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Effect of climate warming on a change in thermal and ice conditions in the largest lake in Poland – Lake Śniardwy

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Abstract: Lake Śniardwy is the largest among more than 7000 Polish lakes. So far, it has not been a subject of detailed investigations concerning long-term changes in water temperature or ice regime. A considerable change in thermal and ice conditions has been observed in the period 1972–2019. Mean annual water temperature increased by 0.44°C dec^{-1} on average, and was higher than an increase in air temperature (0.33°C dec^{-1}). In the monthly cycle, the most dynamic changes occurred in April (0.77°C dec^{-1}). In the case of ice cover, it appeared increasingly later (5.3 days dec^{-1}), and disappeared earlier (3.0 days dec^{-1}). The thickness of ice cover also decreased (2.4 cm dec^{-1}). Statistical analysis by means of a Pettitt test showed that the critical moment for the transformations of the thermal and ice regime was the end of the 1980's. In addition to the obvious relations with air temperature for both characteristics, it was evidenced that the occurrence of ice cover depended on wind speed and snow cover. The recorded changes in the case of Lake Śniardwy are considered unfavourable, and their consequences will affect the course of physical, chemical, and biological processes in the largest lake in Poland.

Keywords: Lakes; Water temperature; Air temperature; Ice cover; Climate change; Central Europe.

INTRODUCTION

Lakes constitute an important element of the natural environment, shaping its character both in their direct vicinity and throughout their catchments (affecting the hydrological conditions, microclimate, etc.). They are a landscape-forming element, and guarantee biodiversity – of both flora and fauna (Ptak, 2013a). The functioning of lake ecosystems is largely dependent on the abiotic conditions (both morphometric properties of lakes and the occurring physico-chemical phenomena and processes). One of the basic properties of the type is water temperature and the related occurrence of ice phenomena on lakes in the winter season. The appearance of ice cover determines the occurrence of new conditions for physical, chemical, and biological processes (Ptak, 2013b). The isolation of water masses from external conditions maintained for a longer time may endanger living organisms. Winter losses in fish can be intensive under ice in shallow lakes, and have a cascade effect on the food chain, and consequently on water cleanliness in the lake (Balayla et al., 2010). Detailed investigation of the course of variability of water temperature and ice phenomena occurring in lakes is therefore important for many reasons (Ptak, 2013b). That is why it is an extensively discussed research problem (Choiński et al., 2015a, b; Huang et al., 2019; Naumenko et al., 2012; Piccolroaz et al., 2019; Ptak et al., 2017, 2018; Zhu et al., 2020). The issue gains particular importance in the context of the observed global warming. As a result, substantial transformations are observed not only in properties of lakes, but also in other elements of the hydrosphere. It is particularly evident in an increase in water temperature (Austin and Colman, 2008; Hampton et al., 2008), as well as the commonly recorded reduction of the ice season (Magnuson et al., 2000; Nowak et al., 2018).

The objective of the paper was to determine the directions and rate of changes in the thermal regime of waters and ice regime in Lake Śniardwy (Fig. 1) in the period 1972–2019. Additional objectives of the paper included the analysis of the predictability of occurrence of ice phenomena in reference to stability and seasonality, and investigation of mutual interactions between parameters describing the ice regime of Lake Śniardwy. The paper adopted the following research hypotheses: (1) the highest rate of changes in water temperature occurs in the spring season, (2) ice cover duration is reduced, (3) maximum ice cover thickness is reduced, (4) ice cover start is delayed, (5) ice cover end is accelerated.

Lake Śniardwy has been the subject of many scientific studies so far. They focused on the lake itself (Kopiejewska, 1989; Lisicki, 2001; Popielarczyk and Templin, 2014; Robbins and Jasinski, 1995), as well as on the system of the Great Masurian Lakes – the largest lake complex in Poland, where Śniardwy constitutes an important element (Bukowska et al., 2017; Dąbrowski, 2001; Kiersztyn et al., 2018; Wrzesiński and Ptak 2016). Nonetheless, no long-term analysis of changes in water temperature or ice regime, i.e. parameters of key importance for a number of other processes and phenomena occurring in the lake, has been conducted to date.

STUDY OBJECT, MATERIALS AND METHODS

Study object

Lake Śniardwy is the largest among more than 7000 existing lakes in Poland. The lake's morphology developed particularly during phase I and II of the main stadial of the Baltic glaciation. Lumps of dead ice were of basic importance for the genesis of Śniardwy (Szostak, 1967). It is a lake of the bottom moraine (generally: considerable surface area, diverse shoreline, many bays, islands and peninsulas, relatively mild bottom slopes, variable and unevenly distributed depths). According to Siuda

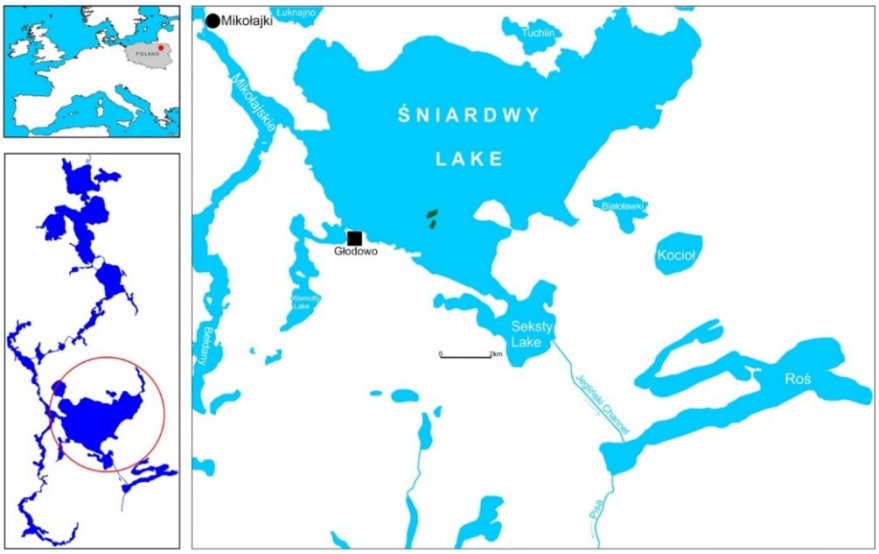


Fig. 1. Location of the study area.

et al. (2020), its basic parameters are as follows: surface area – 113.4 km^2, volume – 660.212 10^6 m^3, maximum depth – 25.9 m, average depth – 5.8 m, shoreline length – 97.15 km. In terms of water resources, it is the third largest lake in Poland. Water flows from Lake Śniardwy through Lake Seksty and the Jegliński Channel, then south to Lake Roś, through the Pisa and Narew Rivers, to the Vistula River. Lake Śniardwy shows no thermal stratification (Olszewski, 1951). The analysed object is an element of a largest hydrographic network, the so-called Great Masurian Lakes System. In the 19th century, as a result of construction of a channel connecting Lake Śniardwy with the complex of Lake Mamry, it ceased functioning as a separate hydrographic unit. The resulting interconnected system featured even water table at a level of approximately 116.0 m a.s.l., regulated by means of weirs on the Węgorapa River and Jegliński Channel (Kowalski, 1954). The Great Masurian Lakes System is composed of 24 lakes connected with a natural hydrographic network and artificial channels with a total surface area of more than 30 km^2 (Dąbrowski, 2012).

Materials and methods

The paper employed data from station Głodowo provided by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB). The data concerned mean monthly water temperatures and occurrence of ice phenomena from hydrological years 1972–2019. Water temperature measurements were performed daily at 6.00 UTC, on a point basis at a depth of 0.4 m. Data concerning ice phenomena covered: terms of ice cover start (ICS) and ice cover end (ICE), and maximum ice cover thickness values (MICT). Terms of ice cover start and end are provided in reference to the beginning of the hydrological year (number of days from the beginning of the hydrological year). The dates of ice cover start and end provided the basis for the calculation of ice cover duration (ICD). The terminology was adopted after earlier papers addressing this issue (Choiński et al., 2015; Leppäranta 2015). In reference to climatic data, the study employed mean monthly air temperatures and wind speed values from, the period 1972–2019 from the synoptic station of IMGW-PIB in Mikołajki, approximately 10 km north-west of the hydrological station (Fig.1). Moreover for Mikołajki station the data presenting snow cover duration (SCD), maximum snow cover thickness (MSCT) and average snow cover thickness (ASCT) were obtained.

The obtained data were subject to statistical analysis by means of a non-parametric Mann-Kendall test (MK) (Kendall and Stuart, 1968).

In the analysis, hypothesis H_0 was adopted regarding lack of a monotonous trend of water temperatures and ice phenomena, and the alternative hypothesis H_1 assumed the existence of such a trend. The value of normalised statistic Z, permitting verification of the adopted hypothesis.

The trend is increasing if Z adopts a positive value, or decreasing if Z adopts a negative value. Normalised statistic Z provided the basis for the calculation of test probability p; if its value is lower than the adopted significance level, the trend is statistically significant. The analysis of significance of trends was performed for significance level 0.05. Values of changes in water temperature in particular months (WT), maximum ice cover thickness (MICT), ice cover duration (ICD), and ice cover start and end (ICS, ICE) were calculated based on a non-parametric Sen's test (Gilbert, 1987). It was assumed that temporal changes in water temperature and ice phenomena can be described with a general formula $f(t) = Qt + B$, where Q is the line slope coefficient, and B is a constant. The slope of Qi between two points of the time series was calculated from the formula:

$$Q_i = \frac{x_j - x_k}{j - k}, \quad k \neq j$$

For a time series composed of n elements, $N = n(n-1)/2$ of value Q_i exists. According to Sen, the general estimator of Q slope is a median from set N of Q_i values, and can be calculated from the following formula:

$$Q = \begin{cases} Q_{(N+1)/2} & \text{if } N \text{ is odd} \\ \dfrac{Q_{N/2} + Q_{(N+2)/2}}{2} & \text{if } N \text{ is even} \end{cases}$$

The value of constant B was calculated as a median from the value $x_i - Q_{ti}$.

Moreover, for the purpose of detection of years of occurrence of potential change in water temperature conditions and ice phenomena, a Pettitt test (1979) was applied. The analysis was performed for significance level 0.05.

An analogical procedure was adopted for the purpose of determination of directions and value of changes in mean monthly air temperatures, mean wind speed, snow cover duration maximum and mean snow cover thickness in station Mikołajki. For the purpose of a full description of the course of ice processes and determination of their mutual dependence, an analysis of correlation between the analysed parameters was performed.

For the purpose of designation of factors determining the occurrence of ice cover in Lake Śniardwy, a Pearson correlation analysis was performed. The analysis considered the following parameters: dates of ice cover start and end (ICS, ICE), ice cover duration (ICD), and maximum ice cover thickness (MICT). They were subject to the analysis in reference to mean periodical air temperatures and wind speed values from the period from November to March (Table 1).

Table 1. Periods for lake drivers used for calculating correlation coefficients.

Ice cover variables	Air temperature (AT) / wind speed (WS)
Ice cover start (ICS)	November (XI) December (XII) November–December (XI–XII)
Ice cover end (ICE)	December–March (XII–III) January–March (I–III) February–March (II–III)
Ice cover duration (ICD)	November–March (XI–III) December–March (XII–III) January–March (I–III)
Maximum ice cover thickness (MICT)	January–February (I–II) February–March (II–III) January–March (I–III)

Moreover, a Pearson correlation analysis was carried out between the values describing the ice regime of Lake Śniardwy and the parameters describing the duration (SCD) and thickness (MSCT and ASCT) of snow cover at the station in Mikołajki.

RESULTS

Mean water temperature in Lake Śniardwy in the analysed multi-annual period was 9.7°C. The warmest months were July (20.3°C) and August (19.6°C), and the coldest January (0.9°C) and February (1.2°C). The study showed a considerable change in the thermal conditions of Lake Śniardwy – Table 2. The table also presents statistics concerning ice over, air temperature, and wind speed. The analysis of mean annual water temperatures showed that the decade increase in water temperature according to Senn's method averaged 0.44°C·dec^{-1}, and an increase in mean annual air temperatures was at a lower level, i.e. 0.33°C·dec^{-1} (Fig. 2).

A consequence of the successive increase in air and water temperature is a change in current processes occurring in the lake. A good indicator of such changes is among others the occurrence of ice cover. Appearance of ice is a property typical of surface waters in temperate and subpolar latitudes, and the presence of ice considerably changes the functioning of water ecosystems, in terms of water mixing, distribution of water flow, dissolution/ release of gases, etc., (Wrzesiński et al., 2013).

The average term of ice start in the analysed multi-annual period was 20 December, average ice end was 16 March, mean maximum ice cover thickness was 29 cm, and mean ice duration was 87 days.

In the case of ice cover, the calculations revealed an evident trend in the scope of later and later occurrence of ice cover start (ICS) (Senn's slope – 5.3 days dec^{-1} – Fig. 3) and ice cover duration (ICD) (Senn's slope – 8.7 days dec^{-1} – Fig. 4) over the period of the last fifty years. In the case of ice cover end in the lake (ICE), a tendency for its acceleration occurred (Senn's slope – 3.0 days dec^{-1}– Fig. 3). A trend for a reduction of maximum ice cover thickness MICT was also determined (Senn's slope – 2.4 cm dec^{-1}– Fig. 5). Assuming that the tendencies presented above in the scope of ice cover start and end are maintained at the specified level, around year 2100 ice cover in Lake Śniardwy might completely disappear.

The analysis of mean monthly water temperatures also showed their increase. The greatest changes at a level of 0.77°C dec^{-1} occurred in April, and lowest in January at a level of 0.14°C dec^{-1} (Table 2). Higher than average changes occurred in April, May, July, August, September, and November, and the lowest in January, February, and November. Increases in a large majority of mean monthly water temperatures in the period 1972–2019 were significant at a level of 0.01, only in

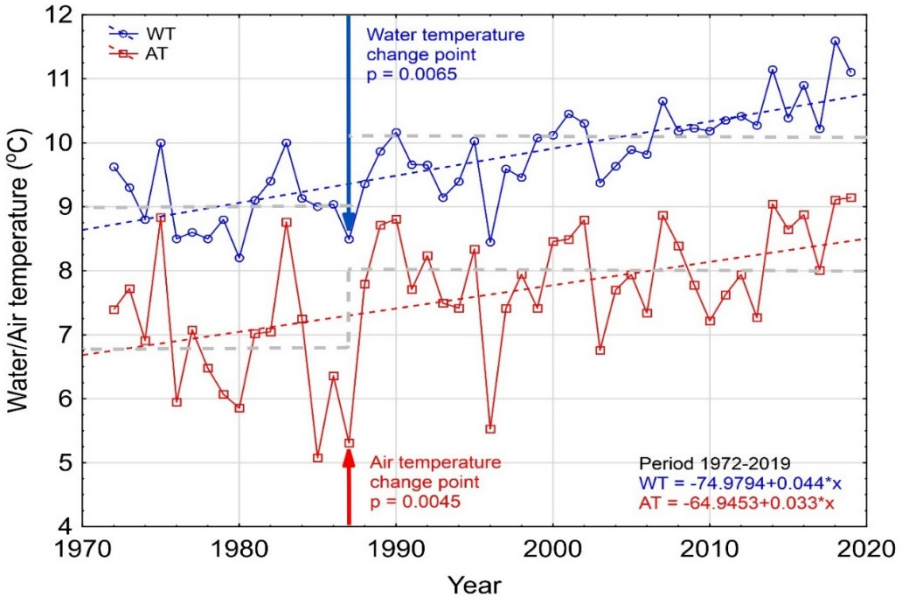


Fig. 2. Mean annual water temperature in Lake Śniardwy (WT), and mean annual air temperature in station Mikołajki (AT).

Table 2. Changes in water temperature and ice cover in Lake Śniardwy, as well as air temperature, wind speed and snow cover in the period 1972–2019.

Months	Mann-Kendall and Senn test statistics				Linear trend line slope	Pettitt's test		
	Z	Mann-Kendall tau	p-value	Sen's slope		S	Probable change point at year	p-value
Water temperature								
XI	3.576	0.360	0.0003	0.057	0.052	361	2000	0.0020
XII	2.664	0.271	0.0077	0.024	0.025	311	2006	0.0117
I	2.593	0.264	0.0095	0.014	0.017	330	1987	0.0061
II	2.886	0.294	0.0039	0.023	0.022	318	1987	0.0093
III	2.481	0.250	0.0131	0.043	0.045	280	2006	0.0310
IV	4.197	0.422	0.0000	0.077	0.076	407	1997	0.0003
V	3.053	0.308	0.0023	0.050	0.053	278	1999	0.0244
VI	2.971	0.300	0.0030	0.043	0.046	293	1994	0.0209
VII	2.526	0.254	0.0116	0.048	0.048	290	1993	0.0229
VIII	3.988	0.404	0.0001	0.052	0.052	394	1993	0.0005
IX	3.646	0.367	0.0003	0.050	0.052	379	1996	0.0010
X	2.911	0.294	0.0036	0.040	0.038	260	1998	0.0551
XI-X	5.976	0.606	0.0000	0.044	0.042	331	1987	0.0065
Ice cover								
ICS	2.714	0.274	0.0066	0.527	0.502	297	2003	0.0184
ICE	–1.610	–0.163	0.1074	–0.302	–0.311	284	1988	0.0275
ICD	–2.783	–0.279	0.0054	–0.869	–0.816	300	1988	0.0167
ICMT	–1.870	–0.190	0.0615	–0.239	–0.226	261	1987	0.0536
Air temperature								
XI	1.850	0.187	0.0642	0.033	0.030	245	2000	0.0823
XII	0.551	0.056	0.5813	0.014	0.004	170	2011	0.4305
I	0.142	0.015	0.8869	0.008	0.018	163	1987	0.4873
II	0.791	0.080	0.4289	0.030	0.034	196	1987	0.2596
III	1.129	0.114	0.2588	0.031	0.037	185	2007	0.3244
IV	3.977	0.401	0.0001	0.067	0.069	389	1988	0.0006
V	1.735	0.175	0.0828	0.029	0.039	178	1999	0.3713
VI	2.884	0.292	0.0039	0.037	0.041	278	1994	0.0329
VII	2.857	0.289	0.0043	0.055	0.053	304	1990	0.0147
VIII	3.425	0.346	0.0006	0.048	0.048	332	1990	0.0057
IX	2.695	0.272	0.0070	0.043	0.039	292	2001	0.0215
X	1.620	0.164	0.1053	0.023	0.022	181	1980	0.3506
XI-X	3.524	0.356	0.0004	0.033	0.036	339	1987	0.0045
Wind speed								
XI	–0.027	–0.004	0.9787	0.000	–0.005	166	1975	0.4624
XII	0.223	0.024	0.8237	0.000	0.000	182	2005	0.3439
I	0.552	0.057	0.5809	0.005	0.002	196	2004	0.2596
II	1.550	0.158	0.1212	0.013	0.010	204	1987	0.2190
III	1.132	0.116	0.2578	0.007	0.005	260	2007	0.0551
IV	1.095	0.112	0.2734	0.009	0.006	248	2008	0.0761
V	0.963	0.099	0.3356	0.006	0.004	255	2003	0.0631
VI	2.338	0.240	0.0194	0.015	0.008	310	2008	0.0121
VII	1.871	0.191	0.0613	0.014	0.008	283	2003	0.0284
VIII	2.237	0.228	0.0253	0.015	0.012	300	2003	0.0167
IX	1.221	0.125	0.2223	0.007	0.007	221	2008	0.1492
X	1.159	0.119	0.2465	0.008	0.005	188	2007	0.3057
XI-X	1.704	0.175	0.0884	0.009	0.005	304	2006	0.0147
Snow cover								
SCD	–1.069	–0.107	0.285	–0.398	–0.263	190	1989	0.329
MSCT	–1.270	–0.128	0.204	–0.153	–0.064	188	2014	0.342
ASCT	–0.681	–6.802	0.496	–0.042	–0.050	152	1990	0.630

March and July the increases were at a level of 0.05. In the case of mean monthly air temperatures, they increased in the period 1972–2019. Mean increases in monthly air temperatures varied from 0.08 to 0.67°C dec^{-1} at a mean value of 0.35°C dec^{-1}. The greatest changes occurred in April (0.67°C dec^{-1}) and July (0.55°C dec^{-1}), and the lowest in January (0.08°C dec^{-1}) and

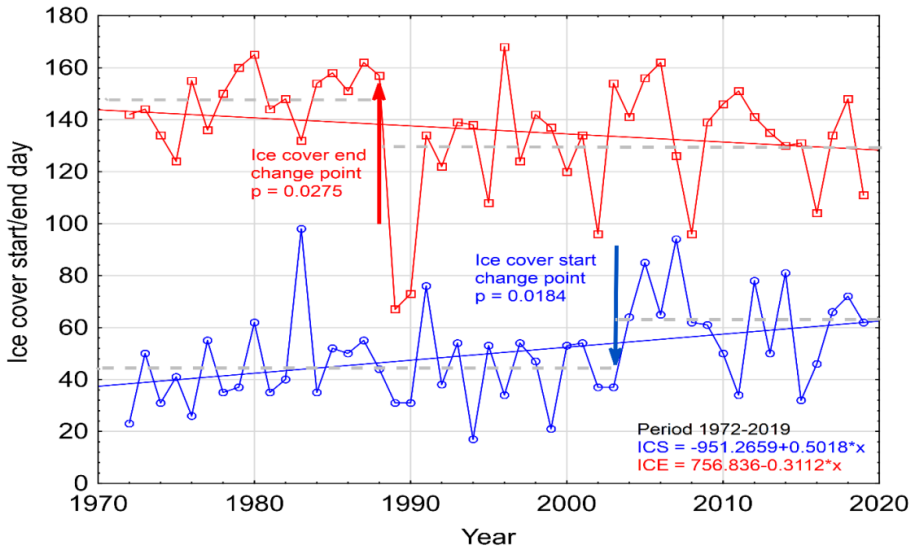


Fig. 3. Course of ice cover start (ICS) and ice cover end (ICE) in Lake Śniardwy.

December (0.14°C dec^{-1}). In the case of mean monthly air temperatures, significant changes at a level of 0.01 occurred in April, June, July, August, and September, and in the remaining months the changes were not statistically significant. In reference to mean monthly wind speed, significant changes occurred only in June and August (0.15 m s^{-1} dec^{-1}). On the other hand, in the period 1972–2019 there was a tendency to decrease the snow cover duration and the maximum and average snow cover thickness, but these changes were not significant.

The statistical analysis by means of the Pettitt test showed that in reference to mean annual water temperatures, a change occurred in 1987 (p = 0.0065). A similar result was obtained in the case of air temperatures (p = 0.0045) (Fig. 2). According to the Pettitt test, a change in wind conditions in the station in Mikołajki occurred in 2006 (p = 0.0147) (Table 2). In the case of ice conditions, points of changes for ice cover beak-up, ice cover duration, and maximum ice cover thickness occurred in 1987 and 1988, and in the case of ice cover start in 2003 (Fig. 3). Considering the aforementioned results, the study period was divided into three shorter (equal) periods, i.e. 1972–1987, 1988–2003, and 2004–2019. Mean values and medians were determined for each of the designated periods for WT, AT, WS, ICS, ICE, ICD, MICT, SCD, MSCT and ASCT. The obtained results were compared by means of a U Mann-Whitney test (Table 3).

The analysis showed that in the case of water temperatures, differences between all the discussed periods were statistically significant at a level of 0.01. In the case of comparison of parameters describing the thermal and ice regime of Lake Śniardwy between periods 1972–1987 and 2004–2019, a significant increase in water temperature was observed (1.4°C), as well as delayed start of ice cover (17 days), earlier ice cover end (13 days), reduction in ice cover duration by 30 days, and a decrease in the maximum ice cover thickness by 9 cm. The comparison of the discussed parameters between periods 1972–1987 and 1988–2003 shows an increase in water temperature by 0.7°C, faster ice cover end (22 days), and a reduction of maximum ice cover thickness by 10 cm. In the case of snow cover, the differences between the mean and medians values in the selected periods were not significant (Table 3).

The statistical analysis showed relatively high variability in the scope of occurrence of points of changes in monthly series of mean water temperatures. In series of mean monthly water temperatures, changes occurred at the turn of years 1987–2006. Points of changes were recorded the earliest in 1987 for January and February, and the latest in reference to March and December in 2006. Differences in mean monthly water temperatures for two periods designated based on a point of change from the Pettitt test are presented in Fig. 6. Water temperatures for the period preceding a point of change (period 1) were lower than those recorded in the second period (period 2); the differences were statistically significant according to the U-Mann-Withney test at a level of 0.05. In the case of mean monthly air temperatures, the analysis by means of the Pettitt test showed that statistically significant points of changes occurred in April, June, July, and September. Changes in thermal conditions in these months occurred over the period 1988–2001. The analysis of changes in mean monthly wind speeds by means of the Pettitt test showed that changes in wind conditions occurred in June, July, and August in 2003 and 2008.

The analysis of correlations between parameters describing the ice regime of Lake Śniardwy and climatic parameters presented in Table 1 showed that dates of ice cover start were correlated the strongest with mean air temperatures from the period from November to December (AT XI–XII). No correlation occurred between ice cover start and wind speed (Fig. 7). In the case of ice cover end (ICE), the strongest correlation was determined with mean air temperatures from the period from February to March (–0.80). Moreover, ICE was negatively correlated with mean wind speeds from the analysed periods, and the correlation coefficients adopted values from a range from –0.35 to –0.42. In reference to ice cover duration (ICD), the strongest correlations were determined with mean temperatures from the period from November to March (–0.72). Correlations of ICD with mean wind speed values from the period from November to March were not statistically significant (–0.23). Somewhat higher values of the correlation coefficient referred to wind speed from the period from December to March, and from February to March. Maximum ice cover thickness in Lake Śniardwy was determined to the greatest extent by mean air temperatures from the period from December to March (correlation coefficient –0.80), and to a considerably lower extent by mean wind speeds from the period from January to February (–0.35).

Table 3. Mean and median values of climate and lake variables for three periods.

Variable	Unit	Period mean (median)			Difference and mean (median)		
		1972–1987 (1)	1988–2003 (2)	2004–2019 (3)	(2) – (1)	(3) – (2)	(3) – (1)
Air temperature (AT)	°C	6.8 (7.0)	7.8 (7.9)	8.2 (8.0)	1.0 (0.9)**	0.3 (0.1)	1.4 (1)**
Wind speed (WS)	$m \cdot s^{-1}$	3.0 (3.0)	2.8 (2.7)	3.3 (3.3)	–0.2 (–0.3)	0.5 (0.6)**	0.3 (0.3)*
Water temperature (WT)	°C	9.0 (9.0)	9.7 (9.7)	10.4 (10.3)	0.7 (0.6)**	0.7 (0.7)**	1.4 (1.3)**
Ice cover start (ICS)	days	45 (41)	43 (41)	63 (63)	–3 (1)	20 (22)**	17 (23)**
Ice cover end (ICE)	days	147 (149)	126 (134)	134 (137)	–22 (–15)**	9 (3)	–13 (–12)**
Ice cover duration (ICD)	days	103 (108)	84 (83)	73 (75)	–19 (–25)	–12 (–9)	–30 (–33)**
Maximum ice cover thickness (MICT)	cm	35 (36)	26 (23)	26 (25)	–10 (–13)**	0 (2)	–9 (–11)*
Snow cover duration (SCD)	cm	76 (85)	65 (58)	63 (57)	11 (27)	13 (29)	1 (2)
Maximum snow cover thickness (MSCT)	cm	30 (29)	25 (22)	27 (21)	5 (7)	3 (8)	–2 (1)
Average snow cover thickness (ASCT)	cm	21 (19)	16 (16)	19 (15)	5 (3)	3 (4)	–2 (1)

**-differences significant at a level of 0.01 *-differences significant at a level of 0.05

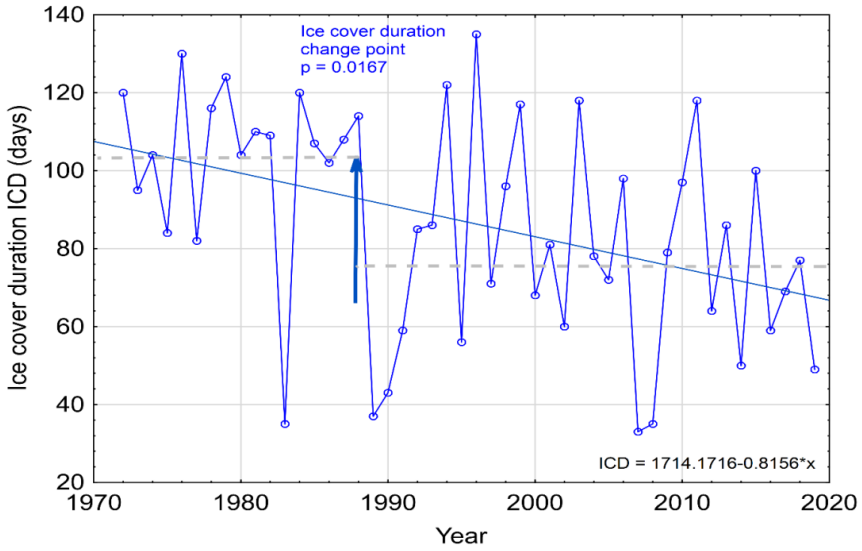


Fig. 4. Ice cover duration in Lake Śniardwy.

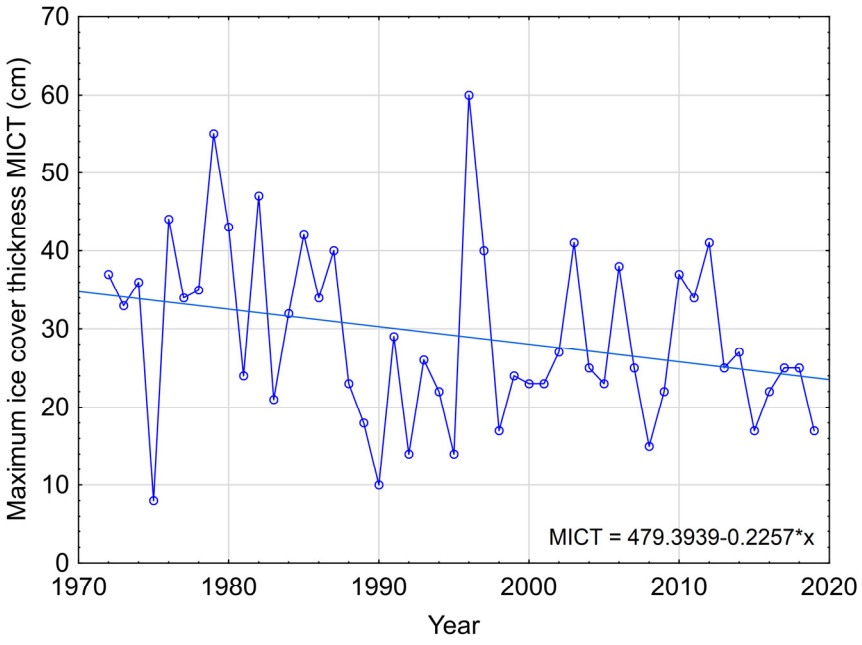


Fig. 5. Maximum ice cover thickness in Lake Śniardwy.

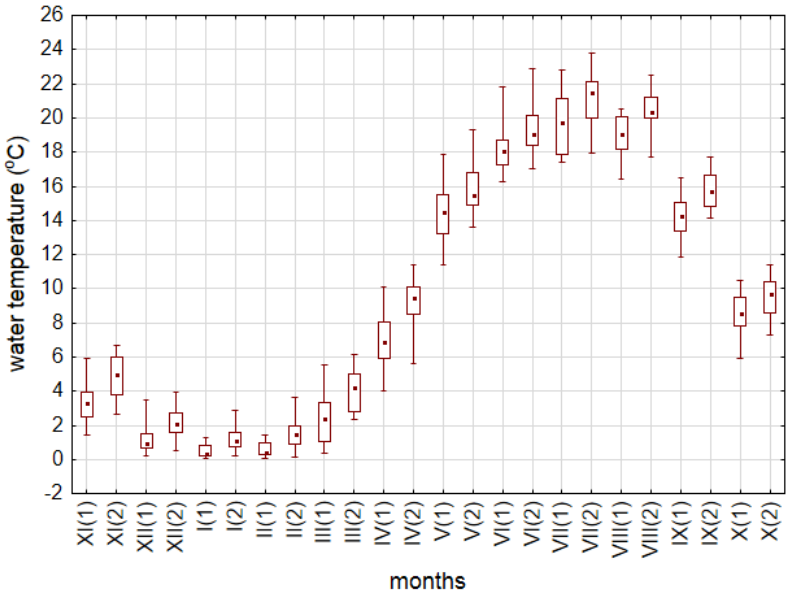


Fig. 6. Differences in mean monthly air temperatures for two data series obtained based on the division by means of the Pettitt test.

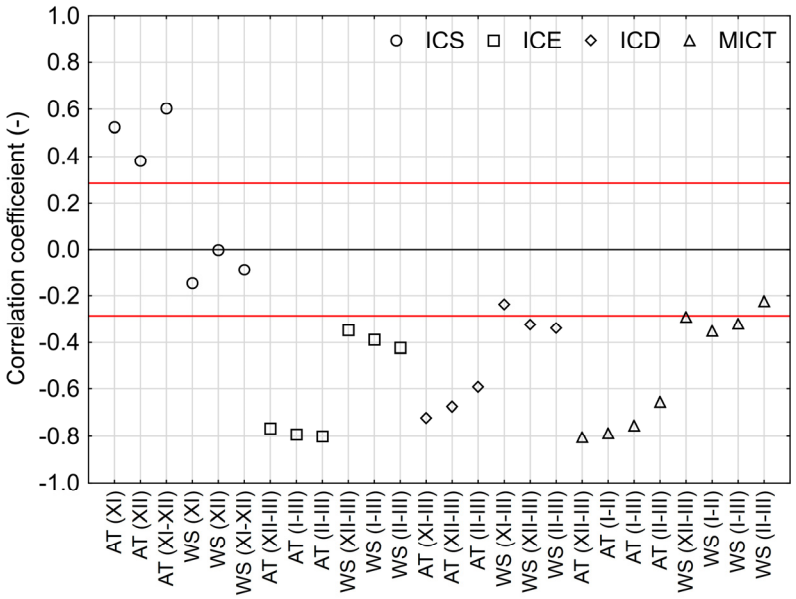


Fig. 7. Correlation coefficients between lake variables and drivers (Red lines – critical value for significant correlation $p < 0.05$).

Correlation analysis showed that ICE, ICD and MICT value were significantly correlated with SCD (correlation coefficients ranged from 0.65 to 0.68), MSCT (correlation coefficients ranged from 0.38 to 0.51) and ASCT (correlation coefficients ranged from 0.37 to 0.56). The ICS value was not correlated with the parameters describing the snow cover (correlation coefficients ranged from –0.25 to –0.04).

DISCUSSION

The study results correspond with the extensive research trend concerning changes in water temperature and occurrence of ice cover in lakes. The rate of changes in both parameters is variable, and depends on a number of factors, including climatic zone, local conditions, morphometric parameters of lakes, etc. According to Piccolroaz et al. (2019) analysing water temperature in several hundreds of lakes in different climatic regions, lakes in temperate regions are the most sensitive to climate changes. In the case of the territory of Poland, studies to date correspond with the above statement. According to Czernecki and Ptak (2018) analysing the tendency of changes in water temperature in lakes in the period 1971–2015, the value was positive and averaged 0.37°C dec^{-1} for ten analysed cases. Like in the presented paper, the rate of water warming was higher than in the case of air. In the case of two lakes Dadaj and Rajgrodzkie (Lake Śniardwy is located between them), a considerable increase in water temperature was determined over the last three decades, equal to 0.63 and 0.44°C dec^{-1}, respectively (Ptak et al., 2020). Further studies in Poland referred to changes in maximum water temperatures in lakes (Ptak et al., 2019c), where an increase at a level of 0.39°C dec^{-1} was recorded in nine cases. Water temperature increase was evidenced in many other lakes in different regions of the world. In the case of 24 lakes in the area of the Mediterranean Sea (Sardinia),

Virdis et al. (2020) determined a positive annual trend of +0.010°C r^{-1}, and variable seasonal trends: positive winter trend of +0.013°C r^{-1}, and cooling of water temperature at a level of –0.038°C r^{-1} in the summer period. A study by Li et al., (2019) conducted in four lakes in the Yangtze River catchment showed that over the 39-year study period, the surface water temperature increased at a rate of 0.26–0.28°C dec^{-1}. Mean annual temperatures in the epilimnion in two lakes in Morocco (Sidi Ali and Sidi Boughaba) in the years 1979–2014 increased by 0.198 and 0.013°C dec^{-1}, respectively (Haddout et al., 2018). It is worth emphasising that the rate of increase in water temperature in Lake Śniardwy was higher than that for air temperatures for the nearby meteorological station in the analogical period. It is a situation characteristic of lakes with occurrence of ice cover (Kintisch, 2015). Shorter ice cover duration on Lake Śniardwy contributed to a longer possibility of water warming. It is particularly evident in the case of April (for which the most rapid temperature increase was recorded), where out of 11 terms of ice cover end in April (throughout the analysed period), only three occurred in the 21st century.

The reduction of the ice season in Lake Śniardwy does not deviate from many studies of the type conducted to date. The study by Preston et al. (2016) conducted for seven lakes in Colorado (North America) showed that ice-off dates shifted to 7 days earlier over a period of 33 years. A strong trend of earlier spring disintegration of ice cover is determined in the case of Arctic lakes (Šmejkalová et al., 2016). The reduction of ice cover duration was recorded for Lake Jagodne (Poland) at an average rate of 5 days dec^{-1} (1975–2015). In this case, ice cover thickness also gradually decreased by an average of 2 cm dec^{-1} (Ptak et al., 2019b). In the case of two lakes in Central Europe (Balaton and NeuSiedler), among others a tendency for shorter ice cover duration was observed (Soja et al., 2014). In the case of two freshwater lakes in Mongolia, 20 days of forward and backward shifts in freeze-up and break-up dates were determined, respectively (Punsalmaa et al., 2004). Negative tendencies of ice phenomena were observed for Lake Abashiri (Japan), where values for particular characteristics were as follows: –1.7 d dec^{-1} for break-up date, 2.4 d dec^{-1} for ice cover duration, and –1.4 cm dec^{-1} for ice cover thickness (Ohata et al., 2017).

The end of the 1980's was a characteristic moment in the course of thermal conditions in Lake Śniardwy. Air temperature was then subject to a considerable change, as evident in the case of station Mikołajki and documented in other studies regarding this parameter (Kolendowicz et al., 2019). The situation also caused a substantial change in the course of water temperature in the case of other objects of the hydrographic network (Bonacci et al., 2008; North et al., 2013). The increase in water temperature slightly slowed down in the years 2008–2012, and from 2013 until the present moment the increase in even more dynamic. The discontinuation of warming lasting until 2012 was evidenced by among others Winslow et al. (2018), also pointing to the fact that lakes are indicators of broader climatic processes. The consequence of changes in thermal regime was a considerable increase in the rate of reduction of the ice season, as evidenced above (Table 3). In addition to the correlations with air temperature, evident for this process, wind was also of importance. The role of wind in shaping ice conditions is emphasised by Magee et al., (2016), analysing long (more than a century-long) trends of the ice cover of Lake Mendota in North America. Changes in the course of ice phenomena in a similar period as those in the analysed lake were also observed in lakes in East Europe (north-western Russia, Estonia, Belarus). Based on this set, Efremova et al. (2013) evidenced that tendencies in the scope of term of occurrence of ice phenomena over the last 20 years are more evident than over the entire 60-year study period.

Lack of thermal stratification in Lake Śniardwy is related to its large surface area, determining the strong effect of wind. The theoretical depth of water mixing is 16.3 m (Szostak, 1967), which as shown by vertical measurements of water thermal and oxygen regime (Olszewski and Paschalski, 1959), determines lack of significant thermal stratification even in the deepest place. This situation was confirmed in the study by Napiórkowska-Krzebietke et al. (2020). According to the authors, the recorded changes in water temperature and oxygen content in Lake Śniardwy were typical of strongly mixed lakes. The inflow of waters from the hypolimnion can obscure (delay) the direct effect of the atmosphere on the thermal regime, and the closely related ice conditions (Ptak et al., 2019a). Smaller depth of non-stratified lakes (or like in the case of Śniardwy – their large surface area) causes smaller possibilities of accumulation of heat, released to the atmosphere faster (in the conditions of lack of inflow of warmer waters from the hypolimnion in the autumn-winter season). This contributed to among others accelerated development of ice cover.

Further perspectives of changes in thermal regime of lakes point to their continuous warming. Based on climatic forecasts from the 21st century, Maberly et al. (2020) determined that by 2080–2099, many lakes will be transformed into a thermal region with a lower latitude. Detailed data concerning the territory of Poland are presented by Czernecki and Ptak (2018), predicting changes in water temperature by the end of the 21st century. Depending on the adopted scenario, changes at a level from +1.4°C (RCP 2.6) to +4.2°C (RCP 8.5) should be expected. In the monthly cycle, the lowest changes will occur in February (2081–2100: RCP 2.6 = +0.5°C, RCP 8.5 = +1.8°C), and highest from May to August (RCP 8.5 = +6.0°C in June). As a consequence of the predicted climatic changes, the ice season will be further reduced. It was evidenced by Hewitt et al. (2018) for nine lakes in North America. Based on the conducted research the authors predict that by 2070, ice will break up 13 days earlier on the average, and the term of freezing of lakes will be delayed by an average of 11 days. As further emphasised by the same authors, the reduction of seasonality of ice cover may increase the risk of algal blooms, reduce habitats for cold water fisheries, and threaten the survival of northern communities dependent on ice passages.

Due to the elementary importance of water temperature and occurrence of ice cover for the functioning of lakes, the observed situation should be expected to contribute to a substantial transformations of the discussed lake. The course of water temperature shows a strong correlation with its oxygenation (Ptak and Nowak, 2016), and dissolved oxygen concentration plays a key role in regulating various biogeochemical processes and communities of biological water ecosystems (Zhu and Heddam, 2020). Water temperature is the most important indicator of the ecological environment of the lake, used for understanding changes between various factors of water quality (Yang et al., 2018). The state of the Great Masurian Lakes raises concerns due to exceptional environmental values that need no justification in the case of this large complex of lakes (Lossow, 1996). Based on data from the years 1976–2011, Ejsmont-Karabin (2013) determined that the trophic status of Lake Śniardwy deteriorated from low meso-eutrophy to low eutrophy. Research on water properties in Lake Śniardwy (summer 2012) by Siuda et al. (2020) shows that depending on the surface area of the lake and sampling site, it is generally eutrophic (its south-eastern part it reached hyper-eutrophic

conditions). The symptoms of hyper-eutrophic conditions in this part of Lake Śniardwy were related to the prevalence of unicellular cyanobacteria in the phytoplankton community. Przytulska et al. (2017) draws attention to the fact that climate changes will increase the risk of harmful cyanobacterial blooms in northern lakes and ponds, with potentially negative effects for higher trophic levels. Considering the forecasted changes in water temperature in Polish lakes (Czernecki and Ptak, 2018), the situation may progress very dynamically in the nearest future. Another important issue is the change of the current components of the water balance. In the analysed context, it concerns the expenditure part of vertical water circulation. One of the most important variables for evaporation volume is water temperature (Aydin and Karakuş, 2016). As emphasised by Nowak and Ptak (2019), or Nowak and Ławniczak-Malińska (2019), evaporation from free water surface is an important element of its exchange, particularly in the case of large water bodies, including Śniardwy. According to global simulations, annual evaporation from the lake will have increased by 16% by the end of the 21st century, and one of the primary factors will be the reduction of ice cover duration (Wang et al., 2018). In the context of the recorded rapid increase in water temperature and considerable reduction of ice cover duration, the value can be subject to continuous transformations, considerably changing the current components of the water balance of the analysed lake. This poses new challenges to proper water management in Lake Śniardwy, but also in the entire system of the Great Masurian Lakes in the scope of regulation and maintenance of appropriate water level. It is important, because water resources accumulated in the hydrological system of the Great Masurian Lakes are important not only for the region, but also for other parts of the country.

CONCLUSIONS

One of the key factors affecting the environment are the currently observed dynamic climate changes. In the case of inland waters, they resulted in a considerable transformation of their current properties. The response of the largest lake in Poland to these processes was approximate to those in many similar studies. The conducted analyses showed a considerable increase in water temperature over the last five decades, accelerating from the end of the 1980's. It was higher than the rate of increase in air temperatures, which constitutes a resultant of a broader interaction of processes occurring in the lake – in this case a reduction of the ice season, also evident in the analysed case. The obtained results describing the response of some of the key parameters (temperature and ice conditions) of the largest lake in Poland to climate changes provides the basis for further, more detailed research in the scope of changes in closely related parameters. They include e.g. issues related to water quality or water resources. In the context of the forecasted further (unfavourable) transformations of water ecosystems, research on the aforementioned issues should be considered important, in the context of an attempt to determine assumptions for mitigation of the effects of climate warming.

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