phenology of ice cover can significantly affect the functioning of the Ladoga Lake ecosystem, as has already been noted for Lake Peipsi located nearby [3]. A change in lake ice cover cannot but affect its thermal regime, its vertical oxygen exchange, the development of phytoplankton, during the period of spring heating, which begins earlier. In the absence of ice, the aquatic mammals feeding cubs on ice [4] have problems. The supply of monastery on the Valaam Island when stable freeze-up in the northern part of the lake was carried out along the ice route. Recent years, shipping to the island has been carried out all year round. This paper shows how climate warming, observed over the past 30 years, has affected the average spatial pattern of freeze-up, break-up, and the duration of fast ice cover on Lake Ladoga.

Materials and methods

Europe's largest freshwater dimictic Lake Ladoga is located in northeastern Europe. Its area is 17.765 km^2, its average depth is 48.3 m, the maximum depth is 233 m in the northern part of the lake, and the water volume is 858 km^3 (Fig. 1). Meteorological data from the Sortavala weather station, located on the northern shore of the lake, were used to assess the meteorology of the Lake Ladoga region. This meteorological station was chosen among others located on the coast and islands of Lake Ladoga as the most filled with data. Data

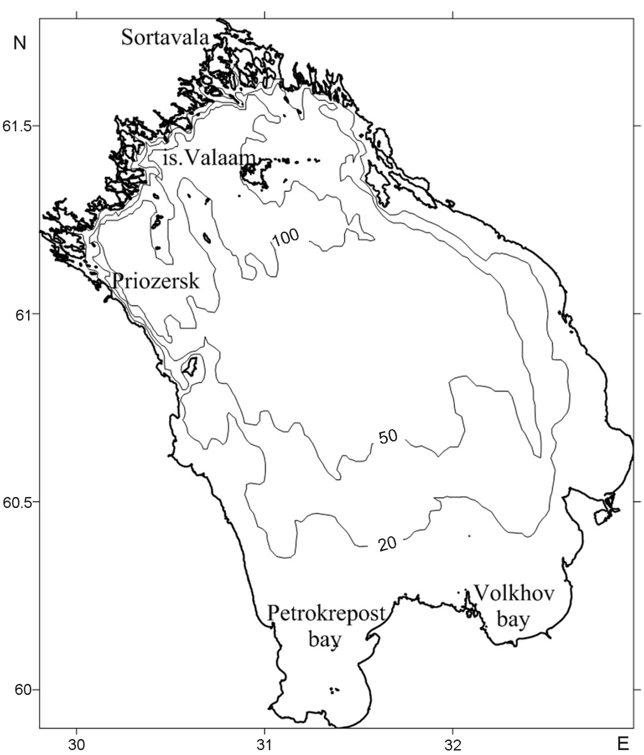

Fig. 1. Lake Ladoga with its depths in meters
Рис. 1. Ладожское озеро с указанием его глубин в метрах

on average daily air temperature for the years from 1913 to 1936, when the weather station was in Finland, allowed [5] to reconstruct ice conditions on Lake Ladoga in the absence of observations on the degree of ice coverage of the lake. A sum of the average daily air temperatures during the entire cold period, including seasonal thaws, was used as an integral winter characteristic associated with the ice events. The duration of a cold period was calculated between the dates of steady transition of average daily air temperatures through 0 °C in the fall and spring. The changes in the duration of the cold period and the sums of average daily air temperatures during this period are shown in Fig. 2. A statistically significant at p-level 0.05 trend is shown by solid line.

Over the past 30 years, these changes have become statistically significant and indicate a decrease in the severity of winters. In 2020, the shortest winter over the entire period of monitoring was recorded with the smallest sum of average daily air temperatures during the cold period. The reduction in the duration of the cold period occurs mainly due to a statistically significant five days shift of a stable transition of the daily average air temperatures through 0°C in autumn to later dates [6]. It should be noted that the article considers only the spatial distribution of ice cover by various remote sensing methods, the data on ice by coastal stations being of a fundamentally different nature. Regular observations of the spatial distribution of ice on Lake Ladoga have been made since 1943. Until 1992, aerial reconnaissance of the ice was carried out by the Hydrometeorological Service about two times a month, and maps of Lake Ladoga's ice cover indicating its cohesion were published [7]. Starting from 1971, space images were added to data obtained by airborne reconnaissance, which made it possible to make schemes of the freeze-up and break-up of the lake depending on the different direction of the prevailing winds [8]. Recently satellite imagery has become the main source for studying the lake ice cover. Over the past 20 years, data from the NOAA series of satellites with kilometer-resolution AVHRR instruments has been supplemented with MODIS satellites with 250-meter resolution and from 2015 Synthesized Aperture Radar (SAR) data from the European Sentinel-1 satellite with 100 m resolution have become freely available.

The annual monitoring of the ice cover starts from the moment its detected by remote sensors. Then, for each suitable image, ice lake coverage is calculated with an accuracy of 10%, taking into account its cohesion. The end of the ice phenomena on the lake is consid-

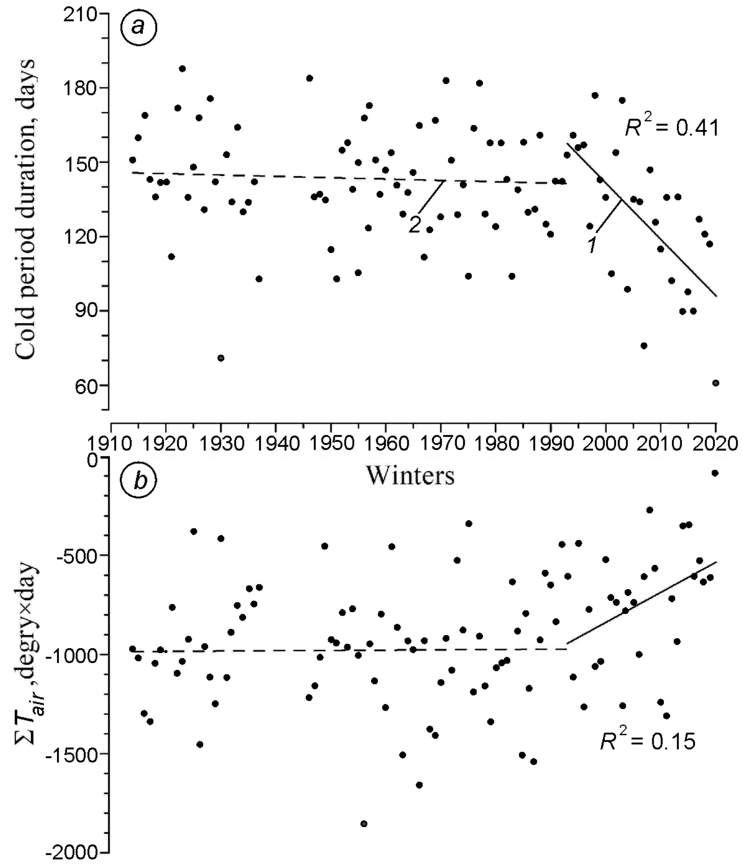

Fig. 2. The duration (*a*) and the sums of the average daily air temperatures (*b*) of the cold period for the years of 1913–2020.

The year number is the end of the winter; the trend is at p-level 0.05 and its determination coefficient R^2: *1* – a statistically significant; *2* – an insignificant trend

Рис. 2. Межгодовая изменчивость продолжительности (*a*) и максимальных алгебраических сумм среднесуточных температур воздуха (*b*) холодного периода для 1913–2020 гг.

Номер года относится к году окончания зимы; тренд при уровне значимости 0,05 и его коэффициент детерминции R^2: *1* – статистически значимый; *2* – незначимый

ered the date when the observed ice occupies less than 5% of the lake. The duration of ice on Lake Ladoga remained at a stable level of about 170 days before the beginning of the 90s, after that the duration shows a clear tendency to decrease (Fig. 3, *a*), mainly due to a shift to a later date of the onset of ice. Lake Ladoga is not completely covered by ice every year. Years with remaining open water areas occur. Fig. 3, *c* shows the number of years with incomplete ice cover per decade. Before the beginning of the 1990s, one to two winters with incomplete ice cover were observed per decade. In recent years this number has increased to six.

From constant observations of lake ice cover by remote sensing, it is possible to calculate the ice cover index each winter. The ice cover index [9] is the integral of lake ice cover over the winter, normalized to the integral of average lake ice cover over the period from 1945 to 1994. This period was chosen for normalization since it is characterized by the absence of a significant trend in the lake ice cover index. From 1945 to 2020 ice cover indices were calculated from field data. At the same time, the linear dependence of the dates of ice cover freeze-up and break-up on the sums of the average daily air temperatures, accumulated to these dates were obtained [5]. This dependence was used to reconstruct the seasonal change in the ice cover and to calculate the ice cover indices for the years from 1913 to 1936, since observations of the ice distribution over Lake Ladoga were not carried out during those years. Fig. 3, *b* shows the change in ice cover index over the past 100 years and its trend [5], extended now up to 2020. The last period has a statistically significant decrease in the ice cover index.

In the process of preparing data on the lake ice cover, an digital file was compiled with more than 1000 aerial and satellite images from 1964 to 2020. Based on linear relationships [10], a way was proposed for calculating the increase and decrease in the average value of ice cover in each of 180 fixed ten-kilometer cells. To construct a smooth seasonal course of ice cover for each cell, the data were averaged by 10 days with 5-day shifts. The course of ice cover for each cell was approximated by two linear equations: for ice percentage increasing and decreasing. In some cells according to the long-term average data, a complete ice cover can be observed for a very short time, in other cells the complete ice cover may last up to several months, or the area may never be completely covered with ice. To analyze the impact of climate change on the ice characteristics of the lake, the

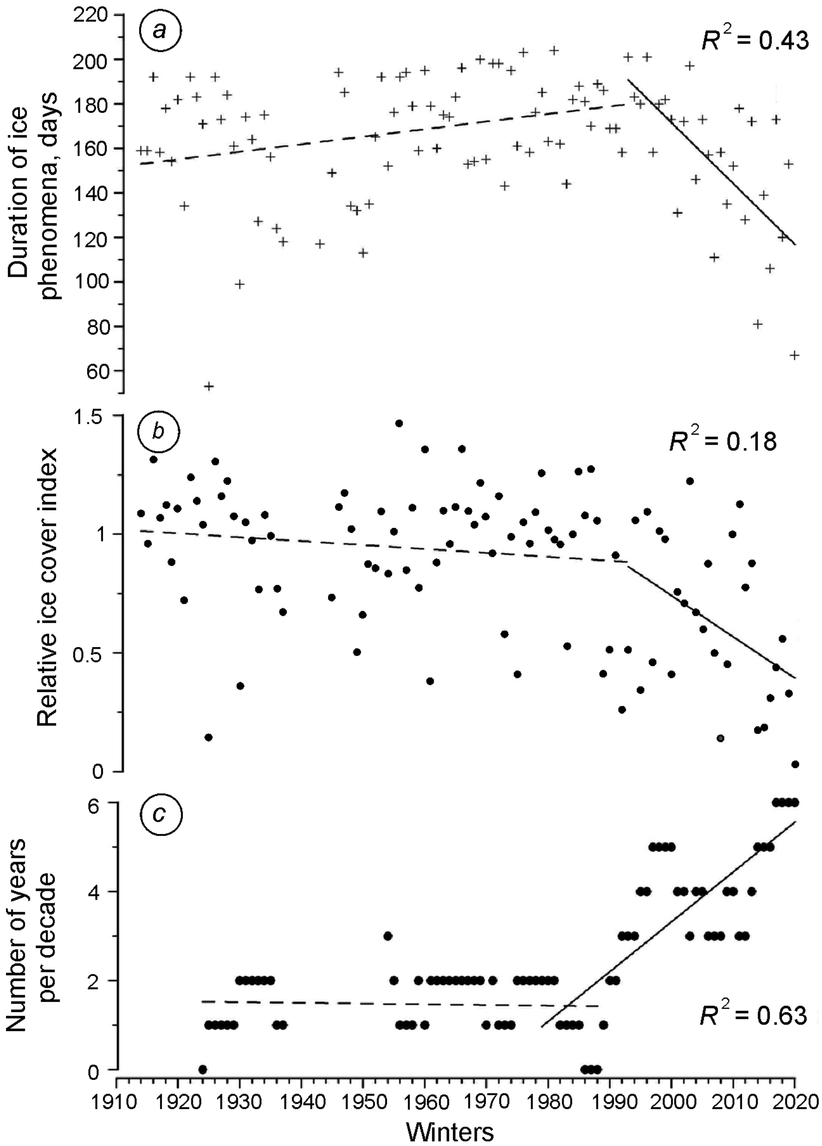

Fig. 3. Annual variability in the ice characteristics of Lake Ladoga:
a – duration of ice phenomena; *b* – trends in the ice cover index of Lake Ladoga; *c* – the number of years with incomplete freezing per ten year running average; see Fig. 2 for symbols

Рис. 3. Межгодовая изменчивость ледовых характеристик Ладожского озера:
a – продолжительность ледовых явлений; *b* – тенденции изменения индекса ледовитости; *c* – число лет с неполным ледоставом из 10 скользящих; усл. обозначения см. на рис. 2

period from 1964 to 2019 was divided into two with one year overlap: from 1964 to 1994 and from 1993 to 2019 years. For each period, the areas of increasing and decreasing of fast ice cover and the duration of the period with fast ice cover were calculated (Fig. 4).

Results and discussions

When constructing average schemes of increasing and decreasing of fast ice cover of Lake Ladoga, data were obtained on the average rates of freeze-up and spring break-up of each cell. These data made it possible to assess the correctness of data processing on the smoothness of their distribution over the lake, and to obtain average schemes of the rates of freeze-up and break-up of the lake for subsequent analysis. The formation of fixed cohesive ice in the first period began at the end of December in shallow Petrokrepost Bay. The ice growth rate of each fixed cell increased from 0.3% to 1.5% per day as the location of the cell off the shore and sum of negative average daily air temperatures accumulated. The results obtained are in a good agreement with data from neighboring Lake Onega [11], where the average value of the increase in the lake ice cover per day is 1.55%. Over the last ten days of February, the area of the lake covered by fast ice increased sharply. By the beginning of March, the formation of fast ice stopped, leaving 20% of the lake surface occupied by floating ice of various cohesion. In the second period, ice formation usually started twenty days later, proceeded at

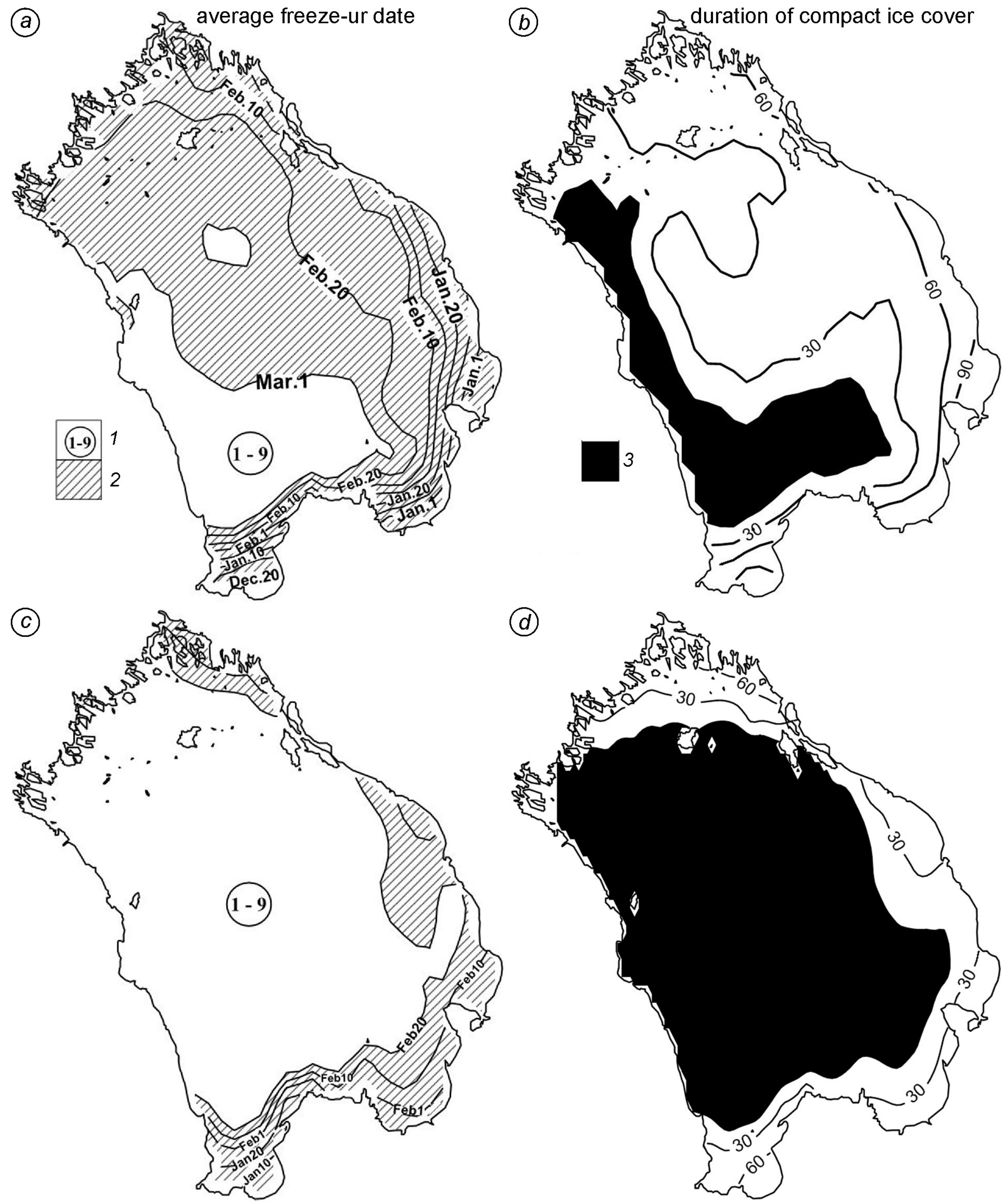

Fig. 4. Spatial distribution of the average characteristics of the complete freezing of the Lake Ladoga:
a – freeze-up date (isoclines show the dates of fast ice spread; *1* – floating ice of varying concentration in tenths, *2* – Fast ice); *b* – the duration in days of fast ice cover (*3* – area without complete ice cover during all the winter) in the first period 1964–1994; *c* and *d* – the same in the second period – 1993–2019

Рис. 4. Пространственное распределение средних для двух периодов характеристик припая на озере:
а – замерзание (изолиниями показаны даты распространения припая; *1* – плавающий лёд различной сплочённости в баллах, *2* – припай); *b* – продолжительность полного ледостава в сутках (*3* – отсутствие полного ледостава на протяжении всей зимы) в первый период 1964–1994 гг.; *c* и *d* – то же самое во второй период – 1993–2019 гг.

about the same rate, but ended ten days earlier than in the first period, while 70% of the lake surface remained occupied by floating ice of various cohesion.

The spring break-up of fast ice cover on Lake Ladoga is faster than its freeze-up due to the significant wind activity in this region. The wind prevents the formation of motionless ice and contributes to its destruction. In the first period, spring ice break-up began in the central part of the lake in early March at a rate of 1% and then up to 2% per day near the shore. The last formations of fast ice were observed along the northeastern coast in early April. In the second period, the process of break-up of fast ice cover usually began ten days earlier, ended also along the northeastern coast, and continued as in the first period for a whole month, despite much less initial ice. The destruction of ice in the second period occurs slower than in the first period at an average rate of 1% per day. However, significant differences in the rate of rise of spring air temperatures between the two periods were not found. One of the possible explanations for such an unexpected result is statistically significant increase in the frequency of calm conditions on Ladoga in the spring that has been observed in recent years. Indeed, according to the data at the Sortavala weather station, in March during the first period wind speeds less than 3 m/s was observed in 66% of the time and in the second period 76% of the time, which weakened the influence of wind as a factor accelerating the break-up of ice.

For more than three months, fast ice cover during the first period was observed in fixed cells along the northeast coast. The central part of the lake remained under the fast ice for about one month. On 20% of the lake surface near the southwestern shore floating ice of various concentrations was usually located. This ice can move freely around the lake depending on the wind. According to data averaged for the second period, fast ice cover was recorded during a month or less only in shallow water. In some winters the central part of the lake was completely ice free. Averaging the second period data showed that usually 70% of the surface of the lake was not covered by compact ice. Such significant changes in the degree of ice coverage of the lake during the winter are manifested in an earlier beginning of the spring warming of the lake, in an increase in the period of vertical oxygen exchange, in a lengthening of the period of development of cold-water forms of phytoplankton during spring heating, which begins earlier. In the absence of ice, aquatic mammals feeding cubs on ice have problems.

Conclusion

Since the beginning of the 1990s, there has been a change in the ice characteristics of Lake Ladoga, directly related to 12 days reduction in the duration of the cold period. The average winter air temperature at the same time statistically insignificantly increased by 1 °C. The duration of ice events averaged over the past 30 years has decreased by about a month compared with the previous thirty-year period. Fast ice began to cover only 30% of the lake surface compared to 80% in previous years. The frequency of winters with incomplete freeze-up (remaining ice free areas) increased from two to six years per decade. The warming effect is most clearly seen in the central part of the lake. Such significant changes in the dynamics of ice phenology cannot but affect the functioning of the entire ecosystem of Lake Ladoga.

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Расширенный реферат

Озёра и их берега – местообитание водных организмов, рыб, диких животных и людей. Каждое озеро специфично по таким характеристикам, как географическое положение, влияние водосборного бассейна, морфология котловины, химический состав воды и населяющей её биоты, гидрологические параметры, в том числе термический и ледовый режимы. В зависимости от размера озера существует предельный диапазон внешних воздействий, при котором его экологическое состояние остаётся достаточно стабильным. Заметные реформации окружающей среды в той или иной степени могут приводить к изменению лимнических характеристик, к которым относится и ледовый режим крупных озёр.

Для озёр Северного полушария за последние 30 лет были зафиксированы более интенсивные темпы изменения ледовых явлений. Ожидается, что последствия продолжающегося зимнего потепления и изменения фенологии ледяного покрова будут иметь решающее значение для функционирования экосистемы Ладожского озера, а также для расположенного рядом Чудского озера. Задача настоящей работы – выяснить, как повлияло потепление климата на изменение средних пространственных схем замерзания, вскрытия и продолжительности полного ледостава Ладожского озера. Представлены результаты наблюдений за тенденцией межгодовых изменений зимних температур воздуха и некоторых фенологических характеристик ледового покрытия Ладожского озера. Сравнение схем сезонного увеличения и уменьшения распределения площадей припая, построенных для двух периодов – 1964–1994 и 1993–2019 гг. с перекрытием в один год, позволило оценить их изменения за последние 55 лет.

По данным метеостанции Сортавала, для региона Ладожского озера в последние 30–40 лет статистически значимо сократились продолжительность холодного периода (на 12 дней) и суммы среднесуточных температур воздуха. Это привело к изменениям и характеристик ледового режима озера. Самое веское изменение установлено в продолжительности существования ледовых явлений на поверхности озера. К аналогичным результатам пришли и исследователи озёр Финляндии. Сравнение средних для двух периодов схем нарастания и разрушения припайного льда позволило определить центральный район озера как наиболее подверженный изменениям. За более короткое для второго периода холодное время года неподвижным льдом покрывалось всего 30% поверхности озера вместо 80% в первый период. В свою очередь столь существенные изменения степени покрытости озера льдом за зиму проявляются в более раннем начале весеннего прогрева озера в увеличении периода вертикального кислородного обмена, в удлинении периода развития холодноводных форм фитопланктона в период весеннего нагревания, который начинается раньше. Испытывают проблемы при отсутствии льда водные млекопитающие, вскармливающие детёнышей на льду озера. Грузы в монастырь на острове Валаам при устойчивом ледоставе в северной части озера доставляли по ледовой трассе. В последние годы судоходство на остров ведётся круглогодично.

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