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Trends of Changes in Minimum Lake Water Temperature in Poland

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Abstract: Water temperature in lakes is their basic property that determines many processes. Changes in average values are thoroughly investigated using a long-term approach. Knowledge of extreme situations such as temperature minimums is still insufficient. This paper analyses changes in the minimum temperature in 10 lakes in Poland in the period 1972–2021. The obtained results show variability over the course of the parameter, both at the annual and monthly scale. In the first case, half of the analysed set showed statistically significant increasing trends (on average 0.10 °C per decade). In the latter case, the greatest changes occurred in the months of the warm half-year (on average 0.57 °C per decade). The reported situation is caused by the individual conditions of particular lakes, i.e., their location, morphometric parameters, or the dynamics of the occurrence of ice phenomena. A successive increase in the minimum temperature in lakes has its consequences for biotic and abiotic processes. Exceeding specific thresholds results in the evident transformation of these ecosystems.

Keywords: lakes; climate change; minimum temperature

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1. Introduction

The response of the hydrosphere to the effect of processes and phenomena occurring in its vicinity is evident due to the characteristic properties of water. Changes in its physical state, high capacity for accumulating energy, or facility for transporting and depositing matter are properties that make water ecosystems subject to continuous, and sometimes impulsive transformations [1,2]. Lakes play a considerable role in the natural environment. Through their high water retention capacity, they serve as a specific buffer mitigating extreme hydrological phenomena such as floods [3,4]. Moreover, freshwater lakes are a stable source of water resources in a given catchment area or region [5]. Water temperature is a key parameter determining the physical, chemical, and biological properties of these ecosystems. Its distribution and course, shape, among others, the course of ice phenomena [6], oxygen conditions [7] or the species composition of organisms [8]. The issue of the thermal conditions of inland waters is therefore among frequently discussed research problems, as evidenced by the abundant literature in the scope of [9–15]. So far, in the long term, papers referring to average temperatures have been dominant [16–19]. Maximum water temperatures in lakes have been investigated to a lower degree [20,21]. Less focus is also put on multiannual changes in minimum temperatures. Woolway et al. [22] conducted research for eight lakes in Europe. They determined an increase in their annual minimum temperature at an average rate of 0.35 °C decade^{-1}. In the case of Lake Tonle Sap (Cambodia), research conducted by Fujihara et al. [23] showed a decrease in its annual water temperature at a rate of 0.91 °C/decade. In this context, the research presented in this paper corresponds with the broad issue of the thermal regime of lakes, simultaneously referring to the so-far marginally discussed issue concerning minimum water temperature. The value is important, among others, in the context of potentially limiting the growth of some fish species [24]. When the surface water temperature reaches 0 °C, any further cooling results in latent heat removal and ice formation [25]. Therefore, changes in the minimum water temperature characteristic of the liquid state will determine the duration of the ice season, and further consequences for lake ecosystems in the remaining seasons.

Proper interpretation of the scale and scope of changes in the thermal regime of lakes provides the basis for the understanding of the entirety of the processes responsible for the functioning of these ecosystems. The availability of detailed information on its transformation in the times of global warming is therefore of utmost importance. It should be emphasised that extreme situations are critical in many aspects, and exceeding a specific threshold can cause a long-lasting and irreversible response [26].

The objective of the paper is the analysis of long-term changes in minimum water temperatures in selected lakes in Poland. The analysis was performed in the context of minimum momentary air temperatures and minimum daily air temperatures in the years 1972–2021. Moreover, the relationship between changes in water temperatures and air temperatures was determined.

2. Materials and Methods

2.1. Study Objects

The article covers 10 lakes in Poland (Figure 1). Lake Studzieniczne is located furthest to the east, Lake Sławskie to the west and south, and Lake Gardno to the north. The analysed lakes are mostly postglacial lakes, and one is a coastal lake (Gardno). All the analysed lakes are of flow-through character. Their basic morphometric parameters are presented in Table 1.

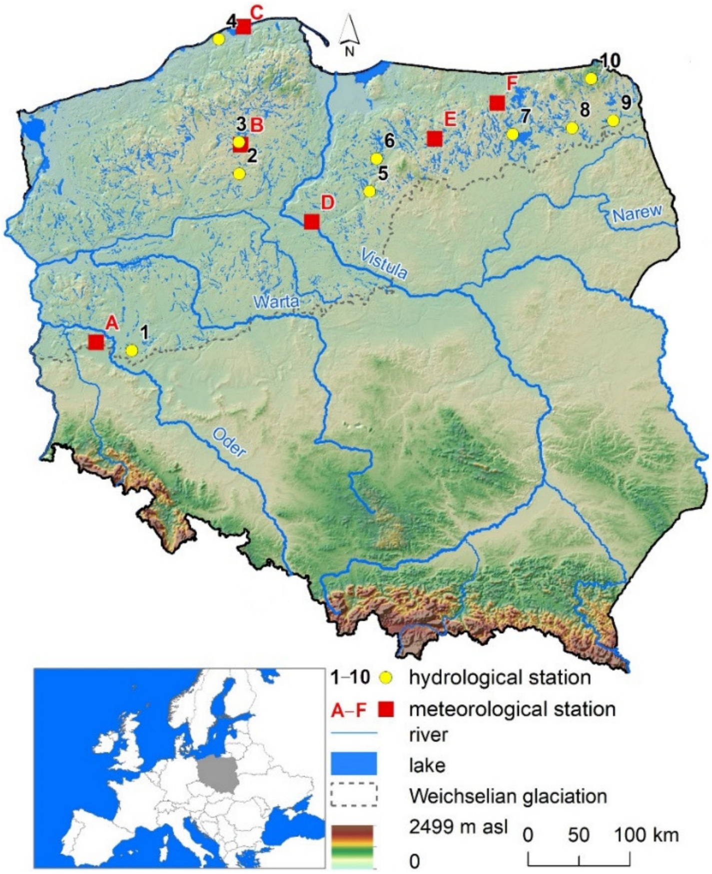

Figure 1. Location of study objects.

Table 1. Lakes' morphometric parameters [27] and environmental characteristics.

No	Lake	Latitude	Longitiude	Area (ha)	Volume (10^3 m^3)	Mean Depth (m)	Ice Cover Max Thickness (Mean) (cm)	Köppen's Climate Classification
1	Sławskie	51.89	16.02	822.5	42,664.8	5.2	20.0	Cfb
2	Sępoleńskie	53.46	17.51	157.5	7501.6	4.8	22.6	Cfb
3	Charzykowskie	53.77	17.50	1336.0	134,533.2	9.8	22.2	Cfb
4	Gardno	54.71	17.39	2337.5	30,950.5	1.3	18.8	Cfb
5	Bachotek	53.30	19.47	215.0	15,394.2	7.2	24.8	Cfb
6	Jeziorak	53.72	19.62	3152.5	141,594.2	4.1	22.4	Cfb
7	Mikołajskie	53.77	21.60	424.0	55,739.7	11.2	27.6	Dfb
8	Selmęt Wielki	53.83	22.48	1207.5	9963.9	7.8	30.2	Dfb
9	Studzieniczne	53.87	23.12	244.0	22,073.6	8.7	29.9	Dfb
10	Hańcza	54.27	22.81	305.0	120,000.0	38.7	24.1	Dfb

2.2. Materials

The paper employed daily water temperatures in 10 lakes in Poland from the period 1972–2021. The data result from measurements by the Institute of Meteorology and Water Management—National Research Institute, performed in the coastal zone at a depth of 0.4 m under the water surface. Standard measurements were conducted at 6 UTC. Moreover, the paper presents information on air temperature, also measured by the Institute of Meteorology and Water Management—National Research Institute. The obtained daily data provided the basis for the determination of minimum monthly and annual values.

2.3. Methods

Changes in minimum water temperatures in the lakes were determined for individual months and for an annual period. The hydrological year in Poland begins on the first day of November of the previous year and ends on 31 October of a given year. For monthly and annual periods, minimum 1-day values were determined. Moreover, for each year, temperature duration curves were prepared, used for reading 90% values. Because air temperatures were measured several times a day, minimum daily and average daily values of air temperature were determined. The resulting data sets provided the basis for the analogical calculation of a 1-day minimum for each month and each year. The resulting data set was subjected to further statistical analysis.

2.4. Statistical Analysis

The determination of the trend of changes in minimum water temperatures in the lakes employed a modified Mann–Kendall test (MK) [28]. The approach is broadly applied in analyses regarding the trends of climatic and hydrological changes [29–34]. A zero hypothesis was stated (H_0) on the lack of a monotonic trend of minimum water temperatures, and an alternative hypothesis (H_1) on the existence of a monotonic trend. The main assumption of the Mann–Kendall test is a lack of autocorrelation. In order to remove the autocorrelation from the series of data, the trend-free prewhitening procedure was used [35]. The determination of the magnitude of changes in minimum water temperatures in the lakes applied a non-parametric Sen test (S) [36]. The Sen test is insensitive to outliers. It can be much more accurate than a simple linear regression for skewed and heteroscedastic data. The analysis of trends and the magnitude of changes by means of MK and S tests employed the modified mk package developed by Patakamuri and O'Brien [37]. The detection of change-points in a series of 1-day minimums of monthly annual water temperatures employed the Wild Binary Segmentation 2 method. Originally, the Wild Binary Segmentation method was developed by Fryzlewicz [38]. The WBS method permits the determination of several change-points. The Wild Binary Segmentation 2 method contains a recursive algorithm that provides a complete solution for the problem of change-point detection. Another improvement is a new model selection procedure for change-point problems which is not based on penalties but uses thresholding. The developed method is fast and requires no selection of a window or span parameter [39]. The calculation of change-points employed the breakfast package developed by [40]. The analysis of changes in minimum lake water temperatures was performed in reference to changes in minimum air temperatures. For this purpose, data on air temperatures were analysed the same way, by applying a modified Mann–Kendall test, Sen test, and Wild Binary Segmentation 2 method. The statistical analysis of the results was performed by assuming standard levels of significance of 0.05 and 0.01. The generalisation of the results involved grouping months and lakes by means of cluster analysis. The clustering was based on the minimum water temperatures and the magnitude of changes in minimum water temperatures described by means of the Sen coefficient. The cluster analysis was performed by means of the Ward method. Square Euclidean distance was used as the similarity measure. The division of sets into clusters used the threshold value of 66%, and a threshold value of 25% for subclusters [41]. Finally, for the purpose of the identification of lakes with the greatest changes in minimum water temperatures, principal component analysis was conducted (PCA). The analysis was performed in reference to explanatory variables, i.e., the morphological parameters of lakes (area, volume, mean depth), their location (the number of significant principal components was adopted based on a Kaiser criterion of eigenvalues higher than 1). The correlation between the principal components and the analysed data was classified as strong, moderate, and weak according to the following values: >0.75, 0.75–0.50, and 0.50–0.30, proposed by Liu et al. [42].

3. Results

Minimum water temperatures in the analysed lakes show a course similar to that of average temperatures. The highest values of the minimum temperatures occur in June, and the lowest in January. In July, the average values and medians of minimum temperatures for the analysed lakes reach 17.9 °C. The range of changes in minimum temperatures in July is from 10.6 to 24.1 °C. In January, the average values and medians of minimum temperatures for the analysed lakes are 0.6 and 0.4 °C, respectively. Minimum temperatures in the analysed lakes in January varied in a range from 0 to 3.1 °C. The highest amplitudes of minimum water temperatures occur in the analysed lakes in May (approximately 9 °C), and the lowest in January—approximately 2.4 °C. The course of the minimum temperatures in the analysed lakes is presented in Figure 2. The annual amplitudes of water temperature fluctuations in lakes were at a level from 19.7 °C in Lake Gardno to 24.1 °C in Lake Studzieniczne. The highest amplitudes of minimum monthly water temperature fluctuations occurred in May (in Lakes Sławskie, Gardno, Bachotek, Jeziorak, Studzieniczne), June (Charzykowskie, Hańcza), July (Sępoleńskie, Selmęt Wielki), and October (Mikołajskie). The lowest amplitudes usually occurred in January, and in Lakes Mikołajskie, Selmęt Wielki, and Hańcza in February.

The cluster analysis allowed for the designation of two clusters of months in terms of the course of minimum water temperatures: the first cluster includes months from November to April, and the second one from June to September (Figure 3a). Based on minimum monthly water temperatures, lakes can also be divided into two clusters. The first one includes 8 lakes. Two subclusters can be designated within this cluster, each covering four lakes. The first subcluster includes Lakes Bachotek, Sławskie, Sępoleńskie, and Jeziorak. They are lakes located in the central and western part of Poland. The second subcluster includes Lakes Studzieniczne, Selmęt Wielki, Charzykowskie, and Mikołajskie, located in the east and central part of Poland. The second cluster includes two Lakes: Gardno and Hańcza (Figure 3b). The lakes, however, differ from each other in terms of minimum water temperatures. This results from their location, but also their type.

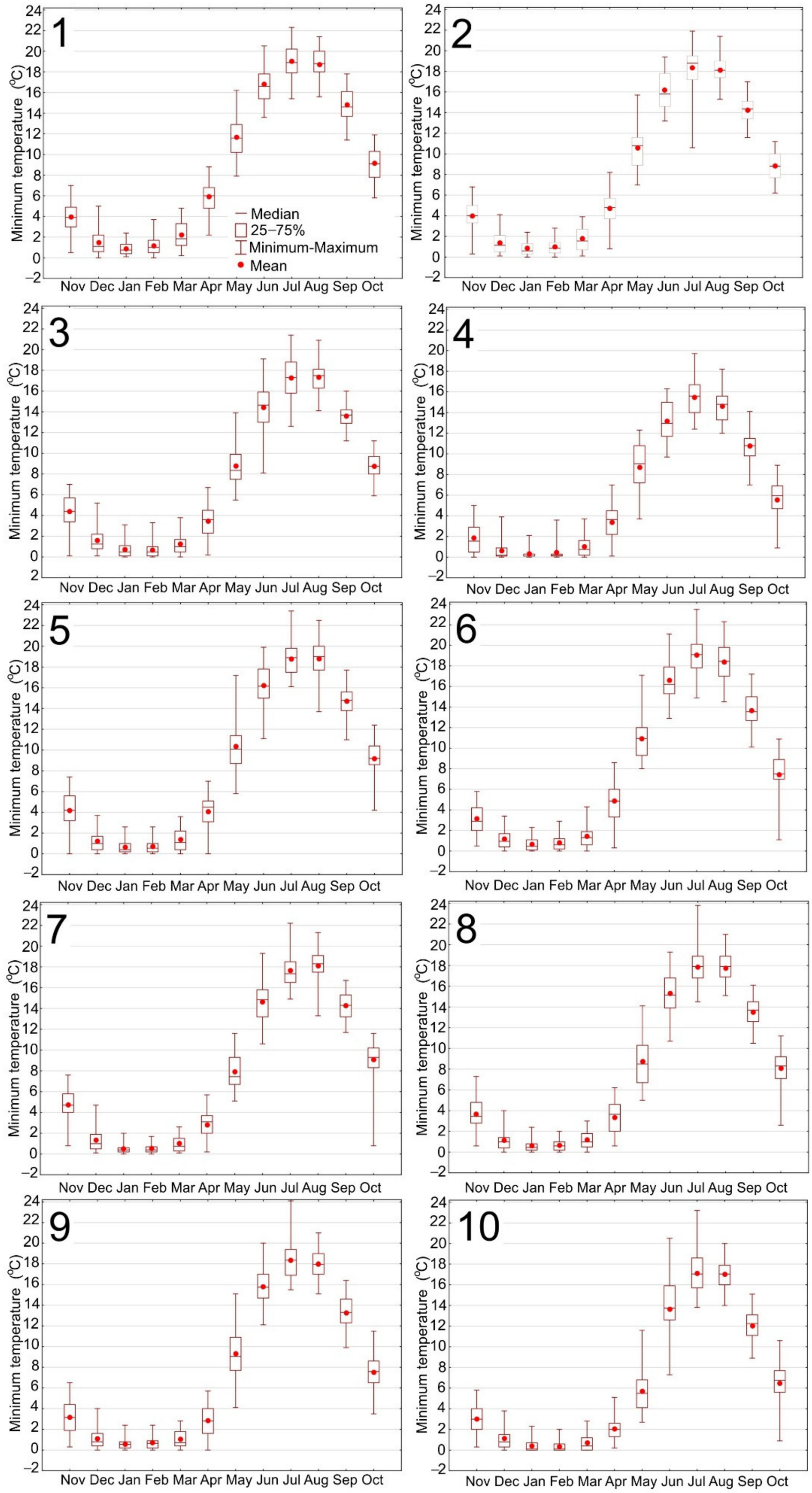

Figure 2. Fluctuations of monthly minimum water temperature in lakes: Sławskie (**1**), Sępoleńskie (**2**), Charzykowskie (**3**), Gardno (**4**), Bachotek (**5**), Jeziorak (**6**), Mikołajskie (**7**), Selmęt Wielki (**8**), Studzieniczne (**9**) and Hańcza (**10**).

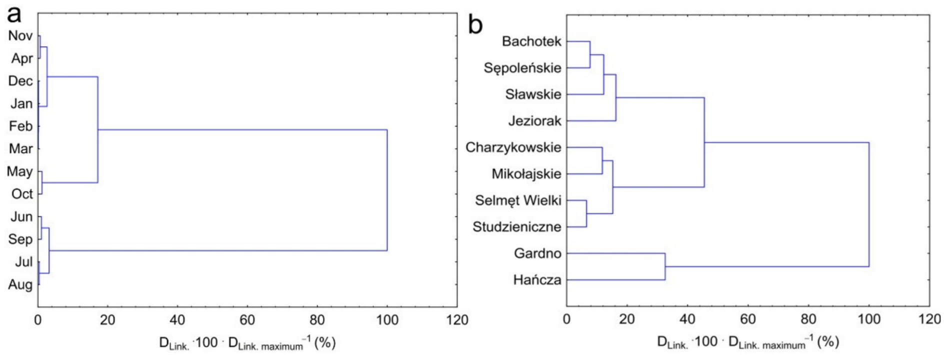

Figure 3. Division of months (**a**) and lakes (**b**) into clusters in terms of similarity of minimum water temperatures.

The analysis of minimum water temperatures in the lakes in the period 1972–2021 showed an increasing trend in 5 of them. The greatest fluctuations of minimum water temperatures occurred in Lake Selmęt Wielki (0.15 °C per decade) and in Lakes Sławskie and Charzykowskie (0.13 °C per decade). Moreover, considerable fluctuations also occurred in Lakes Bachotek and Hańcza (Figure 4). In the remaining five lakes, the changes were not statistically significant. Particularly high temperatures in the background of the analysed multiannual period were recorded in 2020. This is associated with the lack of ice cover in the winter season. Data analysis by means of the Wild Binary Segmentation 2 method showed the occurrence of numerous change-points in the data set of minimum annual water temperatures in Lakes Charzykowskie, Gardno, Studzieniczne, and Hańcza. This primarily results from the specifics of the determination of minimum annual values that usually occurred in January, but also in December and February. The analysis of values of minimum temperatures T90% read from the curve of durations of water temperatures showed an increasing trend, except for Lakes Gardno and Jeziorak. Increasing trends of minimum water temperatures were increasing at a significance level of 0.01, and for Lake Sępoleńskie they were significant at a level of 0.05. The changes described by means of the Sen coefficient were within a range from 0.15 to 0.37 °C per decade (Table S1). Different results were obtained for minimum air temperatures. At the annual scale, air temperature fluctuations in the period from 1972 to 2021 were not statistically significant for each meteorological station (Table S2).

More detailed results refer to monthly minimum temperature fluctuations in the analysed lakes (Figure 5). In the period from May to August, an increasing trend occurred in all cases, generally significant at a level of 0.01. Only in the case of Lakes Hańcza and Studzieniczne were the changes significant at a level of 0.05 (Figure 5a). The greatest changes occurred in May. The Sen coefficient values averaged 0.77 °C per decade at fluctuations from 0.59 to 0.99 °C per decade (Figure 5b). In the period from June to August, the fluctuations usually exceeded a value of 0.05 °C per decade. The lowest fluctuations of minimum monthly water temperatures occurred in January. The changes were statistically significant only for Lakes Charzykowskie, Selemęt Wielki, and Hańcza. The analysis of change-points by means of the Wild Binary Segmentation 2 method showed the occurrence of numerous change-points in December, January, February, and March in most of the analysed lakes. In the case of Lakes Bachotek, Selemęt Wielki, and Studzieniczne, numerous changes also occurred in April, and in Lakes Hańcza and Jeziorak in May. In February, March, and May in 1989, change-points occurred, and in April and December in 2006. In the remaining months, single change-points were observed. Considering the above, it appears more credible to conduct analyses for months from May to October, when no ice phenomena or disturbances in water mixing occur in the analysed lakes. The analysis of minimum monthly air temperatures showed significant changes in the period from June to August. It should be emphasised that the greatest changes in minimum air temperatures occurred in June, ranging from 0.63 to 0.78 °C per decade at an average value of 0.71 °C per decade. Moreover, in meteorological stations in Chojnice, changes also occurred in

December and September, in Kętrzyn and Olsztyn in December and April, and in Toruń in December and September.

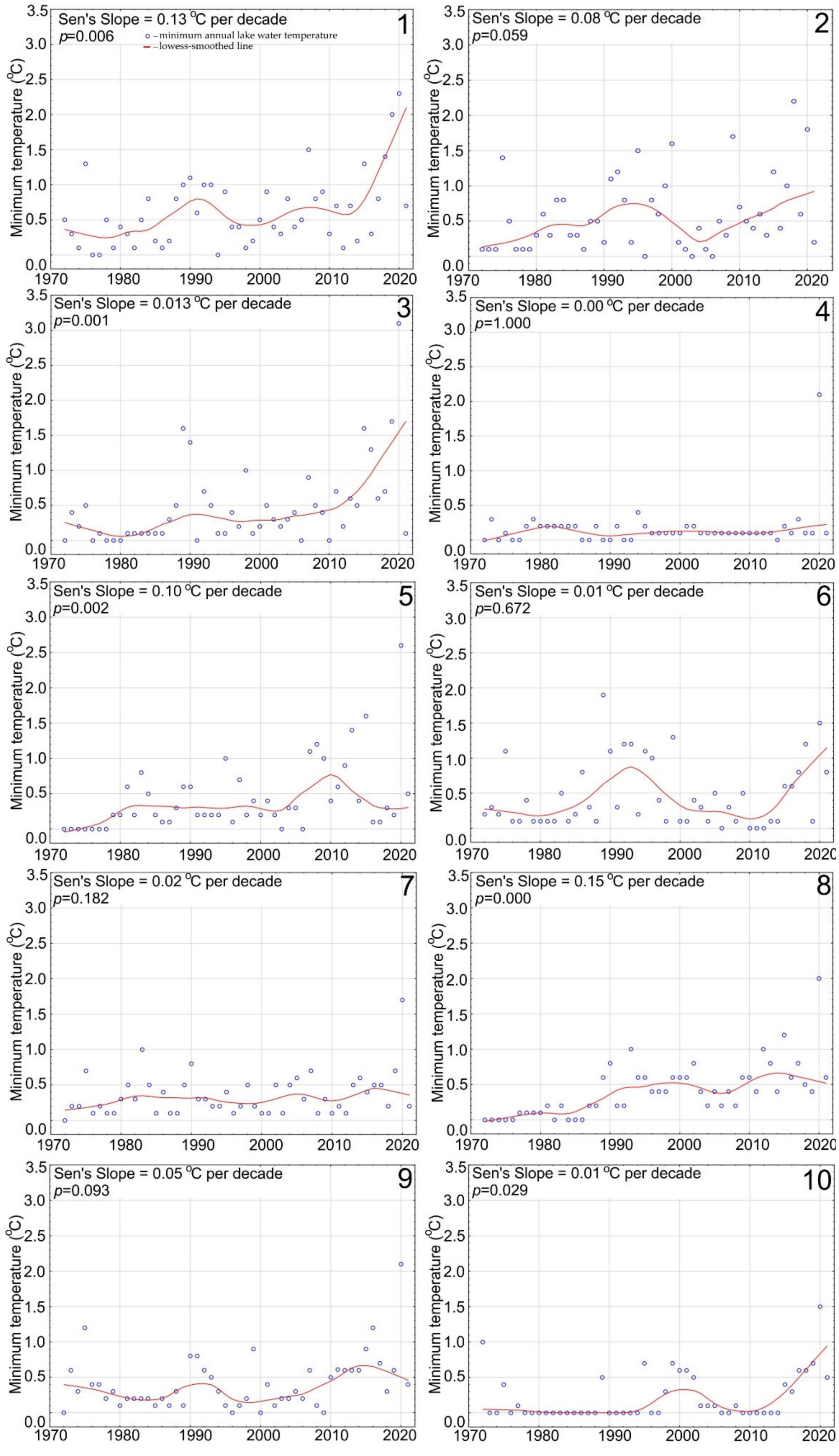

Figure 4. Course of minimum annual water temperatures in lakes: Sławskie (**1**), Sępoleńskie (**2**), Charzykowskie (**3**), Gardno (**4**), Bachotek (**5**), Jeziorak (**6**), Mikołajskie (**7**), Selmęt Wielki (**8**), Studzieniczne (**9**) and Hańcza (**10**).

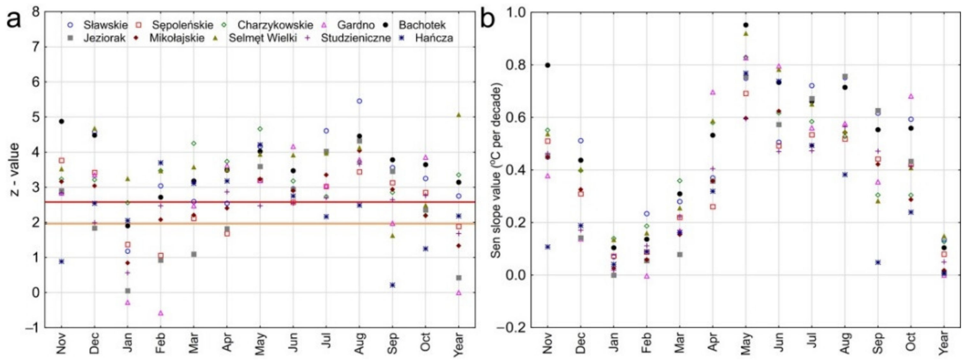

Figure 5. Significance (**a**) and magnitude (**b**) of fluctuations of minimum monthly and annual water temperatures in lakes in the period 1972–2021 (orange line designates threshold value to a significance level of 0.05, red line designates a threshold value to a significance level of 0.01).

The obtained values of the Sen coefficient provided the basis for the division of the analysed months into two groups (Figure 6). The first group includes months with the greatest fluctuations of minimum water temperatures. This group can be divided into 2 subgroups. The first one covers the months of April, September, October, and November with fluctuations at a moderate level (on average 0.44 °C per decade, at fluctuations in a range from 0.05 to 0.80 °C per decade), and the second one from May to August with the greatest water temperature fluctuations (on average 0.64 °C per decade, at fluctuations from 0.38 to 0.95 °C per decade) (Figure 6a). The last group includes December and the period from January to March when fluctuations of the minimum water temperatures were at the lowest level (on average 0.17 °C per decade, at fluctuations from 0 to 0.51 °C per decade).

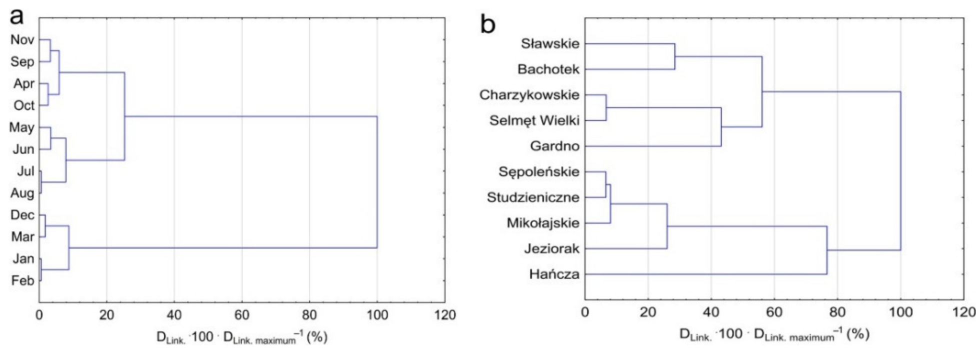

Figure 6. Division of months (**a**) and lakes (**b**) into groups in terms of similarities in minimum water fluctuations.

A more complex situation concerns the analysed lakes. They can be separated into 3 groups (Figure 6b). The first group includes Lakes Sławskie, Bachotek, Charzykowskie, Selmęt Wielki, and Gardno. In these lakes, minimum water temperature fluctuations were at an average level of 0.48 °C per decade. The second group covered Lakes Sępoleńskie, Studzieniczne, Mikołajskie, and Jeziorak, with fluctuations at a level of 0.38 °C per decade. Lake Hańcza stands out in terms of minimum water temperature fluctuations, averaging 0.30 °C per decade. Generally in all the lakes, increases in minimum temperatures are higher in the months of the warm half-year (May–October) than in the months of the winter half-year (Figure 7). The differences are at an average level of 2.3 at a range of fluctuations from 1.4 to 3.5 times. The lowest seasonal differences occur for Lakes Selmęt Wielki, Charzykowskie, and Bachotek, from 1.4 to 1.8. The greatest disproportions occur in Lakes Gardno, Jeziorak, and Hańcza. In those lakes, the increasing trend of water temperature in the period from May to October is from 2.8 to 3.5 times higher than in the period from November to April.

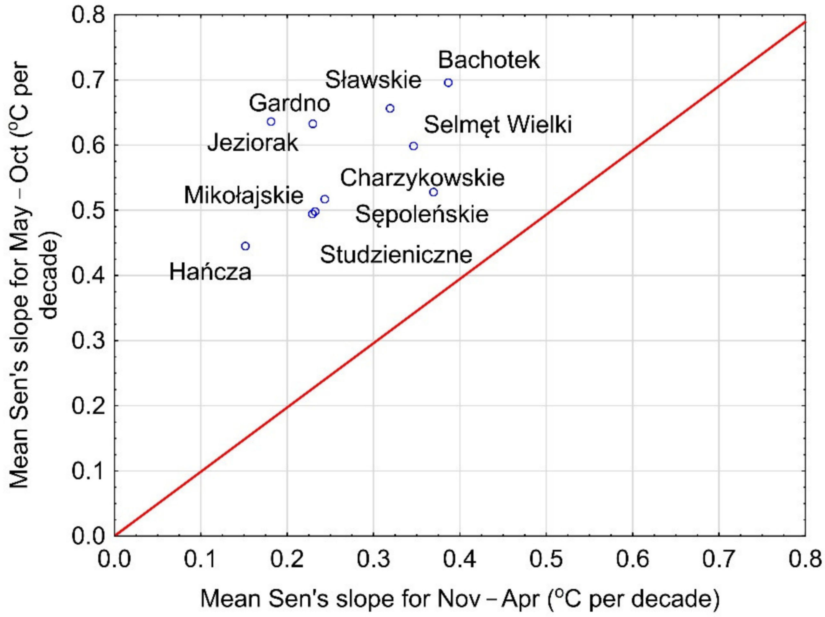

Figure 7. Increases in minimum water temperatures in lakes in the period from November to April and from May to October.

The principal component analysis aimed at identifying factors that can contribute to an increase in the minimum water temperatures in lakes. The analysis permitted the designation of two significant factors, PC1 and PC2, with values of 2.81 and 1.01, respectively. The designated factors account for 70.43% and 25.17% of the internal data structure, respectively. The obtained results suggest that an increase in the minimum temperatures in lakes in the summer periods related to the depth of lakes, their location between the west and east of Poland, and altitude (Figure 8). This means the lakes that warm up faster in the summer period are lakes that are shallower, located at a lower height, or in the west of Poland.

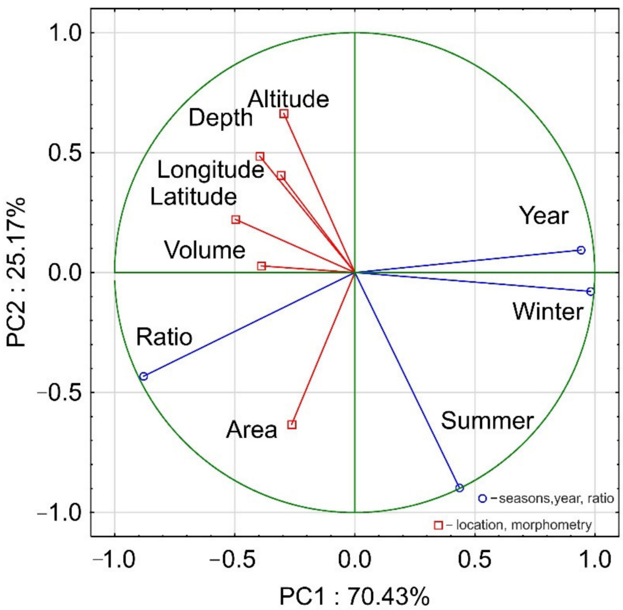

Figure 8. Results of PCA analysis for changes in half-annual and annual minimum water temperatures in lakes (Summer—mean Sen's slope value to the period from May to October; Winter—mean Sen's slope value to the period from November to April, Ratio—ratio of the Sen's slope value for summer and winter).

The PCA analysis conducted for months allowed for the designation of 3 principal components with values higher than 1. The designated components account for 40.35%, 24.40%, and 19.56% of the internal data structure, respectively (Figure 9). The obtained results suggest that in the analysed lakes, an increase in minimum water temperatures in July, August, September, and October is related to the location of the lake (latitude, longitude and altitude) and its depth.

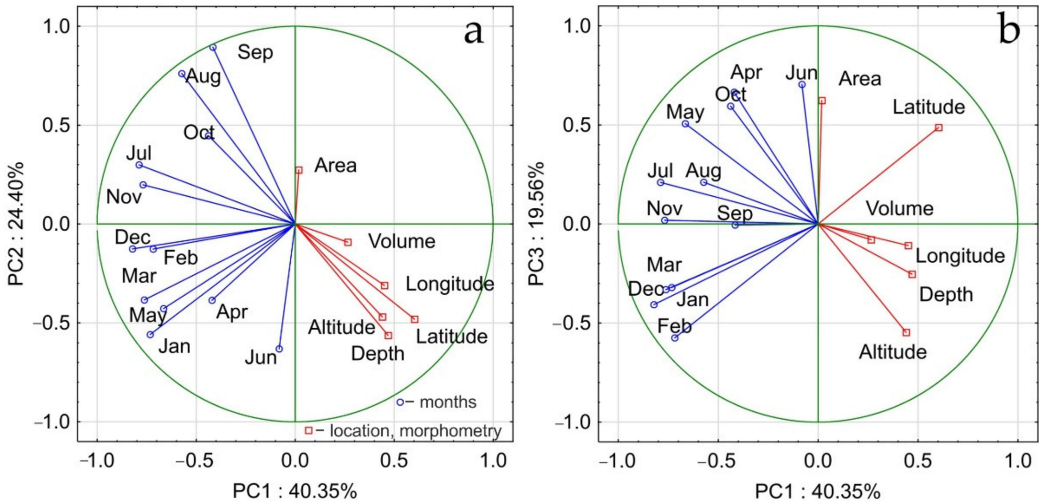

Figure 9. Results of the PCA analysis for fluctuations of monthly minimum water temperatures in lakes, projection on the background of components PC1 and PC2 (**a**) as well as PC1 and PC3 (**b**).

4. Discussion

The research conducted in the paper refers to minimum temperatures, and particularly to the long-term direction and scale of changes, pointing to their variable character. In the case of minimum annual water temperature, an increasing trend was recorded for half of all the analysed lakes. This result is in accordance with, among others, research by Woolwey [22] for other lakes in Europe (primarily in the UK, as well as Ireland, Austria, and Switzerland). In five cases for which no statistically significant changes in annual minimum temperatures were recorded, the dynamics of ice phenomena are of key importance (identified with temperature of 0 °C). This is well illustrated in the case of Lake Sępoleńskie (Figure 4), where the increasing trend line plateaued after 2000, and then increased again. As a result, however, for the entire multiannual period analysed in the paper, the observed changes were not statistically significant.

From a broader perspective, the long-term course of minimum water temperature analysed in the paper supplements the current state of knowledge on the thermal regime of lakes in Poland, referring to average [41] and maximum temperatures [26]. At a monthly scale, minimum temperatures show an evident division—with a higher increase in the warmer half-year. It should also be emphasised that it also occurs in the winter season (Figure 5). The reported situations have consequences in many aspects related to the functioning of lakes, in reference to both biotic and abiotic elements. Lakes show their characteristic features in the annual cycle. For example, Winslow et al. [43] emphasise that phenological events such as phytoplankton success and the spawning of fish respond to specific seasonal temperatures. According to Currie et al. [44], a great portion of laboratory research on fish tolerance concerns high temperatures, whereas most deaths of fish in nature is caused by their exposure to low temperatures. Pełechata et al. [45], analysing changes in phytoplankton in Lake Jasne (located in the study area presented in the paper), determined that the abundance of the selected species was related to, among others, lower water temperature in the growing season. The characteristics of the ichthyofauna of Lake Druzno presented by Martyniak et al. [46] largely overlaps with the species composition of fish in the analysed lakes, allowing for a detailed determination of, among others, the thermal conditions of their functioning in the analysed region. In reference to selected examples, the reproduction of pike occurs at a water temperature of 6–14 °C, roach 12–14 °C, Crucian carp >14 °C, and bream at a temperature of 17–20 °C. Therefore, the increasing trend of the bottom threshold water temperature will be of key importance for changes in the entire chain of trophic relations for lakes in north Poland. This in turn will affect the fishery management or angling use of the lakes, important for the functioning of the lake district zone in economic terms. Moreover, an increase in temperature in lakes will have further consequences for rivers flowing out of these lakes. It will probably increase the size of longitudinal temperature gradients, which will probably affect the distribution of cold water fish species [47].

The quantity of oxygen dissolved in water is important for life processes, providing for the proper functioning of aerobic organisms and biodiversity of these ecosystems. In the context of successive increases in minimum water temperatures, the possibility of dissolving oxygen becomes increasingly scarce, as confirmed in earlier research from Poland. The analysis of the thermal and oxygen conditions in five lakes showed an increase in water temperature in the epilimnion zone and a simultaneous decrease in the content of dissolved oxygen [48]. In addition to the aforementioned effect on hydrobiological conditions, a decrease in the amount of oxygen dissolved in water limits its self-cleaning properties [49].

Changes in temperature remain in a close relationship with water density, which in deep lakes is of key importance for shaping the stratification system. As emphasised by Woolwey et al. [50], stratification is a factor affecting the distribution of energy, oxygen content, and the availability of nutrients, i.e., elements determining the abundance and biomass of organisms. The reported increasingly shorter terms of minimum water temperatures (characteristic of particular seasons) are of key importance for the dynamics of circulation conditions, and consequently the duration of water stratification. An increase in water temperature will contribute to, among others, the increased strength of stratification that will be dependent on the depth, surface area, and transparency [51]. Peeters et al. [52], analysing the case of Lake Zurich in central Europe, determined that an increase in water temperature will cause a situation in which the near-surface layer will be maintained above 4 °C throughout the year, contributing to a change in the system of vertical water circulation from dimictic to monomictic. Seven of the lakes analysed in the current paper also show dimictic properties, and the possible change in the system of water mixing signalled above will radically affect the current course of processes that occur in them.

Another important aspect for lakes in the temperate zone is the presence of ice cover [53–55]. Slower cooling of water determines a delay in the moment of development of the ice cover, and consequently a change in the ice regime. For example, an increase in minimum water temperature in Nam Co Lake recorded by Guo et al. [56] was the primary cause of changes in its ice phenology and the reduction in ice duration. Additionally, in the case of lakes analysed in the paper, an evident reduction in the ice season is recorded with a simultaneous decrease in ice thickness [57]. For a dozen of the analysed lakes, they evidenced that the delay in the development of ice cover reached an average of 3.0 days/decade. On the other hand, the evident acceleration of the ice end (3.8 days/decade) creates a situation where water is not isolated from external factors, therefore accelerating and prolonging warming. The effect of this process at the turn of the winter–spring season finds confirmation in the analysed lakes characterised by an increase in minimum temperature that progresses in subsequent months.

5. Conclusions

Due to the number of close relations and dependencies on water temperature in lakes themselves, as well as in their vicinity, this characteristic is one of the key ones for these elements of the hydrosphere. The course of average values is investigated in detail using a long-term approach. Knowledge of extreme situations such as maximums and minimums is still unsatisfactory. This paper presents an analysis of the changes in minimum temperature in 10 lakes in Poland at an annual and monthly scale over the period of the last five decades. The obtained results show that at both temporal scales, the course of this parameter is variable, whereas in the first case, half of the analysed set showed statistically significant increasing trends, and in the second case, the greatest changes occurred in the months of the warm half-year. The reported situation is determined by the individual conditions of particular lakes, namely their location, morphometric parameters, or dynamics of the occurrence of ice phenomena. A successive increase in the minimum temperature threshold in lakes will have its consequences for biotic, as well as abiotic processes, and will finally lead to substantial transformations of these ecosystems. Therefore, future research in the context of the results obtained in this paper should focus on the detailed determination of such dependencies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app122412601/s1, Table S1: Changes in lake minimum water temperatures in the period 1972–2021, Table S2: Changes in air temperatures in selected meteorological stations in the period 1972–2021.

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