Bulletin of Geography. Physical Geography Series, No. 11 (2016): 27–33
http://dx.doi.org/10.1515/bgeo-2016-0012

ISSN 2080-7686

Effect of climatic changes on the development of the thermal-ice regime based on the example of Lake Charzykowskie (Poland)

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Abstract. The paper discusses the course of air temperature in the years 1961-2014 in Chojnice (Central European Lowland), and its effect on water temperature and occurrence of ice cover on Lake Charzykowskie. An increase in mean annual air temperature was determined by 0.31°C per 10 years, and its even faster increase in the winter season (December-March), by 0.37°C per 10 years on average. An increase in mean annual water temperature in the lake by 0.24°C per 10 years also occurred. An increase in air and water temperature in winter months caused a reduction of the period of occurrence of ice cover. In the years 1961-2014, the persistence of ice cover was subject to a decrease by 3.7 days per 10 years on average, and the mean thickness of the ice cover decreased from 30 to 19 cm.

Key words:
climate change,
Charzykowskie lake,
water temperature,
ice phenomena,
Poland

Introduction

In the period of climatic changes, considerable changes in the physical parameters of lake waters are increasingly frequently observed. They particularly involve changes in the duration of periods of occurrence of ice cover (Magnuson 2000; Livingstone et al. 2010; Weyhenmeyer et al. 2011), as well as water temperature. Such changes are particularly possible to document in an area with moderate transitional climate in which mean temperature during winter seasons oscillates from several Celsius degrees below zero to several degrees above zero. Climate warming, including air temperature increase above 0°C in winter, leads to a reduction in the persistence of ice cover on lakes, or even its complete lack. In the moderate climate zone, the presence of ice cover on lakes is an important element determining the functioning of the ecosystem characteristic of this climate zone. Ice cover causes slowing down of physical, chemical, and biological processes during winter seasons. In the case of lack of ice cover, a lake receives more energy which in turn affects the physical-chemical parameters of lake waters. Lack of ice cover contributes to an increase in the range of the zone of light penetration in the lake, supply of additional amounts of oxygen from the atmosphere, and an increase in the amount of nutritious (biogene) compounds. Moreover, higher water temperature favours the productivity of the lake ecosystem. These are seemingly positive changes, although any imbalance leads to many disturbances in the functioning of the lake ecosystem. Water temperature determines the course of physical and chemical processes. It also has considerable impact on the life cycle of aquatic organisms. Laboratory research showed substantial impact of changes in water temperature on the possibilities of their reproduction and development (Wałkuska and Wilczek 2010).

Considering the above, this paper draws attention to the range of changes in water temperature and persistence of ice cover in the European Lowland (in the moderate transitional climate zone) based on the example of Lake Charzykowskie (Poland).

Study area and methods

Lake Charzykowskie is located in the Central European Lowland (northern part of Poland), in a young glacial area (53°46'N 17°30'E). It is a post-glacial channel lake. It developed at the end of the period of the last glaciation on the northern hemisphere, i.e. approximately 13 thousand years ago. The surface area of the lake amounts to 13.6 km^2, maximum depth 30.5 m, mean depth 9.8 m, and volume 134.5x106m^3 (Fig.1). The water level in the lake is located at 120.2 m a.s.l. on average. The area of the lake's catchment amounts to 920 km^2. The land use structure in the catchment is dominated by forests (58%) and agricultural areas (35%).

High contribution of forests in the catchment and low impact of anthropopressure contribute to the preservation of good quality of water and good trophic status. In spring and summer 2015, water transparency averaged 3.3 m (max. up to 5.5 m), and electrolytic conductivity 288 µS·cm^{-1}. The content of chlorophyll was also low (9.5 mg·dm^{-3} on average), as well as total phosphorus (0.093 mg·dm^{-3}) and total nitrogen (0.85 mg·dm^{-3}). The trophic status of the lake can be described as meso-eutrophic (according to research by the Regional Inspectorate of Environmental Protection in Gdańsk).

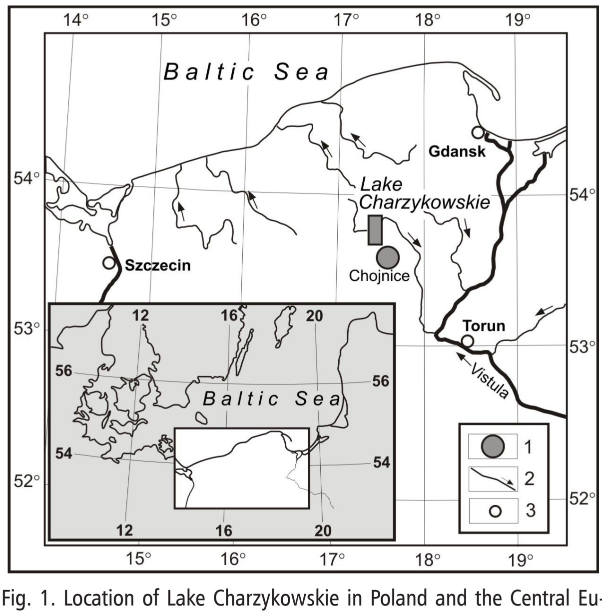

Fig. 1. Location of Lake Charzykowskie in Poland and the Central European Lowland. Explanations: 1 – meteorological station; 2 – main rivers; 3 – main cities

This paper is based on results of observations of air temperatures from the meteorological station in Chojnice and water temperatures from the hydrological station on Lake Charzykowskie. Both of the stations belong to the Institute of Meteorology and Water Management – National Research Institute, and are located near each other (5 km). The analysis employed values of mean monthly air temperatures from winter periods, mean annual air temperatures, as well as results of observations of ice phenomena and water temperature in Lake Charzykowskie. The meteorological and hydrological observations were performed every day in the years 1961-2014 at 6 GMT: first at an altitude of 200 cm above ground level, and second at a depth of 40 cm.

Trends in time series were estimated using two methods. The multiannual variability of air temperature, water temperature, and ice cover in the lake were evaluated based on the linear regression parametric test and the Mann-Kendall non-parametric test. This method was adopted due to the limitations in applying linear regression requiring assumptions of distribution normality and values independent in a time series. Mann-Kendall's sum S divided by the root of variance:

$$S = \sum_{i=t}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(X_j - X_i)$$

where: sgn(x) = 1 for x>0, 0 for x=0, -1 for x<0, where x denotes individual data series, and n denotes the total number of years in a time series.

Obtaining significant results from both of the tests was assumed to be a more convincing proof of undergoing changes in air temperature, water temperature, and ice cover in a time series. If contrary results were obtained (one showing an existing trend and the other not), such a time series was considered as not showing a trend (the rule of searching for strong changes in data). The application of more than one test for the estimation of a trend is recommended (Robson et al. 2000). The extent of an increase or decrease in temperature of lake waters was estimated using coefficients of simple regression directions.

The analysis of simple regressions does not allow for fluctuations or short-term oscillations in a time series. As a result, a method of the rescaled adjusted partial sums (RAPS) of series in relation to the multiannual value was applied.

$$\text{RAPS} \quad Y_k = \sum_{t=1}^{k} \frac{x_t - \bar{x}}{\sigma_x} \qquad k \in (1,2,\ldots n)$$

x_t - element of the studied series,
$\bar{x}$ - mean value of the studied series,
$\sigma_{\bar{x}}$ - mean deviation of the series values,
n - number of observations.

The RAPS method permits detecting trends and fluctuations in certain parts of a time series. Consequently, two fundamental sub-periods with different values of water temperature were distinguished in the analysed time series. In the years 1961-1986, temperature values were noticeably lower than in the years 1987-2014. The test of differences between means was applied in order to compare temperature differences in the distinguished sub-periods. The test verified the null hypothesis of the equality of the two means of water temperature in the two sub-periods: 1961-1986 and 1987-2014. The T-Student test for unrelated variables was used. Homogeneity of variances was checked by the F test.

The adopted significance level for all the analyses was $p < 0.05$. Pearson's correlation at the significance level of 0.05 was assumed as an indicator of the relationship between air temperature and temperature of river waters and ice cover.

Results

In the years 1961-2014, mean annual air temperature in Chojnice (53°42'N 17°31'E), i.e. in the vicinity of Lake Charzykowskie, amounted to 7.3°C. Year 1970 was the coolest (5.2°C), and 2007 the warmest (9.3°C). An increase in mean annual air temperature was distinguished by uneven rate over the analysed period, whereas two sub-periods can be designated: 1961-1986 and 1987-2014.

The first sub-period, lasting 26 years, was cooler by 1.4°C than the second sub-period. During the period, mean annual temperature was lower than mean multiannual air temperature in as many as 20 cases (1961-2014; for comparison, during the second sub-period, only four such cases occurred). Therefore, in the years 1987-1988, an evident air temperature increase occurred, continued until today (Fig. 2).

Throughout the analysed period (1961-2014), mean annual air temperature increased by 1.7°C, i.e. by 0.31°C per 10 years on average. It is worth emphasising that an increase in mean air temperature

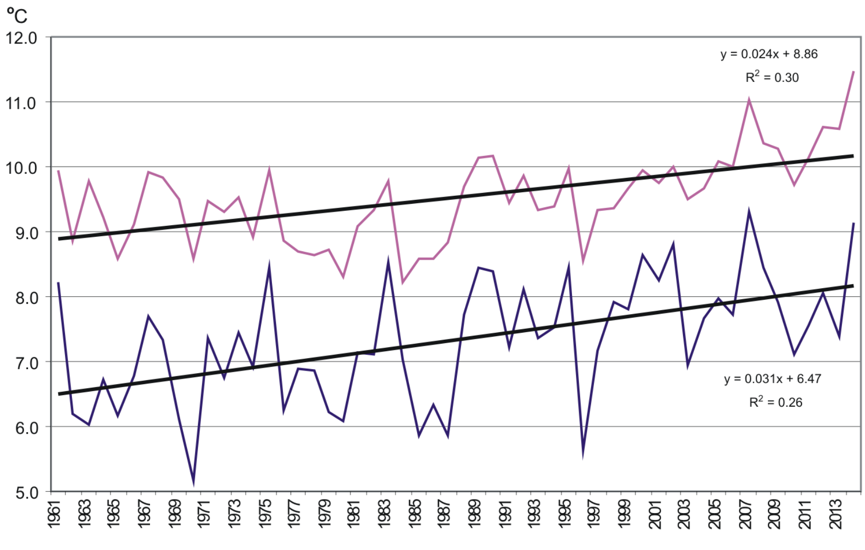

Fig. 2. Course of the mean annual air temperature in Chojnice (lower line) and mean annual water temperature in Lake Charzykowskie (upper line) in the years 1961-2014

occurred in all of the months, although it was largely varied: from 0.03°C per 10 years in June to 0.52°C per 10 years in July (Table 1). Apart from July, the rate of temperature increase was also high in winter months: January and February (0.44°C per 10 years) and March (0.39°C per 10 years). Fast rate of air temperature increase in all winter months (from December to March) caused fast increase in the mean temperature in winter from −1.9°C to +0.1°C, i.e. by 0.37°C per 10 years on average. Therefore, an increase in air temperature in winter proceeds faster in comparison to the mean value calculated for the entire year (Fig. 3).

As a result of an increase in air temperature in the years 1961-2014, water temperature in the lake also increased by 0.24°C per 10 years on average. Therefore, the increase in water temperature was considerably slower than that in air temperature (compare Table 1). Similarly as in the case of air temperature, the fastest water temperature increase commenced in 1987 (compare Fig. 2). Until that year, i.e. in the years 1961-1986, mean annual water temperature was lower than 7°C as many as 15 times. In the years 1987-2014, mean annual water temperature below 7°C occurred only twice, i.e. 1996 and 2013. Moreover, at the end of the analysed

Table 1. Increase in mean (1961-2014) air temperature (Ta) in Chojnice and mean surface water temperature (Tw) in Lake Charzykowskie (in °C/10 years). Bold font denotes values of significance level of 0.05

Parameter	NOV	DEC	JAN	FEB	MAY	APR	MAY	JUN	JUL	AUG	SEP	OCT	Year
Ta	0.14	0.29	0.44	0.44	0.39	0.49	0.34	0.03	0.52	0.40	0.20	0.08	0.31
Tw	-0.08	0.15	0.20	0.15	0.30	0.47	0.65	0.15	0.35	0.35	0.16	0.05	0.24

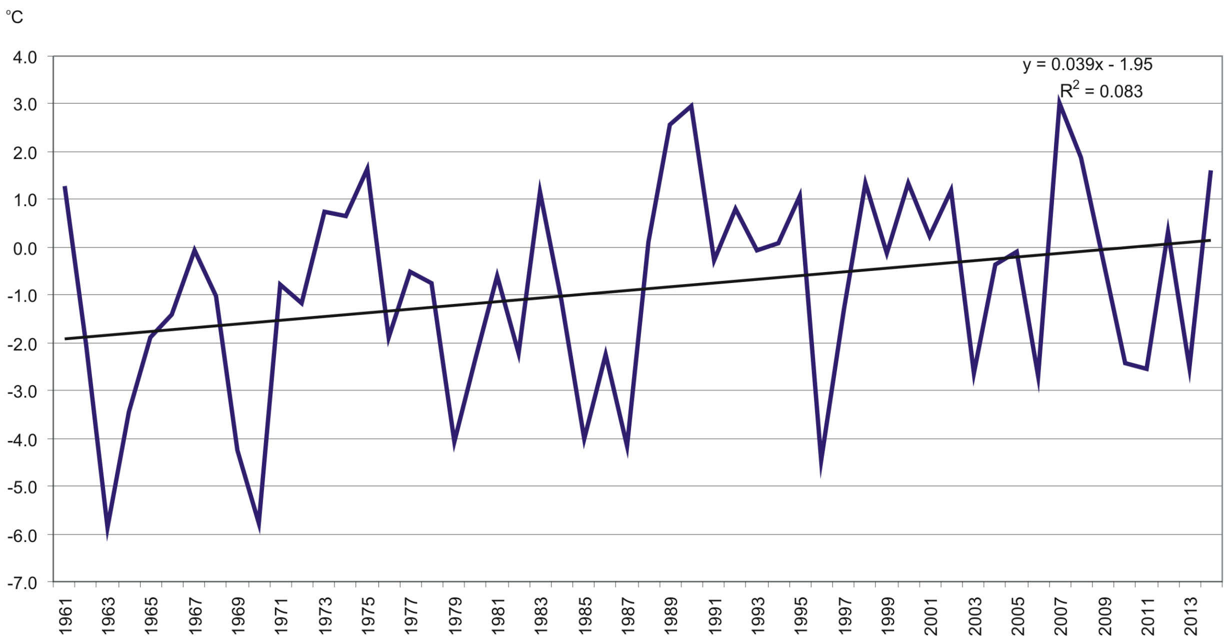

Fig. 3. Course of the mean air temperature in winter (DEC-MAR) in Chojnice in the years 1961-2014

period (in the 21st century), very high mean annual water temperature occurred increasingly frequently, with values exceeding 10 and 11°C (compare Fig. 2).

The analysis of mean monthly multiannual water temperatures showed that its fastest increase occurred in July and August (0.35°C per 10 years), as well as in winter months: March (0.30°C per 10 years) and January (0.20°C per 10 years).

An increase in air and water temperature in the lake in winter months caused a reduction in the persistence of ice cover. In the years 1961-2014, an evident increase in the rate of decline of ice cover occurred. At the beginning of the period (1961-1970), ice cover usually declined in the third decade of March (23 March on average), and at the end of the study period already in the first decade of March, on 8 March on average. As a result of earlier decline of ice cover, the duration of the period with ice cover considerably decreased. Whereas in the decade of the 1960's ice cover persisted on the lake for an average of 71 days during one winter season, in the following decades the period with ice cover was largely reduced to 48 days (on average) in the last decade of the 20th century. In general in the years 1961-2014, the persistence of ice cover was subject to a decrease by an average of 3.7 days per 10 years, although the value is not statistically significant. The thickness of ice cover also decreased over the analysed period from 30 to 19 cm.

Discussion

The existence of strong correlations between air and water temperature fluctuations in lakes in this part of Europe has been already evidenced before (Dąbrowski et al. 2004). Since 1987, however, considerably faster increase in air temperature growth occurred, and as a consequence also that of water temperature. In the analysed area, temperature increase was recorded both at the scale of the entire year and during particular seasons, and particularly during winter. The phenomenon is confirmed by the course of cumulative curves for air and water temperatures during winter seasons (Fig. 4). The curves were prepared based on mean values of air and water temperatures from periods from December to March in each year from the years 1961-2014. Their course is very similar to that of the same type of curves prepared for values of mean annual air and water temperatures in rivers (Marszelewski and Pius 2015).

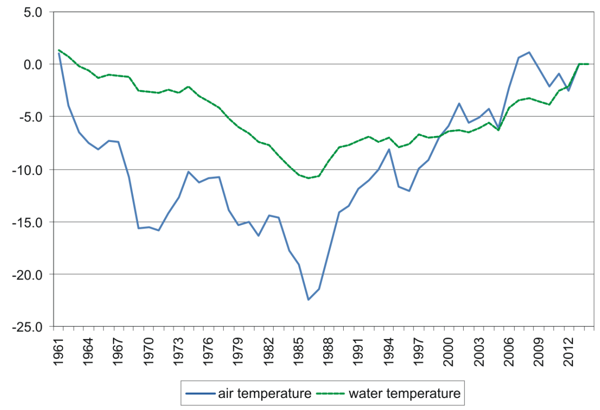

Fig.4. Cumulative curves of air temperature (°C) in Chojnice, and water temperature (°C) in Lake Charzykowskie in the years 1961-2014

Data presented in this paper suggest that in the period of climate changes, various types of correlations occur between air temperature and physical parameters of lake waters. At moderate latitudes, the correlation between mean temperatures of the winter season (from December to March) and the persistence of ice cover is the most evident. In the case of Lake Charzykowskie, the correlation is significant (r = -0.87, Fig. 5). This confirms the earlier finding that ice cover should be considered as an indicator of climate changes (Marszelewski and Skowron 2006; Wrzesiński et al. 2015). During winter seasons with mean temperature from 2°C to 3°C, the occurrence of ice cover is limited to only several days, or ice cover does not occur at all. During very cold winter seasons with mean air temperature from −4 to −5°C, ice cover persists over a period of approximately 100 days (compare Fig. 5). Considering the fact that during the occurrence of ice cover the lake dynamics are completely different than during winters with no ice cover, high variability of its persistence considerably changes the conditions of functioning of the entire lake ecosystem both during winter and subsequent seasons, i.e. spring and summer. The finding refers among others to oxygen conditions in lakes and development of phytoplankton (Adrian et al. 1999).

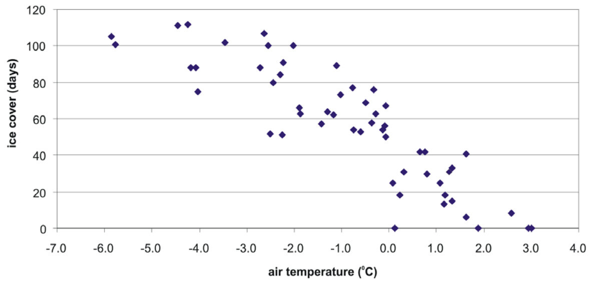

Fig. 5. Correlation between mean air temperature in winter (DEC-MAR) and persistence of ice cover in Lake Charzykowskie in the years 1961-2014

Another, so far rarely discussed correlation occurring in the period of climate changes is that between water temperature in the lake and the persistence of ice cover. In the case of Lake Charzykowskie, such a correlation is statistically significant, and amounts to r = 0.65. Increasingly higher water temperature in the lake during subsequent winters contributed to an evident reduction of duration of periods with ice cover. In the case of mean temperature in winter (December-March) higher than 3°C, ice cover may not develop during winter at all. During some winters, however, even with higher mean temperature (e.g. 4°C), ice cover may occur (Fig. 6). Such situations are related to winter seasons with high variability of weather conditions, i.e. short periods with very cold weather, and short periods with high air temperature, on some days reaching even 10°C.

High variability of weather conditions in winter seasons with the occurrence of alternating periods with temperature well below 0°C and well above 0°C is becoming increasingly characteristic in the period of climate changes.

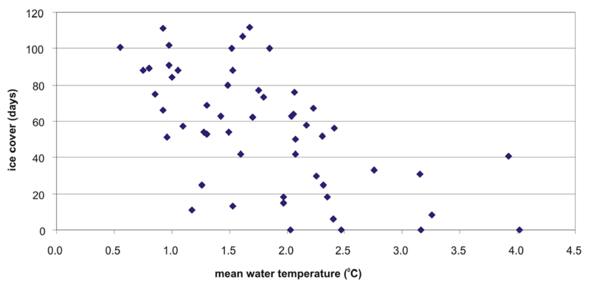

Fig. 6. Correlation between mean water temperature in the winter season (December-March) and persistence of ice cover in Lake Charzykowskie

Conclusion

Research on the regime of ice phenomena in lakes, particularly including ice cover, are important from the point of view of protection of lake ecosystems. A reduction in the occurrence of ice cover favours an increase in the lake's fertility, and therefore contributes to an increase in its trophic status. It may be soon necessary to prepare a forecast of changes in lake ecosystems in the future. It is a complicated task, because each lake is distinguished by different parameters and conditions. Due to this, the need exists to collect data showing effects of climate changes in the highest possible number of lakes located in various climate zones.

Acknowledgement

The work was supported by the the National Centre for Research and Development in Warsaw (Poland) through the ERALECC project (ERA.Net RUS Plus; ID 226).

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Received 25 October 2016
Accepted 13 November 2016