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ФАКТОРЫ, ОПРЕДЕЛЯЮЩИЕ ДИНАМИКУ ТЕМПЕРАТУРЫ ПОВЕРХНОСТНЫХ ВОД В ОТДЕЛЬНЫХ ОЗЕРАХ ПОЛЬШИ И БЕЛАРУСИ ПО ДЕСЯТИЛЕТИЯМ В ПЕРИОД ИЗМЕНЕНИЯ КЛИМАТА

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Аннотация. Рассматриваются изменения температуры поверхностного слоя воды 13 озер, расположенных в Беларуси и на севере Польши, за 60-летний период (1961–2020), а также причины этих изменений. С помощью графических программ *Excel*, *Corel Quattro Pro* (версия 8) и *Corel Draw* (версия 9) были рассчитаны и представлены среднегодовые и среднемесячные значения, экстремальные значения, а также среднегодовые и среднемесячные тренды изменения температуры поверхностных вод по десятилетиям (дополнены данными о среднемесячных температурах воздуха для 13 метеорологических станций). Исследование показало, что температура во всех озерах характеризуется положительным трендом: в среднем она изменяется на 0,044 °C в год. Наибольшее повышение температуры воды отмечено в оз. Червоное в Беларуси (0,066 °C в год), а наименьшее – в оз. Ганча в Польше (0,029 °C в год). Эти значения коррелируют со средними температурами воздуха в декабре – марте и с зимним индексом североатлантического колебания.

Ключевые слова: озеро; температура поверхностного слоя воды озера; изменение климата; Польша; Беларусь.

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DETERMINANTS OF THE COURSE OF DECADAL SURFACE WATER TEMPERATURES IN SELECTED LAKES IN POLAND AND BELARUS DURING THE PERIOD OF CLIMATE CHANGE

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Abstract. The paper presents the results of surface water temperature measurements from 13 lakes located in northern Poland and Belarus over a 60-year period (1961–2020) and the reasons of these changes. Using the *Excel*, *Corel Quattro Pro* (version 8) and *Corel Draw* (version 9) graphic programmes, annual and monthly average values, extreme values, average annual and monthly trends over a decade were calculated and presented. It is supplemented by average monthly air temperatures for 13 meteorological stations. Research has shown that the temperature in all lakes is characterised by a positive trend of 0.044 °C per year. The highest increase of water temperature was noted in Chervonoe Lake in Belarus (0.066 °C per year), while the smallest temperature was noted in the deep Hancza Lake in Poland (0.029 °C per year). These values correlate with average air temperatures in December – March and with the winter North Atlantic oscillation index.

Keywords: lake; lake surface water temperature; climate change; Poland; Belarus.

Introduction

The temperature of lake water plays a critical role in regulating the physical, chemical, and biological characteristics of aquatic ecosystems. It influences the distribution and abundance of aquatic organisms, nutrient cycling, and overall ecosystem productivity. Changes in lake surface water temperature can also serve as an indicator of climate change impacts on freshwater bodies, making it a valuable parameter for monitoring and assessing environmental health and resilience. Therefore, investigating lake surface water temperature is crucial for gaining insights into the dynamics of aquatic systems and their responses to environmental stressors. The upper layer is a zone of interaction of water mass and atmosphere. Understanding of heat exchange between air and water helps us to study heat balance and the hydrological regime [1; 2].

It is known that the water temperature in lakes is characterised by a positive trend for the entire multi-year period of 1961–2020, the authors of the study determine these trends for individual decades in its course. The aim of the work is to assess the natural conditions for decadal periods.

Materials and methods

The analysis of surface water temperature concerns 13 lakes. One of them is located in the Greater Poland lake district (Slawskie), three in the Pomeranian lake district (Lubie, Lebsko and Charzykowskie), four in the Masurian lake district (Jeziorak, Mikolajskie, Nidzkie and Hancza). Three lakes are situated in the area of the Belarusian lake district (Naroch, Drivyaty, Lukomskoe) two – in the area of Polesie (Vygonoshchanskoe, Chervonoe). Figure 1 shows the location of studied lakes.

All lakes except those located in Polesie are post-glacial lakes. Their location is marked in the west by Lubie Lake (15.9° E.), in the east by Lukomskoe Lake (29.1° E.), in the north by Drivyaty Lake (55.6° N.), and in the south by Chervonoe Lake (52.4° N.). The distance between the location of the extreme lakes from west to east is approximately 1130 km [3].

The largest lakes are Naroch (7960.0 ha) and Lebsko (7020.0 ha), while the smallest are Hancza (291.5 ha). In terms of depth, the deepest lakes are Hancza (106.1 m) and Lubie (46.2 m), and the shallowest lakes are Vygonoshchanskoe (2.3 m) and Chervonoe (2.9 m). In terms of capacity, the analysed lakes are also clearly differentiated. Naroch (710.40 mln m^3) and Lukomskoe (249.0 mln m^3) lakes have the largest capacity, and Chervonoe Lake (27.35 mln m^3) has the smallest capacity. Other morphometric data are presented in table 1.

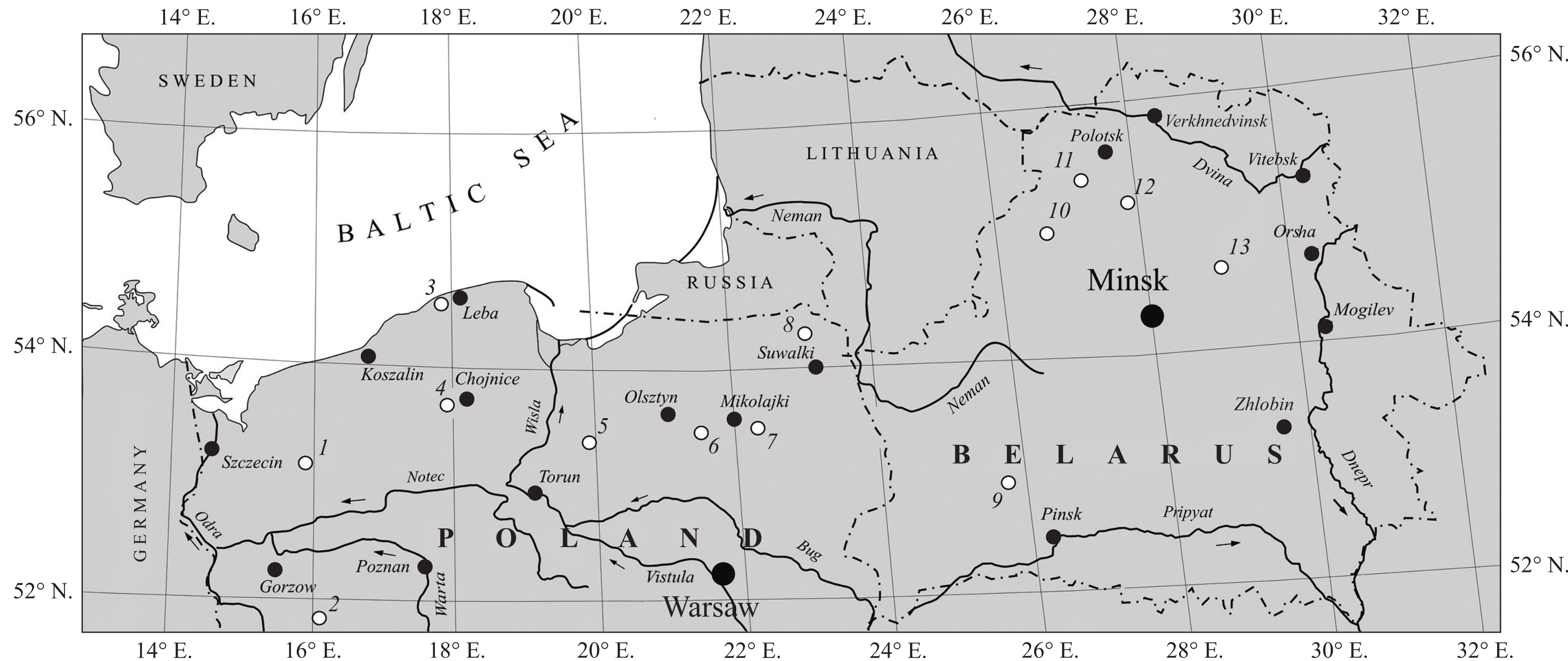

Fig. 1. Location of lakes for surface water temperature measurements and for ice phenomena measurements recorded in 1961–2020 in Poland (*1* – Lubie, *2* – Slawskie, *3* – Lebsko, *4* – Charzykowskie, *5* – Jeziorak, *6* – Mikolajskie, *7* – Nidzkie, *8* – Hancza), in Belarus (*9* – Vygonoshchanskoe, *10* – Naroch, *11* – Drivyaty, *12* – Chervonoe, *13* – Lukomskoe), and meteorological stations (black points)

Table 1

Location and morphometry of the studied lakes

Lake	Geographic location		Area, ha	Lake volume, mln m^3	Maximum depth, m	Mean depth, m	Average width, m
	Latitude, degree	Longitude, degree					
Lubie	52.5	15.9	1487.5	16.98	46.2	11.6	1040
Slawskie	51.9	16.0	822.5	42.66	12.3	5.2	898
Lebsko	54.7	17.4	7020.0	117.52	6.3	1.6	4366
Charzykowskie	53.8	17.5	1336.0	134.53	30.5	9.8	1360
Jeziorak	53.7	19.6	3152.5	141.59	12.9	4.1	1172
Mikolajskie	53.8	21.6	424.0	55.74	25.9	11.2	866
Nidzkie	53.6	21.6	1750.0	113.87	23.7	6.2	790
Hancza	54.3	22.8	291.5	120.36	106.1	38.7	688
Vygonoshchanskoe	52.7	26.0	2600.0	32.10	2.3	1.2	3710
Naroch	54.9	26.8	7960.0	710.40	24.8	8.9	6200
Drivyaty	55.6	27.0	3614.0	223.52	12.0	6.1	3570
Chervonoe	52.4	28.0	4032.0	27.35	2.9	0.7	3500
Lukomskoe	54.7	29.1	3771.0	249.0	11.5	6.6	3500

The analysis of surface water temperature for eight lakes located in Poland was presented based on daily temperature measurements from the Institute of Meteorology and Water Management in Warsaw for the period of 1961–2020, and for lakes located in Belarus from the Hydrometeorological Service of the Republic of Belarus in Minsk (in every volume 3 of State Water Cadastre for 1972–2019), for the period of 1971–2020. In Poland, surface water temperature measurements were taken at a depth of 0.4 m in the coastal zone at 7:00 a. m. (6:00 GMT), in Belarus – at 8:00 a. m. (5:00 GMT). On the basis of these data, average annual and monthly values and trends in the decade ranges of the analysed multi-year period, as well as their amplitudes, were calculated.

Taking into account the clear differences in the surface water temperature in lakes over the analysed period, the authors distinguished decadal intervals to emphasise their differences. The location of the lakes in a region with a transitional climate, from more oceanic in the western part to more continental in the eastern part, which is expressed by distinct climatic conditions. Therefore, the aim of this work is to present changes in the course of surface water temperature in six decadal periods of the analysed multi-year period in selected lakes in Poland in 1961–2020 and in Belarus in 1971–2020, its spatial diversity and natural conditions during the period of climate change.

The reconstructions of climate change, mainly air temperature in the northern hemisphere and in Poland and neighbouring areas, indicate that its course is easy to notice clear fluctuations. Based on instrumental observations, it can be concluded that in the last 200 years the maximum and minimum temperatures have been increasing, and the average annual air temperatures have been characterised by a significant increase [4–6], as fig. 2 shows.

It was also noted that in the last 20 years of the 20th century and at the beginning of the 21st century there was a significant increase in the warming rate, which was noticeable not only in the winter and spring months, but also in summer [7]. In turn, A. Marsz and A. Styszyńska state the impact of two main climatic phenomena. The first of them is the winter atmospheric circulation, described by the winter North Atlantic oscillation (NAO) index (DJFM) and well reflecting the nature of short-term changes, the second important factor in long-term changes is the variable activity of the Sun, defined by the average number of sunspots [8].

Solar radiation is of fundamental importance for the thermal regime of aquatic ecosystems. Almost all of the energy that controls the lakes' metabolism comes directly from solar energy. The absorption of solar energy and its distribution in lakes play a fundamental role in the mechanisms shaping the thermal structure of surface waters, the degree of stratification of water masses, water circulation, and then influence the circulation of nutrients.

The distribution of annual sums of total solar radiation in the area of the Polish Lowlands ranges from below 3600 MJ/m^2 to above 3800 MJ/m^2. Its lowest values (<3600 MJ/m^2) occur in the area of the Mysliborskie, Waleckie and Lagowskie lakes districts, as well as the Suwalki lake district and the Augustow Plain. However, the highest values are (>3800 MJ/m^2) in the Baltic Sea zone and in the Gniezno and Kujawy lakes districts. Research by J. Uscka-Kowalkowska [9] showed that in the analysed area in 1951–2005 they showed a clearly positive trend (fig. 3).

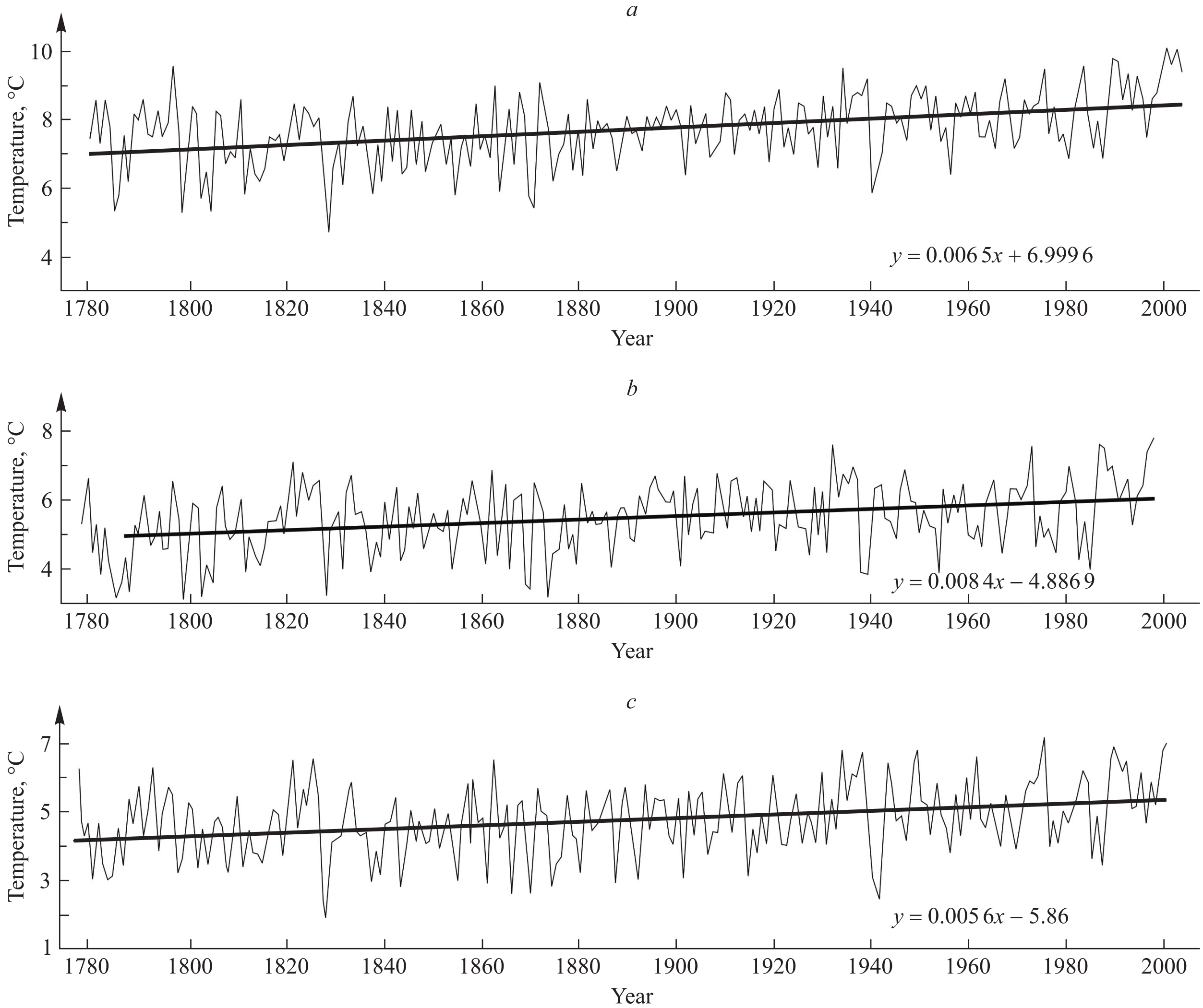

Fig. 2. Course of annual air temperature values and the trend line in Warsaw (*a*), Vilnius (*b*) and Tallinn (*c*).
Sources: [10–12]

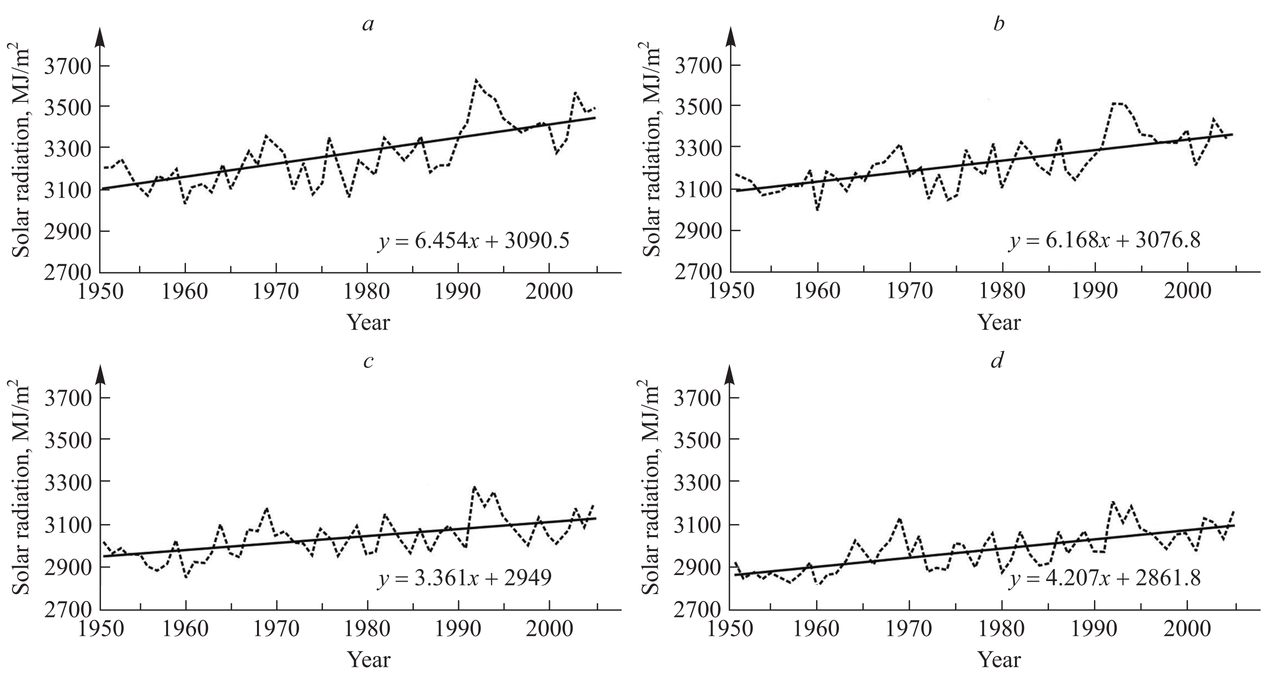

Fig. 3. Multi-annual course of total solar radiation for selected grid points in Central Europe in the period of 1951–2005: *a* – 54.29° N., 16.88° E.; *b* – 54.29° N., 20.63° E.; *c* – 50.48° N., 16.88° E.; *d* – 50.48° N., 20.63° E.
Source: [9]

Changes in the course of average annual air temperatures are confirmed by measurements in Belarus, where I. Danilovish indicates a significant increase by 1.1 °C [13], while for the areas of Karelia to the end of the first decade of 21st century the linear trend for annual air temperature was positive, and the average annual air temperature increased by 1.0–1.2 °C [14]. The nature of these changes is shown for Warsaw, Vilnius and Tallinn (see fig. 2).

Transitional climate features characterise the area where the analysed lakes are located: from more oceanic in its western part to more continental in its eastern part, which is expressed by a clear difference in climatic conditions. This is noticeable in the course of average annual air temperatures at posts in northern Poland and Belarus (fig. 4) in the period of 1961–2020, which is characterised by high variability.

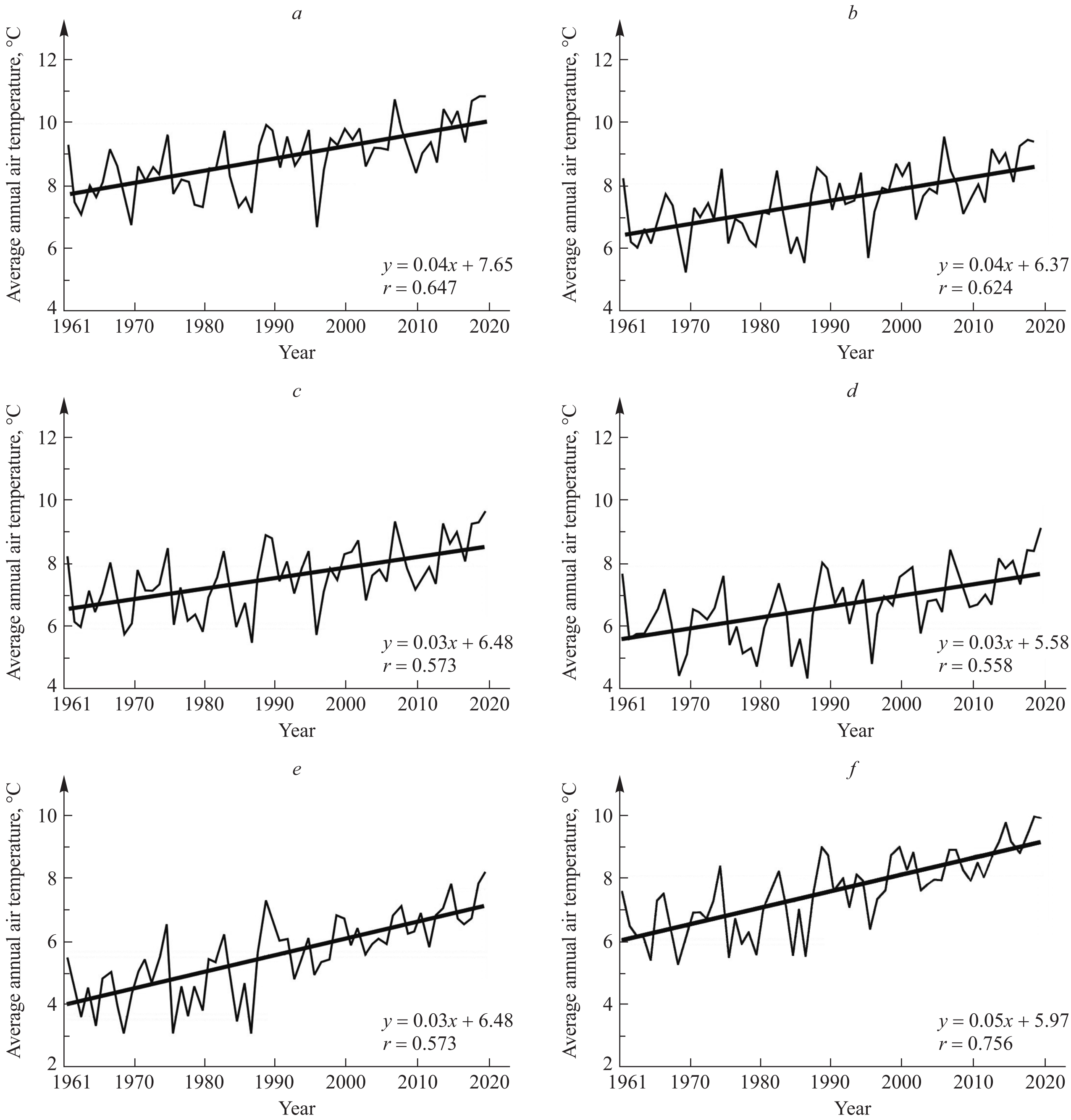

Fig. 4. The course of average annual air temperatures at selected meteorological stations in Poland and Belarus in 1961–2020 and trend lines: Gorzow (*a*) and Chojnice (*b*), Olsztyn (*c*) and Suwalki (*d*), Vitebsk (*e*) and Pinsk (*f*)

Results

Generally, the average annual air temperature in the period of 1961–2020 in the area west of the Vistula River was higher than 8.3 °C, in the Masurian and Suwalki lakes districts it was approximately 7.2 °C, clearly decreasing in the northern part of the Belarusian lake district to below 6.0 °C (Orsha). Only in the area of Polesie Volhynia it was approximately 7.7 °C. This difference is even more visible for average monthly temperatures. In December – March, the area east of the Vistula River is characterised by clearly negative air temperatures, while west of the river it rarely drops below 0 °C. Average decadal air temperatures range from 0.92 °C in the area west of the Vistula, through −1.63 °C in Masuria and the Suwalki region, decreasing to −4.4 °C in the Belarusian lake district reaching −4.73 °C at the Orsha station in January. In its decadal course, a systematic decline is observed at all meteorological stations (tables 2 and 3). In 2011–2020, the values of decadal air temperature west of the Olsztyn station are characterised by positive values.

Table 2

Average air temperatures during December – March in decadal ranges in 1961–2020 at selected meteorological stations in Poland, °C

Period	Meteorological station									
	Szczecin	Gorzow	Koszalin	Poznan	Leba	Chojnice	Torun	Olsztyn	Mikolajki	Suwalki
1961–1970	0.45	−0.85	−0.83	−1.22	−0.68	−2.42	−2.14	−2.73	−3.44	−4.38
1971–1980	1.17	0.71	0.61	0.51	0.50	−0.80	0.14	−1.15	−1.58	−2.59
1981–1990	1.26	0.72	0.97	0.51	0.66	−0.80	−0.02	−1.0	−1.58	−2.54
1991–2000	1.8	1.29	1.37	0.98	1.20	−0.12	0.37	−0.51	−0.80	−1.88
2001–2010	1.41	1.14	1.26	0.87	1.03	−0.16	0.27	−0.69	−1.11	−2.03
2011–2020	2.21	2.0	1.91	1.87	1.64	0.52	1.03	0.12	−0.26	−1.16

Table 3

Average air temperatures during December – March in decadal ranges in 1961–2020 at selected meteorological stations in Belarus, °C

Period	Meteorological station						
	Verkhnedvinsk	Polotsk	Pinsk	Orsha	Vitebsk	Zhlobin	Mogilev
1961–1970	−6.50	−6.50	−6.88	−6.94	−6.88	−5.87	−6.33
1971–1980	−4.47	−4.58	−5.12	−5.10	−5.12	−4.02	−4.88
1981–1990	−4.26	−4.15	−4.51	−4.71	−4.51	−3.50	−4.54
1991–2000	−3.03	−2.99	−3.43	−3.59	−3.43	−2.40	−3.44
2001–2010	−3.54	−3.53	−3.83	−4.03	−3.83	−2.82	−3.93
2011–2020	−2.18	−2.32	−2.69	−3.91	−2.68	−1.90	−3.0

This spatial variation in air temperature is emphasised by average annual amplitudes. In the western part of Poland, they are approximately 21 °C (Szczecin), while in the eastern part of the Belarusian lake district they reach 27 °C (Mogilev and Vitebsk).

The spatial thermal pattern over the discussed area, especially during December – March, also well highlights the course of ice phenomena on lakes. It also determines the significant impact of air temperature on the surface water temperature. Climatic conditions during the winter months are of particular importance for the formation of ice phenomena. These conditions are well represented by the course of thermal winter, treated as a daily air temperature equal to or lower than 0 °C. The beginnings of thermal winters and their course in 1961–2015 confirm the very high variability of thermal conditions in the cold season. Only in the north-eastern part of Poland a thermal winter was recorded every year. However, in the remaining areas, the course of thermal winter is most often interrupted by periods of warming [15]. However, the variability of the dates of the beginning and end of thermal winter in the analysed period does not show statistically significant changes. However, there was a slight tendency to shorten the thermal winter. Almost every winter, cold and frosty periods are interrupted by thaw periods, which vary in intensity and duration. This pattern well reflects the dependence of the average air temperature in December – March on the winter NAO index (fig. 5). Climatological winter, however, is the time of year in which the greatest interannual fluctuations occur, but also the greatest spatial variability of air temperatures [16].

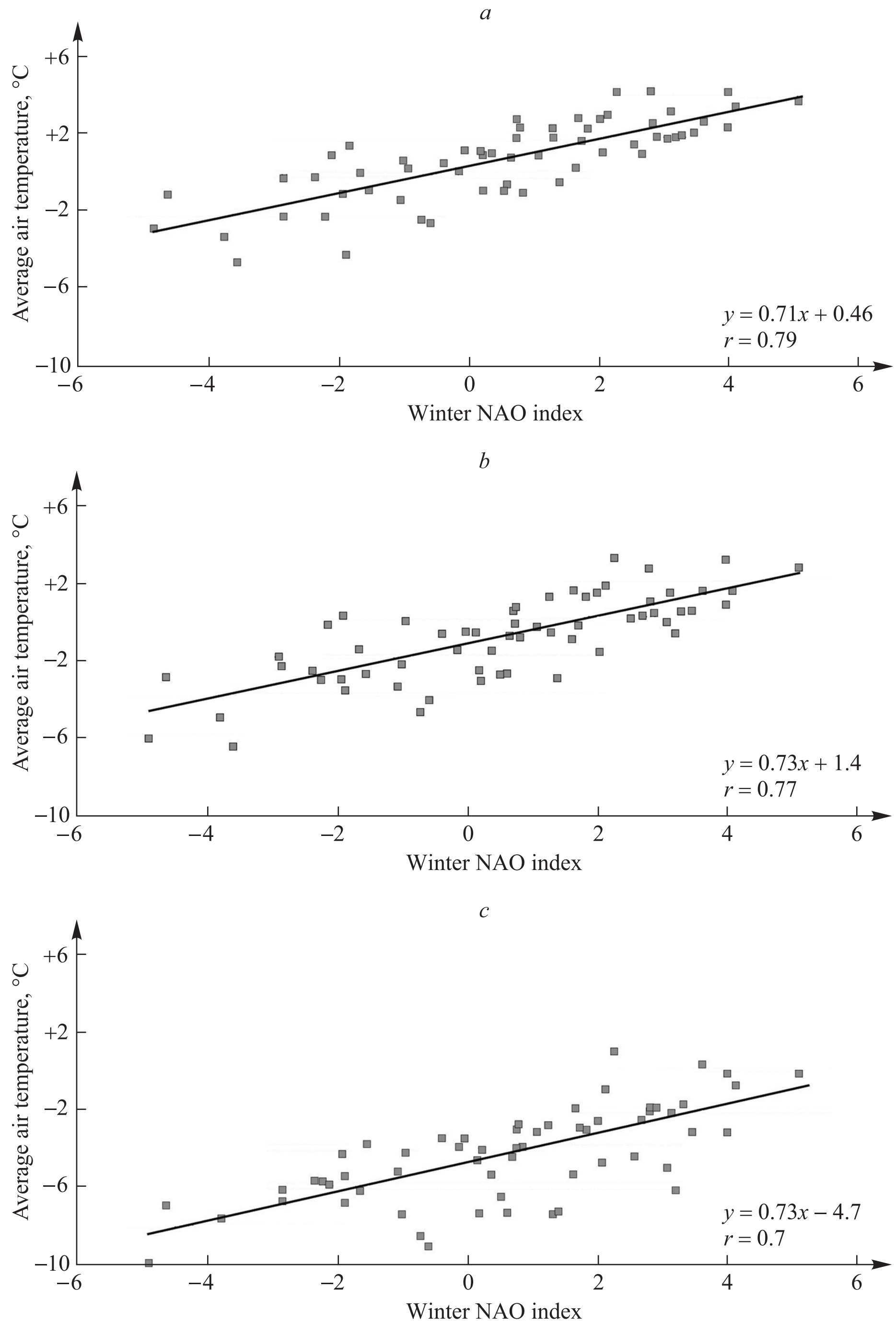

Fig. 5. The relationship between the average air temperature in December – March and the winter NAO index (DJFM) in the period of 1971–2020 for the stations Gorzow (*a*), Olsztyn (*b*), Vitebsk (*c*)

Already preliminary information about the occurrence of ice cover in the analysed area indicates significant differences in its appearance dates. The beginning of the appearance of ice cover on lakes was between 14 December in the lakes in Belarusian lake district and 28 December in the lake districts in Poland [3]. In turn, the dates of its disappearance fall on average between 8 March in the lakes west of the Vistula River, 17 March east of it and 22 March in the Belarusian lake district. This spatial differentiation is emphasised by its duration, which ranges from 61 days in lakes located west of the Vistula River, 75 days in the Masurian lake district to 108 days in lakes located in the Belarusian lake district. The duration of its retention is significantly reduced, which confirms the trend of −0.63 days per year on average [3].

Two directions of changes can be noticed in the course of average decadal annual air temperatures for 1961–2020. The first results from the geographical location of individual stations and the second from decadal changes in 1961–2020. The decrease in the average annual air temperature from west to east is confirmed by the average annual air temperatures, which vary in Poland from 8.99 °C in Szczecin to 6.68 °C in Suwalki, and in Belarus from an average of 5.85 °C in Orsha up to 7.77 °C in Pinsk (tables 4 and 5).

Table 4

Average annual air temperatures in decadal ranges in 1961–2020 at selected meteorological stations in Poland, °C

Period	Meteorological station									
	Szczecin	Gorzow	Koszalin	Poznan	Leba	Chojnice	Torun	Olsztyn	Mikolajki	Suwalki
1961–1970	8.07	7.96	7.31	7.96	7.25	6.67	7.37	6.79	6.61	5.99
1971–1980	8.45	8.21	7.64	8.18	7.43	6.94	7.75	6.95	6.97	6.01
1981–1990	8.84	8.58	8.11	8.46	7.78	7.23	8.16	7.35	7.21	6.31
1991–2000	8.99	8.92	8.39	8.74	7.97	7.60	8.46	7.50	7.59	6.68
2001–2010	9.15	9.34	8.75	9.34	8.41	8.03	8.80	7.94	7.97	7.14
2011–2020	9.69	9.94	9.31	10.09	8.93	8.59	9.45	8.57	8.52	7.74

Table 5

Average annual air temperatures in decadal ranges in 1961–2020 at selected meteorological stations in Belarus, °C

Period	Meteorological station						
	Verkhnedvinsk	Polotsk	Pinsk	Orsha	Vitebsk	Zhlobin	Mogilev
1961–1970	4.79	4.85	6.43	4.66	4.65	5.79	5.41
1971–1980	5.27	5.29	6.62	5.03	5.08	6.17	5.26
1981–1990	5.60	5.05	7.30	5.36	5.66	6.63	5.60
1991–2000	6.10	6.90	7.77	5.85	6.14	7.20	6.06
2001–2010	6.36	6.46	8.21	6.31	6.62	7.59	6.45
2011–2020	7.10	8.06	10.11	6.98	8.24	8.26	7.02

One more important feature of air temperature patterns is their variability in individual decades of the analysed period. The calculated average decadal air temperatures at virtually all stations, both in Poland and Belarus, show a systematic increase from decade to decade. The lowest values were recorded in 1961–1970, while the highest in the last decade covering the years 2011–2020. At the posts located in Poland, the trend was characterised by positive values at the level of 0.32–0.42 °C per decade, while in Belarus it was 0.28–0.74 °C per decade.

The transitional nature of the climate on the European continent is characterised by a clearly marked degree of continentalism, showing the significant influence of oceanic air masses in its western, central and northern parts [17]. The degree of continentalism varies spatially and fluctuates over time and it is related to the observed global warming and changes in atmospheric circulation [18; 19]. The thermal index of continentalism in Europe varies from 15 to over 80 %, while in Poland and Belarus it ranges from below 38 % in the Szczecin Lowland to over 60 % in the eastern part of the Belarusian upland. The continentalism index is confirmed by average annual air temperature amplitudes. Air amplitudes as the difference between the average maximum and minimum monthly air temperatures in the discussed area are clearly differentiated. The lowest values are characteristic of the Baltic Sea coastline and amount to 19.52 °C in Leba and 21.05 °C in Szczecin. As you move further east, they increase significantly and amount to 23.38 °C in Mikolajki and 23.84 °C in Suwalki. The highest values exceed 26 °C and are 26.92 °C in Mogilev and 27.05 °C in Vitebsk.

The course of average annual surface water temperatures in all analysed lakes is characterised by a positive trend of 0.044 °C per year. The highest is characteristic of Chervonoe Lake (0.066 °C per year), and the smallest (0.029 °C per year) for the deep Hancza Lake [3].

The average annual surface water temperatures in the analysed period of 1971–2020 were clearly diversified and ranged from 8.45 °C for Drivyaty Lake in the Belarusian lake district to 11.04 °C for Slawskie Lake in the

Greater Poland lake district. In the individual years of the analysed multi-year period, the highest values were recorded in 1990, 2002 and 2007, and by far the warmest year was 2007. The coldest year was 1980, when in all lakes the average annual water temperature was lower than 9.5 °C [3].

In the course of average monthly surface water temperatures, the highest values were most often recorded in July, less often in August. They ranged from 18.91 °C in Lebsko Lake to 21.84 °C in Chervonoe Lake. The highest values of the average monthly surface water temperature on lakes in Poland occurred in July 1994, when the monthly average exceeded 24 °C in Jeziorak Lake (25.2 °C) and Slawskie Lake (24.1 °C).

The course of average annual surface water temperatures in all the lakes presented in this work is characterised by a positive trend of 0.044 °C per year. The highest temperature is found in Chervonoe Lake (0.066 °C per year), while the lowest temperature is 0.029 °C per year in the deep Hancza Lake. There is also a positive trend in the course of average monthly water temperatures, ranging from 0.015 °C per year in January to 0.069 °C per year in May.

The course of average decadal values (tables 6 and 7) of water surface temperatures in the analysed lakes shows significant differences between them. The lowest water temperatures on lakes in Poland occurred in 1971–1980 and ranged from 8.01 °C (Hancza Lake) to 10.20 °C (Slawskie Lake). The following decades were characterised by a systematic increase, reaching the highest values in 2011–2020. The highest temperature was recorded in Slawskie Lake (12.09 °C), while the lowest temperature was recorded in Hancza Lake (9.36 °C). In Belarusian lakes, the lowest surface water temperatures also occurred in 1971–1980 and ranged from 7.71 °C in Naroch Lake to 8.59 °C in Chervonoe Lake. In turn, the highest temperatures also characterised the decade 2011–2020 and its range was from 9.26 °C (Drivyaty Lake) to 10.96 °C (Chervonoe Lake). The average increase in decadal water temperature in Polish and Belarusian lakes was characterised by a positive trend of 0.37 and 0.38 °C per decade, respectively.

Table 6

Average annual surface water temperatures in decadal ranges in 1961–2020 in selected lakes in Poland, °C

Period	Lake							
	Lubie	Slawskie	Lebsko	Charzykowskie	Jeziorak	Mikolajskie	Nidzkie	Hancza
1961–1970	9.50	10.35	8.60	9.33	9.54	9.38	9.18	8.54
1971–1980	8.52	10.20	8.73	9.06	9.43	9.08	9.26	8.01
1981–1990	9.28	10.56	9.19	9.24	9.96	9.45	9.58	8.40
1991–2000	9.73	10.90	9.31	9.49	10.48	9.60	9.69	8.56
2001–2010	10.31	11.43	9.66	10.05	10.63	10.16	10.33	8.90
2011–2020	11.11	12.09	10.12	11.06	11.50	10.72	10.96	9.36

Table 7

Average annual surface water temperatures in decadal ranges in 1971–2020 in selected lakes in Belarus, °C

Period	Lake				
	Vygonoshchanskoe	Naroch	Drivyaty	Chervonoe	Lukomskoe
1971–1980	8.38	7.71	7.89	8.59	8.25
1981–1990	8.58	8.23	8.08	8.86	9.25
1991–2000	8.75	8.31	8.29	9.85	9.44
2001–2010	9.26	8.98	8.78	10.12	10.25
2011–2020	10.12	9.61	9.26	10.96	10.45

Selected patterns of average decadal surface water temperatures in lakes in Poland and Belarus are presented in fig. 6 and 7.

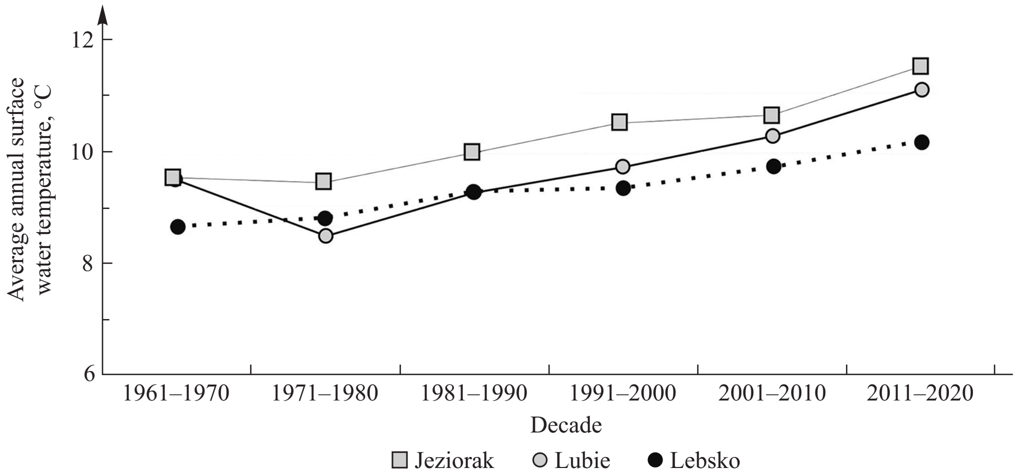

Fig. 6. Average annual surface water temperatures in selected lakes in Poland in decade intervals in 1961–2020

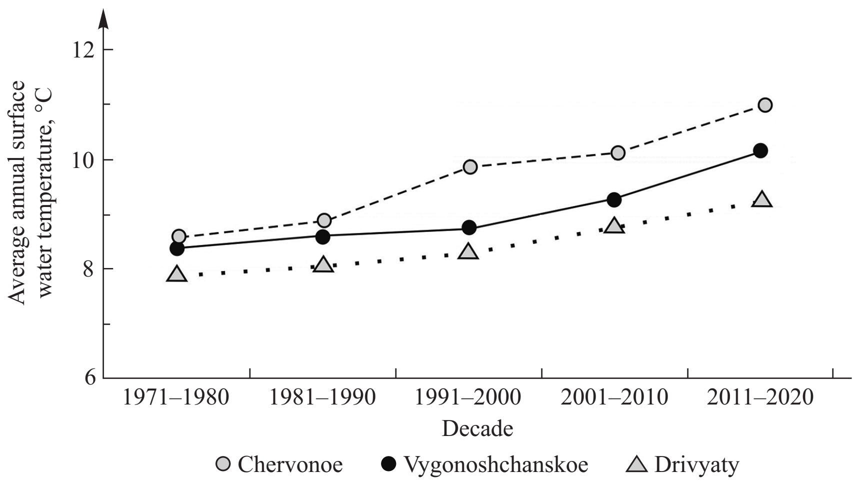

Fig. 7. Average annual surface water temperatures in selected lakes in Belarus in decade intervals in 1971–2020

A measurable aspect of the thermal regime of the studied lakes is their regional diversity. As table 8 shows, there is a clear regional variation in its value in individual decades of the 1971–2020 period. Temperatures show a clear increase in individual decades and a decrease in their values in the spatial distribution from west to east. Interdecadal differences between water temperatures in lakes located west of the Vistula and in the lakeland in Belarus they reach an average of 1.32 °C.

Table 8

Average decadal surface water temperatures in lakes located in selected regions of the Baltic Sea catchment area in 1971–2020, °C

Period	Region		
	West of the Vistula	Masurian and Suwalki lakes districts	Belarusian lake district
1971–1980	9.13	8.78	7.99
1981–1990	9.57	9.14	8.30
1991–2000	9.86	9.28	8.45
2001–2010	10.36	9.80	9.02
2011–2020	11.10	10.35	9.66

These results are consistent with the warming efficiency of Belarusian lakes. The warming efficiency coefficient in summer averages 1.45 and varies from 1.09 for Drivyaty Lake to 2.47 for Naroch Lake. Summer warming efficiency is directly dependent on the water surface area. The correlation coefficient in this case was 0.96. On an annual basis, the increase in air temperature most actively affects the increase in water temperature in shallow Chervonoe Lake, the warming efficiency for which is 1.42, i. e. the water temperature increases 1.42 times faster than the air temperature. It should be noted that Vygonoshchanskoe Lake is characterised by the slowest increase in water temperature compared to air temperature (0.68), which can most likely be explained by the watershed position of the lake. The large area of bogs in the catchment area and the active inflow of cold groundwater form a large percentage in the reservoir's nutrition. The average value of the coefficient was 1.07, which is 0.28 lower than in summer.

If in summer the warming efficiency is closely dependent on morphometric parameters, then for annual coefficients such interrelations were not revealed. No connection of this indicator with the catchment area and the period of water exchange was also found. The assumption about the dependence of the warming efficiency of a lake on the structure of its catchment and the ratio of water balance components requires further detailed studies.

Discussion

The analysis of long-term changes in surface water temperature in many lakes in Europe indicates a significant increase since the early 1990s and the 2020s [20–24]. Research in Poland also confirmed a similar trend [1; 2; 16].

The increase in air temperature causes significant changes in the entire lake ecosystem. This applies especially to the temperature of surface water in lakes, its thermal structure of water (increase in epilimnion temperature and its range, deepening of the thermocline, increase in temperature gradients in the thermocline) [1; 16; 24; 25].

This is confirmed by the increasing trends in surface water temperature in Windermere Lake (England) in 1960–2000 (an increase of 1.4 °C), and in Lough Feeagh Lake (western Ireland) in 1960–1997 (an increase of 0.7 °C). The average water temperature in Zurich Lake (Switzerland) in 1950–1990 increased at a rate of 0.16 °C per decade, and in Constance Lake by about 0.1 °C [23; 26]. This trend is complemented by exceptionally high increases of 1.6 °C per decade in Stensjon Lake (Sweden) [27]. Also, the surface water temperature in many lakes in Finland, Austria and Switzerland increased on average by 0.38; 0.43 and 0.29 °C per decade during summer, respectively [23; 28]. These conclusions are confirmed by more detailed results of regional studies [29; 30].

In the lakes Latvian, in 1946–2002, the long-term average annual surface water temperature in lakes showed a statistically significant positive trend of 0.4–0.8 °C [31]. This is confirmed by studies on large lakes in Estonia (Peipus and Vortsjarv), where the temporal variability of climatic seasons was determined in 1946–2000 [21]. The most significant trend was obtained for winter (ice cover period), which was shortened by 17 days. In Ladoga Lake, a positive trend was found at the level of 0.05–0.07 °C per year [32].

The results of research conducted on Lithuanian lakes showed that the average annual surface water temperature in 1991–2000 was by 0.6 °C higher than the average in 1981–1990 [33]. In turn, the increase in water temperature in Lithuanian lakes began in the years 1981–1985 and continues to this day [34]. Similar increases in water temperature were found in lakes and artificial reservoirs in Belarus [13]. The effect of these changes is the earlier occurrence of water temperatures of 0.2; 4.0 and 10.0 °C in spring, even from 5 to 11 days, and in autumn by 7 days.

Surface water temperature studies conducted in Polish lakes, covering the period of 1961–2000, also confirm the positive trend occurring in European lakes. For most lakes it ranges from 0.2 to 0.9 °C per decade and only in Lebsko and Jeziorak lakes they exceed 1 °C per decade [1; 2; 35; 36].

The obtained results coincide with the results of calculating the warming efficiency of the American Great Lakes, where the highest coefficient was noted for Superior Lake, which is the largest in the lake system. For the period from May to July it was 1.8, for the period from July to September it was about 2.0. From May to July, a high value (above 1.8) was also recorded in Ontario Lake, while in other months and for the year as a whole it does not exceed 1.4, but is generally close to 1.0 [37].

Conclusions

To highlight changes in shorter time periods, decadal periods were adopted. Measurements of water temperature in European lakes have confirmed the increasing influence of zonal atmospheric circulation, especially since the early 1990s [23; 26; 38]. The intensity of the inflow of air masses over the area of Western Europe, the Baltic Coast and the East European Low is determined by the activity of permanent atmospheric pressure systems – the Icelandic Low and the Azores High, expressed by the NAO coefficient. Studies have shown that the NAO has a significant impact on the thermal regime of lake waters in the analysed area, especially in winter [1; 39].

The course of surface water temperatures in lakes in Poland and Belarus over the last 50 years is characterised by large variations in their values. This mainly concerns their annual and monthly average values [3].

The largest annual changes in the surface water temperature in lakes occur on average in the range of 9.7–14.7 °C at the turn of April and May, while its largest decreases occur on average in the range of 7.6–9.6 °C at the turn of October and November. The results of calculations of temperature trends in the course of decadal averages are consistent with average increases and decreases in water temperature.

It is widely accepted that after 1980 in the areas of Central Europe, winter periods generally became warmer compared to earlier winters. The authors agree that in the southern and eastern parts of the Baltic Sea catchment area (Poland and Belarus), the main cause of climate change is the variability of atmospheric circulation and the properties of air masses that shape the climate of Central Europe.

Surface water temperatures show a significant increase in each decade of the 1971–2020 period and decrease in spatial distribution from west to east. Research has shown that the water temperature in all lakes is characterised by a positive trend of an average of 0.044 °C per year. The highest is characteristic of Chervonoe Lake (0.066 °C per year), and the smallest is characteristic of Hancza Lake (0.029 °C per year). The course of average monthly water temperatures is characterised by a positive trend ranging from 0.015 °C per year in January to 0.069 °C per year in May.

These features are related to the revival of zonal atmospheric circulation and the increase in oceanic climate features, which results in warmer winter periods, especially in January and February.

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