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ORIGINAL ARTICLE

The impact of global warming on lake surface water temperature in Poland - the application of empirical-statistical downscaling, 1971-2100

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ABSTRACT

The paper presents historical (1971-2015) and scenario-based (2006-2100) changes in surface water temperatures in 10 lakes of Poland. The analysis of historical measurement (1971-2015) showed that mean annual lake surface water temperature (LSWT) was characterised by an increasing tendency by 0.37°C dec^{-1} on average, and was higher by 0.01°C dec^{-1} than air temperature in the analogical period. The highest increase in LSWT was recorded in spring months (April, May) and in summer (July). The future changes in LSWT was based on simulations of 33 AOGCMs available in the scope of CMIP5 project for RCPs: 2.6, 4.5, 6.0, and 8.5. The developed empirical-statistical downscaling models (ESD) use the air temperature field as predictors, with consideration of autocorrelation for two preceding months. ESD models are characterised by high quality of reconstruction of water temperatures in the historical period, with correlation from 0.82 (December, February) to 0.93 (July). The future CMIP5 scenarios for the period 2006-2100 assume an increase in air temperature at the end of the 21st century from +1.8°C (RCP 2.6) to +5.1°C (RCP 8.5) in reference to the period 1971-2005. According to the downscaling models, this corresponds to an increase in water temperature in the analysed lakes ranging from +1.4°C (RCP 2.6) to +4.2°C (RCP 8.5) in the years 2081-2100, respectively, with evident variability between the adopted emission paths beginning from the period 2041-2060. At a monthly scale, water temperature will increase the slowest in February (2081-2100: RCP 2.6=+0.5°C, RCP 8.5=+1.8°C). The highest increase in temperature will occur from May to August (RCP 8.5=+6°C in June). Substantial effects of transformations of the thermal regime of lakes are already observed today, *e.g.* in the reduction of the ice season length. According to developed scenarios, a further considerable increase in water temperature will be the primary factor determining the transformation of lake ecosystems and also will reduce water resources per capita. Therefore, it should constitute for the possibly fast development of multidisciplinary concepts of mitigation policy to potential impact of climate change.

Key words: Climate change; warming; water temperature; lakes; downscaling; model; Poland.

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INTRODUCTION

Global warming is one of the most serious problems now being faced by humanity (IPCC, 2014). The mean air temperature has increased faster over the last several decades than at any other time since the use of instrumental measurements (Jones *et al.,* 1999; Jones and Moberg, 2003; Damborská *et al.,* 2016). An even more unfavourable situation has occurred in lake environment where the heat of surface waters is in many cases greater than that observed for air temperature (Austin and Colman, 2007; O'Reilly *et al*., 2015).

The reason for such an alarming situation is not so straightforward since change in lake surface water temperature (LSWT) is affected by many factors resulting in some complex thermodynamic fluxes (Wilhelm *et al*., 2006; Tanentzap *et al*., 2008; Piccolroaz and Toffolon, 2013; Piccolroaz *et al.,* 2015; Woolway *et al*., 2015; Schmid and Köster, 2016). Although there are numerous processes impacting LSWT, a rise in near-surface air temperature is considered a key factor behind the imbalance in heat fluxes (Livingstone and Padisak, 2007; Piccolroaz and Toffolon, 2013). The influence of a recently observed increase in near-surface air temperature is clearly seen in terms of different components of the natural environment, and not surprisingly, it is also clearly visible in both global and local water cycles (IPCC, 2014; Bazrafshan, 2017; Prăvălie *et al.,* 2017). Enhanced lake-air temperature gradients (Desai *et al.,* 2009) due to increasing instability of planetary (atmospheric) boundary layer (Pucik *et al.,* 2017) are likely to result in enhanced heat loss, gas fluxes, and evaporation from lakes (Woolway *et al*., 2017a), that may also have further consequences *e.g.* in a decrease of lake water level.

The relations between changes in the air temperature and the dynamics of LSWT have so far been the subject of several studies on Polish lakes (Dąbrowski *et al.*, 2004; Wrzesiński *et al.*, 2015a; 2015b; Ptak *et al.*, 2017; Woolway *et al.,* 2017a). The aforementioned studies have confirmed strong dependencies between both components which obviously would be modified by the local parameters of particular lakes. Moreover, these studies revealed an increasing tendency towards change in the LSWT of Polish lakes over the last several decades. The results are generally coherent with similar studies carried out in the northern hemisphere (Hampton *et al.,* 2008; Schneider and Hook, 2010; Magee *et al.* 2016). By the same token, a recently observed rapid increase in LSWT has raised another fundamental question regarding future changes according to different studies that show a further increase in LSWT in a not too distant future (Trumpickas *et al.,* 2009; Kirillin, 2010; Toffolon *et al.*, 2014, Piccolroaz *et al.*, 2018).

In Poland, no such research has ever been undertaken despite the relatively long historical time series of LSWT. In addition to its strictly cognitive character, such knowledge can have an applicative value. Any increase in water temperature facilities the degradation of its quality (through reduced possibilities for oxygen dissolution), or contributes to a reduction in water resources. The latter issue is particularly important in the case of Poland, where the problem is becoming increasingly acute, and water resources per resident are now comparable to those in desert countries (Kowalczak *et al.*, 1997).

In light of the above, the paper aims to contribute to the existing knowledge on the effect of climate change on lake ecosystems in this part of Europe. Moreover, the study results are intended to provide a starting point for more detailed analyses concerning, among others, the development of a concept towards counteracting further degradation of water quality or reduction in water resources.

Based on the above, the primary objective of the paper is to determine the dynamics of changes in Poland's LSWT in the years 1971-2015, and to create multiensemble scenarios for changes until the year 2100 based on the available General Circulation Model (GCM) simulations. Since many of the previous studies on the response of LSWT to climate change have focused mostly on the world's largest lakes this paper presents an empirical-statistical downscaling approach to quantify long-term trends of historical and future responses that might well be applicable to typical-size of lakes in this part of Europe.

DATASET AND AREA OF RESEARCH

Study region

In Poland, lakes are mostly located in the northern part of the country. This is related to the range of the last glaciation that occurred approximately 12,000 years ago (Fig. 1). The area is associated with regions of lakelands that include 96% of all lakes in Poland (Choiński, 2006), thereby co-determining the economic state of the region. The vicinity of such lakes and hence easy access to water has been vital for the development of many industrial branches, tourism, energy engineering, *etc*.

The study area is characterised by a transitional climate (Woś, 2010). The western part is dominated by a marine climate, transitioning into a continental climate towards the east. This is manifested among others in the mean annual air temperature amplitude, which is lower by approximately 3°C in the western zone compared to the eastern part of the country.

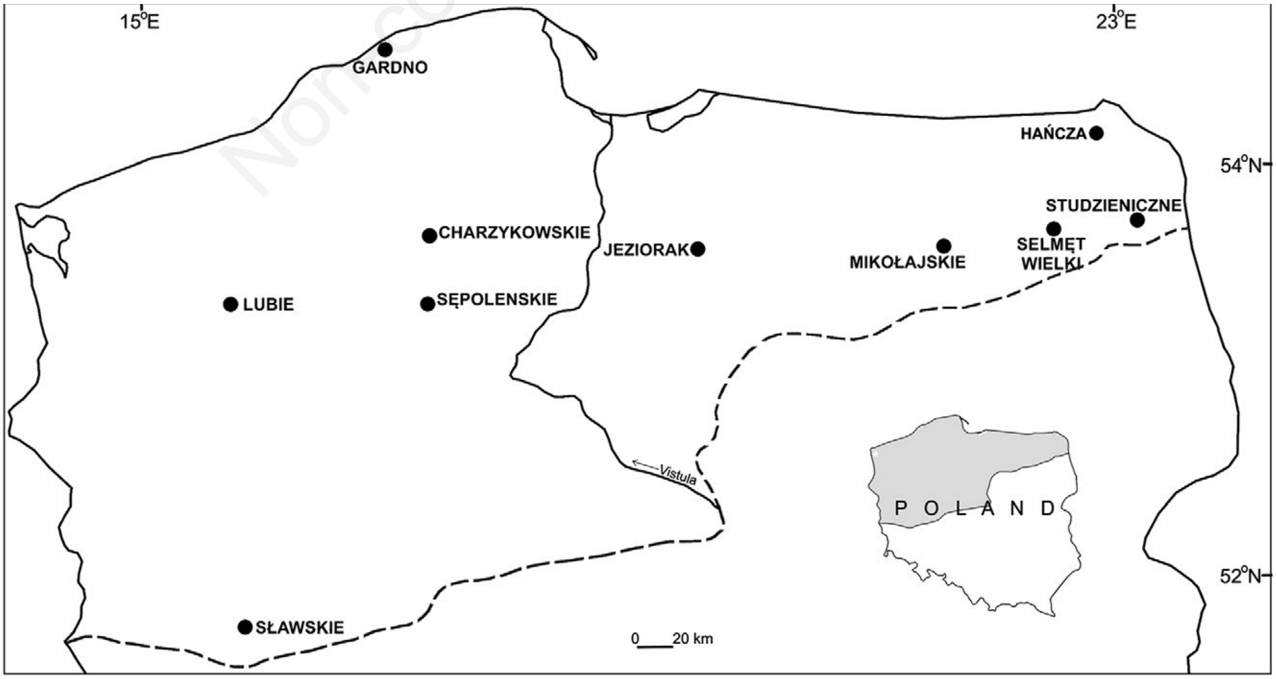

Fig. 1. Location of study lakes. Dotted line denotes maximum range of the last glaciation.

The paper presents the analysis of water temperature fluctuations in 10 lakes. Their selection was based on the availability of data with possibly long and coherent observation series. The basic morphometric data of these 10 lakes are presented in Tab. 1.

Lake temperatures

The study applies LSWT measurements from 1971 to 2015 in the cycle of the hydrological year (beginning on November 1 and ending on October 30) within the scope of the national hydrological monitoring conducted by the Institute of Meteorology and Water Management - National Research Institute. Measurement of water temperature in the aforementioned period was carried on a daily basis at a depth of 0.4 m below water surface at 7 or 8 a.m, local time (*i.e.,* 06:00 GMT). Such an approach excludes daily temperature fluctuations, as emphasised by Woolway *et al.* (2016). Out of 10 lakes, 8 had complete data. In the case of Lakes Lubie and Lake Selmęt Wielki, one year of observations was reconstructed based on empirical-statistical downscaling models later described in the methodological section.

Air temperature - historical

Historical series of meteorological data for the mean monthly air temperature at a 2 meters height were obtained from a high resolution (0.25° x 0.25°) E-OBS gridded dataset ver. 13.1 (Haylock *et al.,* 2008). This reanalysis product is characterised by a high degree of coherence with the observational dataset (Haylock *et al.,* 2008). Given the geometric centroid of the lake, the location of the nearest grid point was taken in order to obtain the closest (in terms of location) air temperature time-series. Adopting the reanalysis dataset instead of *in situ* measurement allows for permitting a reduction in inhomogeneities that result from observational errors, changes of the stations' location, or varied distances between a lake's centroid and the nearest meteorological stations. The latter problem would also involve another issue related to finding the most optimum spatial interpolation technique since some of the nearest meteorological stations are located more than a few tens of kilometres from the lakes.

CMIP5 dataset

Determination of scenario-based future changes in LSWT is based on the downscaling of 36 AOGCM models (Atmosphere-Ocean Coupled General Circulation Model) obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Due to a coarse-grid resolution typically in a range of 0.5° to 4° (Taylor *et al.*, 2012), the data were linearly interpolated onto 0.25° x 0.25° grid to coincide with the E-OBS dataset. Details of the AOGCM models applied in the downscaling procedure, to be described in following parts of this paper, are presented in Tab. 2.

To avoid overrepresentation of some of the AOGCM models with a high number of available runs, the first run marked as 'r1i1p1' was selected. The notation 'r1i1p1' stands for the number of model realization ('r'), initial conditions ('i'), and model's settings ('p'). Simulations for four Representative Concentration Pathways (RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5; van Vuuren *et al.*, 2011) covering projections for the years 2006-2100 and historical simulations from the period 1971-2005 were used to determine the robustness of the selected AOGCMs (Tab. 2). The names of the RCPs refer to the probable scope of radiation enforcement in 2100 in reference to climate from the pre-industrial era (*i.e.*, before 1850), and amount to +2.6, +4.5, +6.0, and +8.5 W·m^{-2}, respectively (van Vuuren *et al.,* 2011).

METHODS

The empirical-statistical downscaling concept

Due to the aforementioned low spatial resolution of (AO)GCMs, their direct application into research on future climate changes at the regional scale is not always

Tab. 1. Morphometric parameters of the studied lakes.

No.	Lake	Area(ha)	Volume(m^3)	Depth (m)	
				Average	Max
1	Sławskie	822.5	42,664.8	5.2	12.3
2	Lubie	1487.5	169,880.5	11.6	46.2
3	Sępoleńskie	157.5	7501.6	4.8	10.9
4	Charzykowskie	1336	134,533.2	9.8	30.5
5	Gardno	2337.5	30,950.5	1.3	2.6
6	Jeziorak	3152.5	141,594.2	4.1	12.9
7	Mikołajskie	424	55,739.7	11.2	25.9
8	Selmęt Wielki	1207.5	99,463.9	7.8	21.9
9	Studzieniczne	244	22,073.6	8.7	30.5
10	Hańcza	291.5	120,364.1	38.7	106.1

possible. The reliability of GCMs in reproducing local and regional patterns against the ‘reality’ obtainable by means of re-analysis data is not always coherent (Wójcik, 2015). Therefore, the use of information contained in GCMs usually requires the application of additional tools that allow for the ‘translation’ of a large-scale signal of a given variable into processes occurring at the local scale (Benestad *et al.,* 2008).

In research into the thermal regime of lakes, the concept of downscaling usually boils down to the approach of the

Tab. 2. CMIP5 models and their future projections used in this article.

No.	Model name	Institution and country	RCP			
			2.6	4.5	6.0	8.5
1	ACCESS1.0	CSIRO (Commonwealth Scientific and Research Organization) and BOM (Bureau of Meteorology), Australia	-	X	-	X
2	ACCESS1.3	–	-	X	-	X
3	BCC-CSM1-1	Beijing Climate Centre, China Meteorological Administration, China	X	X	X	X
4	BCC-CSM-1-1M	–	X	X	X	X
5	BNU-ESM	Beijing Normal University, China	X	X	-	X
6	CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	X	X	-	X
7	CCSM4	National Centre for Atmospheric Research, Boulder, USA	X	X	X	X
8	CESM1-BGC	Community Earth System Model Contributors, USA	-	X	-	X
9	CESM1-CAM5	–	X	X	X	X
10	CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy	-	X	-	X
11	CMCC-CMS	–	-	X	-	X
12	CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique, France	X	X	-	X
13	CSIRO-Mk3-6-0	CSIRO in collaboration with the Queensland Climate Change Centre of Excellence, Australia	X	X	X	X
14	EC-EARTH	EC-EARTH consortium, cooperation of 22 research institutes from 10 European countries	X	X	-	X
15	FGOALS_g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University, China	X	X	-	X
16	FIO-ESM	The First Institute of Oceanography, SOA, China	X	X	X	X
17	GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory, USA	X	X	X	X
18	GFDL-ESM2G	–	X	X	X	X
19	GFDL-ESM2M	–	X	X	X	X
20	GISS-E2-H	NASA Goddard Institute for Space Studies, USA	X	X	X	X
21	GISS-E2-H-CC	–	-	X	-	-
22	GISS-E2-R	–	X	X	X	X
23	GISS-E2-R-CC	–	-	X	-	-
24	HadGEM2-CC	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais), UK	-	X	-	X
25	HadGEM2-ES	–	X	X	-	X
26	IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France	X	X	X	X
27	IPSL-CM5A-MR	–	X	X	X	X
28	IPSL-CM5B-LR	–	-	X	-	X
29	MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	X	X	X	X
30	MIROC-ESM	–	X	X	X	X
31	MIROC-ESM-CHEM	–	X	X	X	X
32	MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	X	X	-	X
33	MPI-ESM-MR	–	X	X	-	X
34	MRI-CGCM3	Meteorological Research Institute, Japan	X	X	X	X
35	NorESM1-M	Norwegian Climate Centre, Norway	X	X	X	X
36	NorESM1-ME	–	X	X	X	X
		Total number of available scenarios	27	36	19	33

so-called dynamical (numerical or deterministic) downscaling, based on the application of physical laws (computational fluid mechanics and thermodynamics) in the description of energy fluxes that determine the transformations of a lake's thermal stratification (Schmid *et al.,* 2014). Despite the provision of physical coherence in the simulated processes, such an approach requires robust processing (or a high degree of simplification, see Jones *et al.,* 2010). As a result, it is often too costly to allow for the performance of a multi-ensemble analysis of the available emission scenarios' broad spectrum (Benestad *et al.,* 2008). In some cases, also due to some physical assumptions (*e.g.*, numerical stability) require input datasets are not always accessible to run the simulations (*e.g.*, typical problem is a short-time step).

An alternative to a dynamical approach is empirical-statistical downscaling (ESD), which is a less demanding method in terms of required computational capacity. The developed models are based on the diagnosis of cause-and-effect relations between large-scale and local processes through relevant tailoring of the diagnosed relations by means of mathematical procedures. Recent studies by Huth *et al.,* (2015) showed that although the concept of ESD is often perceived as simplistic compared to a dynamical one, the final results obtained by means of both approaches are similar, particularly in reference to thermal conditions. This means that the ESD approach would make it possible to apply many GCM simulations. Moreover, the application of a multi-ensemble forcing also facilitates the determination of a possible range of scenarios and limits the uncertainty related to errors of a single GCM forcing.

Dependency of air temperature on lake surface water temperature

The aforesaid concept of empirical-statistical downscaling requires the finding of a physical relationship between the predictand (also known as 'dependant variable' or 'regressand') and predictor (also known as 'independent variable'). This diagnosed statistical relationship on a monthly time scale between predictor and predictand will be used later in a linkage function applied for reconstruction and future projection purposes. In this study, we aim to assess the response of a LSWT (predictand) to changes in near-surface air temperature (predictor) in the historical period of 1971-2015.

The obtained values of the Pearson correlation coefficient between air temperature and LSWT (Tab. 3) show a strongly seasonal dependency with the lowest values obtained in winter months (December 0.62, January 0.65) and the highest in summer (July 0.92). Low values of correlation coefficients in winter are related to the occurrence of the ice phenomena (Choiński *et al.,* 2015). When the monthly mean temperature of the lake water is equal to or slightly exceeds 0°C and exchange of heat flux between water and ice is limited, lake waters remain more isolated from atmospheric factors which simultaneously respond to decline in the linear relationship between LSWT and air temperature (Woolway and Merchant, 2017).

A lake's morphometry also largely determines the obtained correlation values. In the case of the deepest lakes, it provides statistically weaker correlations at the annual scale (*e.g.,* Hańcza 0.62, Lubie 0.69) than for shallow lakes. This results from the higher heat capacity of the deepest lakes, as also confirmed by the results of temporal autocorrelation that gives higher values than those for shallow lakes. For example, the temperature of a deep lake is correlated at a level of 0.56 with temperature in the previous month, whereas for Lake Gardno the correlation amounts to 0.38 with the mean value for all lakes at 0.46. For consecutive months (2-month lag), such a correlation decreases to 0.26, for 3 months 0.21, approximately 0.03 less for each consecutive month. In the annual cycle, the values do not

Tab. 3. The Pearson correlation coefficients between monthly air temperature and lake surface water temperature, 1971-2015.

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Charzykowskie	0.70	0.82	0.72	0.53	0.62	0.72	0.90	0.86	0.88	0.72	0.83	0.69
Gardno	0.81	0.80	0.93	0.80	0.83	0.78	0.94	0.89	0.92	0.93	0.91	0.81
Hańcza	0.50	0.64	0.65	0.53	0.48	0.70	0.89	0.68	0.71	0.68	0.43	0.54
Jeziorak	0.50	0.56	0.79	0.69	0.78	0.64	0.88	0.75	0.84	0.74	0.61	0.53
Lubie	0.57	0.67	0.69	0.73	0.58	0.65	0.88	0.82	0.68	0.73	0.67	0.66
Mikołajskie	0.57	0.65	0.77	0.70	0.80	0.89	0.93	0.87	0.81	0.63	0.73	0.58
Selmęt Wielki	0.70	0.71	0.78	0.74	0.78	0.88	0.95	0.90	0.83	0.73	0.75	0.47
Sępoleńskie	0.70	0.69	0.86	0.67	0.70	0.81	0.92	0.87	0.82	0.76	0.69	0.65
Sławskie	0.81	0.80	0.78	0.71	0.73	0.86	0.94	0.80	0.73	0.77	0.71	0.67
Studzieniczne	0.63	0.70	0.73	0.79	0.80	0.91	0.94	0.89	0.86	0.69	0.77	0.58

considerably fluctuate even although they are inconsiderably higher in winter and early spring.

The linkage function for downscaling LSWT based on air temperature

The correlations analyses presented above were used to develop a simple (statistical) multiple regression model that allows for the reconstruction and prediction of LSWT series, taking as predictors air temperature from the current and two preceding months. For the purpose of avoiding overfitting of the regression models, the cross-validation procedure was performed based on a 10-fold cross-validation approach repeated 10 times using bootstrap resampling (Kuhn, 2008; Kuhn and Johnson, 2013). After each iteration, the Akaike Information Criterion (AIC, Sakamoto *et al.,* 1986) was used to select the best fitted set of predictors for the regression model in order to penalize a model for increasing number of estimated parameters, and thus causing a potential threat of overfitting. The models were created separately for each lake and month so as to preserve uniqueness of local interaction between air temperature and LSWT (eq. 1).

For the winter months (December-February), the multiple regression adjustment required at polynomial fitting (degree of 2) for the current and two preceding months due to the previously described non-linearity related to the presence of ice cover. The negative values of the reconstructed LSWT were additionally fixed at 0°C to avoid physical inconsistencies. A schematic illustration, showing the general concept of empirical-statistical downscaling of historical and future LSWT conditions based on the monthly mean air temperature, is shown in Fig. 2. The general formulae used to describe the diagnosed statistical relationship for determining LSWT are provided below as eq. 1 (for the period between March and November) and as eq. 2 (for the winter season). The regression coefficients 'a' and 'b' were estimated separately for each of the analysed lakes. In total 45 coefficients were needed to reconstruct the annual cycle of LSWT for every of analysed lakes (eq. 1 and eq. 2).

$$LSWT_{X,M}=a + b_1AT_M + b_2AT_{M-1} + b_3AT_{M-2} \quad \textit{(Mar-Nov)} \qquad \text{(eq. 1)}$$

$$LSWT_{X,M}=a + b_1AT_M + b_2AT_M^2 + b_3AT_{M-1} + b_4AT_{M-1}^2 + b_5AT_{M-2} + b_6AT_{M-2}^2 \; \textit{(Dec-Feb)} \qquad \text{(eq. 2)}$$

where:

a, b_1, b_2, b_3, b_4, b_5, b_6 are the estimated regression coefficients

$LWST_{X,M}$ is the lake surface water temperature at $Lake_X$ in $month_M$

AT_M is the air temperature at location of $Lake_X$ in $month_M$

AT_{M-i} is the air temperature at location of $Lake_X$ "i" month(s) earlier.

The temporal autocorrelation signal introduced by the air temperature of the preceding months allows the created ESD models consider the initial thermal state of the lakes which, due to the water's high heat capacity, is

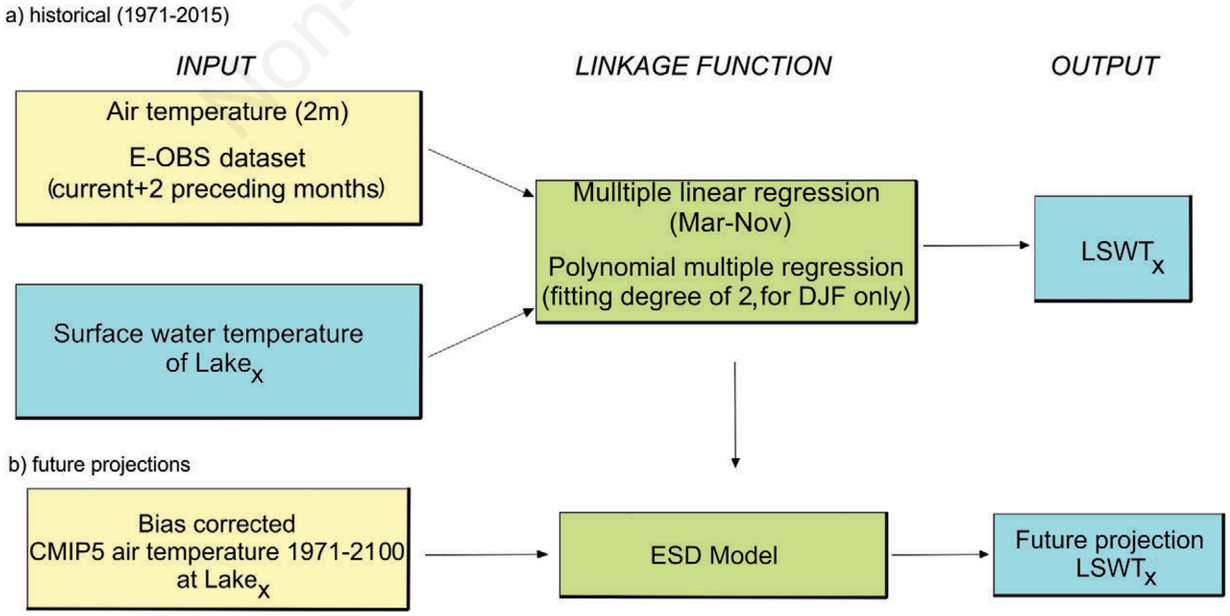

Fig. 2. The general scheme applied in this study for empirical-statistical downscaling of lake surface water temperature.

of great importance to the possibility of modeling the phenomenon. When averaged over orderings among regressors as computed by the 'lmg' algorithm (Grömping, 2006), the relative contribution reveals that air temperature in the current month explains from 56% (January) to 96% (July) of 'information' used in the models. At the seasonal scale, the values change from 63% in winter to 82% in summer. Of considerably greater importance is the autocorrelation factor diagnosed in the period from November to May when air temperature in the two preceding months has a more than 35% influence on the reconstructed LSWT time-series.

The importance of the diagnosed surface heating for the following months is that LSWT stays in agreement with other studies dealing with this issue. Zhong *et al.* (2017) explain this phenomenon in terms of mild winters and solar radiation that increase heat accumulation in the lakes. A similar explanation is also given by Piccolroaz *et al.* (2015), who determine the role of a warm spring in increasing the strength of lake stratification and thus bolstering the temporal autocorrelation signal.

Evaluation of ESD models in reference period (1971-2015)

The developed ESD models were evaluated against the observational dataset in the reference period of 1971-2015. The results presented in Fig. 3 in a form of scatter plot show dependencies between the reconstructed and observed monthly LSWT for particular lakes. On the right panel of Fig. 3, the Taylor diagram (Taylor, 2001; Carslaw and Ropkins, 2012) was used to present a models' robustness in terms of the Pearson correlation coefficient, root mean square error (RMSE), and normalised (on a monthly time scale) standard deviation values.

In general, both charts show good performance in reconstructing the historical time-series of lake temperatures based on the created ESD models. The best fitting of the reconstructed and observational series was obtained for the period from March to November, for which correlation coefficient values varied from 0.89 (June, November) to 0.93 (July). Considerably lower, although still reasonably high values were obtained for January (r=0.82) as well as December and February (r=0.84). In each of the reconstructed months, a variance inflation is observed, which is a typical artefact when applying downscaling based on regression methods (Benestad *et al.,* 2008; Liu *et al.,* 2011). The obtained values for the (annually) normalised standard deviation amount to 0.82-0.84 in winter, and in the remaining months they rose from 0.89 to 0.93, with a maximum in the summer months.

Similar dependencies were recorded for the RMSE values, *i.e.* increasing in winter and decreasing in summer months. It is worth mentioning that in the case of non-normalised RMSE values, the actual values in the winter season amount to <0.5°C. In the remaining seasons, its values increase to 0.6-0.8°C, and in the case of April, May, and July to 1.0-1.4°C. The selected bias indices confirm a better fitting of the model series in the summer

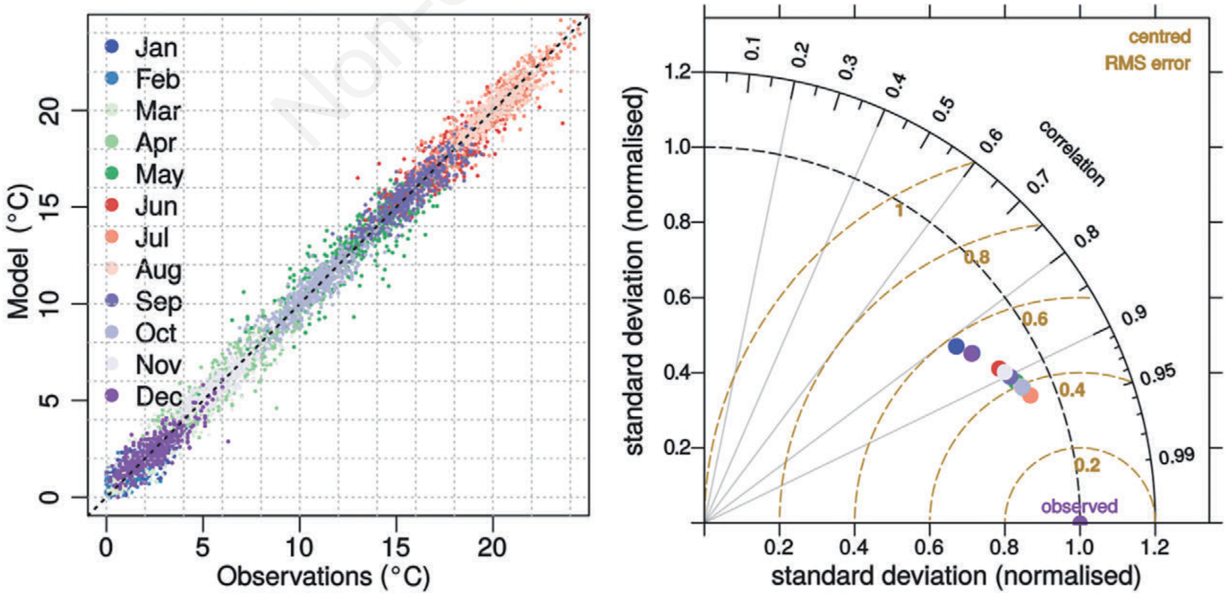

Fig. 3. Scatter plot (left panel, values given in degree Celsius) and Taylor diagram (right) of reconstructed monthly lake surface water temperature in the reference period (1971-2015).

months, as well as the more problematic issue of LSWT reconstruction in this period with possible occurrence of ice cover.

Empirical-statistical downscaling against a deterministic approach

The ESD presented above was not the only tested solution. Despite numerous attempts to improve the ESD model's performance, *e.g.* by the means of applying other predictors including large-scale sea-level pressure and air temperature pre-processed with Empirical Orthogonal Functions (Preisendorfer, 1988; Benestad *et al.*, 2008, 2017), the reconstructed time series hardly improved. Especially for the winter period, the improvement in the models' performance remained negligible.

Statistical models that require little input are often equally questionable as too simplistic to capture certain fundamental processes, while their usefulness might be limited in new climatic conditions (Piccolroaz, 2016). Although the main aim of this paper is not concerned with accuracy of the statistical approaches against dynamical ones, the authors decided to show a brief comparison between the created ESD models and a hybrid 'air2water' model characterized by a physically based structure associated with stochastic calibration, that requires only air temperature and a lake's morphological parameters as input (Piccolroaz *et al.,* 2015). For the case study, the simulation of NorESM1-M GCM led by RCP 8.5 was chosen, especially as the highest air temperature increase in the 21st century is expected under this assumption. A calibration period for the 'air2water' model was set for years 1971-2014.

A Probability-Probability (p-p) plot, presented in Fig. 4, shows remarkable agreement between both time-series for the entire temperature ranges for all analysed lakes aggregated on a monthly time-scale. Some visible deviations have been found for near-freezing temperatures which confirms the earlier imperfections of both approaches in representing non-linearities related to presence of ice cover (Fig. 4). The performance statistics of variance inflation in the period 1971-2014 show similar accuracy of 'air2water' against statistical model (ESD: RMSE=0.66°C, 'air2water': RMSE=0.72°C), and only slightly worse results in reproducing long-term trends (ESD: +0.293°C·dec^{-1}, 'air2water': +0.269°C·dec^{-1}, historical data: 0.375°C·dec^{-1}). Keeping in mind that the main aim of this study, which is related to long-term changes in LSWT, the most important feature that should be fully captured by any model is preserving as accurate as possible the rate of change. The calculated slope coefficients of long-term changes for years 2006-2100 show a satisfactory level of agreement (Fig. 5). The deviation in trend of mean annual LSWT for particular lakes was lower than ±0.02°C·dec^{-1} regardless of the adopted method. The authors are aware that also changes in other meteorological parameters associated with the turbulent fluxes, in particular surface wind speed should also be considered for accurate modelling of stratification dynamics, and in some cases it may play an important role for future changes of LSWT (Woolway *et al.*, 2017b).

In our opinion, neither the degree of complexity of the most sophisticated ESD models (based on large-scale predictors) nor the application of deterministic 'air2water' sufficiently compensates for their quality in terms of reproducing long-term trends or possible lack of ESD model accuracy under new temperature ranges. Moreover, simulated changes in air temperature by AOGCMs are relatively robust, with uncertainties in the order of ~50% (Knutti, 2008) while for the remaining meteorological elements (*e.g.,* wind speed, solar radiation, *etc*.), which are required by more accurate deterministic lake models, variability between particular GCMs is often higher than the general signal of the assumed changes. These uncertainties are also of a magnitude higher than differences in performance between statistical and dynamical approaches when only the long-term means of LSWT are investigated.

Therefore, considering the obtained validation results, which are comparable with results obtained by means of the dynamic models (Persson *et al.,* 2005; Piccolroaz,

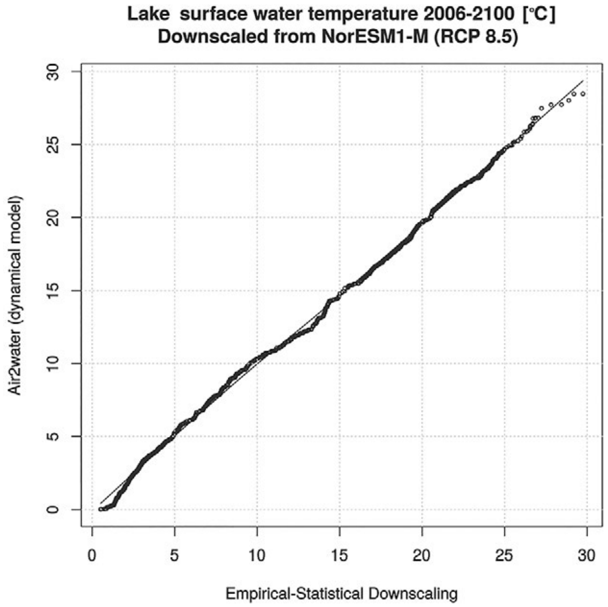

Fig. 4. P-P plot of monthly lake surface water temperature as obtained from empirical-statistical downscaling and 'air2water' models. Simulations based on NorESM1-M (r1i1p1) under the RCP 8.5 scenario.

2016), the decision made to apply the ESD approach was based exclusively on air temperature (and temporal autocorrelation signal), thereby allowing for an easier interpretation of diagnosed causal relationships. Moreover, the use of the ESD approach allows for the use of a wider range of GCM models since only the monthly values are required as input. In the case of deterministic models, the necessity of applying the daily or sub-daily would significantly reduce the number of possible CMIP5 GCMs, thus narrowing the range of possible future scenarios.

Model calibration and CMIP5 datasets

The developed ESD models were also tested with historical CMIP5 simulations (Tab. 2) to determine their convergences with the re-analysis time series. It is common knowledge that GCM simulations involve systematic errors (Yang and Anderson, 2000) that require adjustment in order to provide credibility of simulations for future periods. Therefore, monthly air temperature climatologies as derived from GCMs, were compared with observational climatologies in the period 1971-2005. The calculated differences were then considered as the adjustment value (bias correction) for each of the analysed model series for the entire period available in CMIP5 simulations (1971-2100) and in accordance with the assumptions of the 'delta change' method (Lenderink *et al.,* 2007; Wibig and Jędruszkiewicz, 2015).

The bias-corrected predictors obtained from every of GCM were used as input information for the ESD models. Next, the calculated slope coefficients of the LSWT linear regression in the period 1971-2005 for the reference series (0.37°C dec^{-1}) were compared with those reconstructed by GCMs. Among 36 tested GCMs (Tab. 2), the trend coefficients varied from -0.09°C dec^{-1} to +0.58°C dec^{-1}, averaging 0.28°C dec^{-1}. After eliminating outliers with a negative trend (models: IPSL-CM5B-LR, MRI-CGCM3, FIO-ESM), the mean value of the trend increased to 0.31°C dec^{-1}.

RESULTS

Climatology and current changes in near-surface lake temperature

The course of water temperature in a monthly cycle is typical of lakes located in a moderate climate zone, *i.e.* the lowest values are reached in winter during ice cover, while the maximum is usually observed in July and August (Fig. 6A). The fastest and slowest increase in temperature is analogically in accordance with the situation presented above - concerning lakes located at the boundaries of the analysed area, *i.e.* Lakes Sławskie and Hańcza. Lake Gardno cools the fastest in the second half of the year, and is characterised by the lowest mean depth among the analysed lakes, as well as direct hydraulic contact with the colder waters of the Baltic Sea.

Normally, water temperatures in a major part of the year tend to be higher than air temperature (Fig. 6B). The exception is March and April, when water temperature decreases as a result of the ice cover degradation and presence of meltwaters in the surface layer. Data

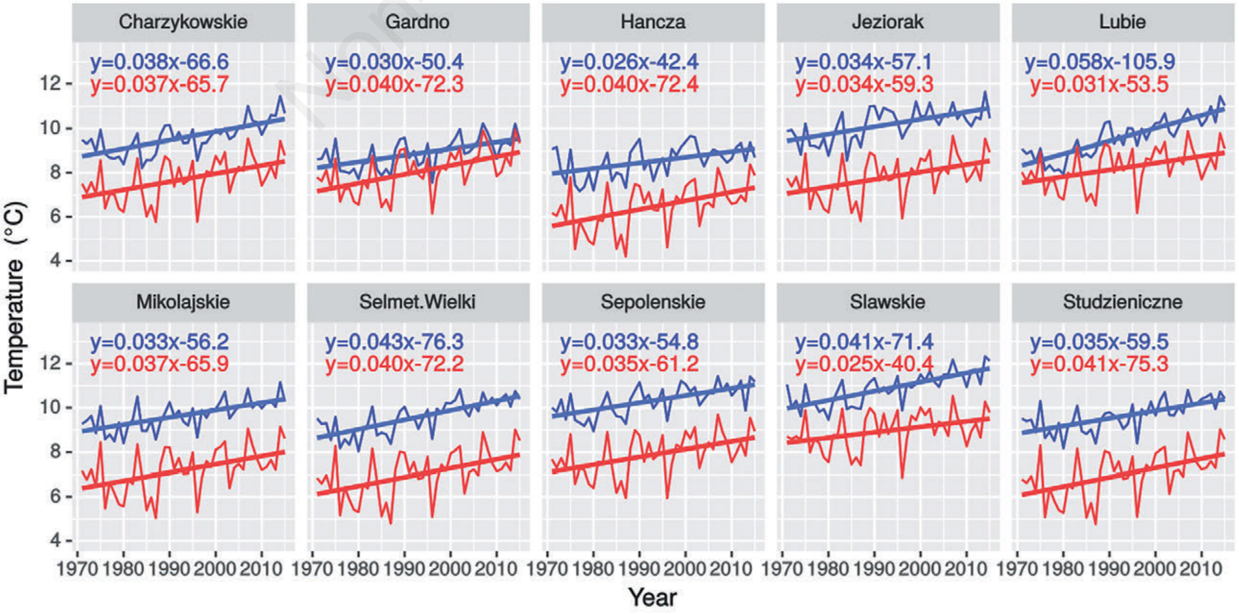

Fig. 5. Tendencies of changes in lake water temperature (blue colour) and air temperature (red colour) in the years 1971-2015.

concerning mean LSWT for the years 1971-2015 suggest that the mean temperature was 9.7°C. The warmest of the analysed lakes is Lake Sławskie, located furthest to the south-west. The mean temperature in this case was 10.9°C. The coldest of the lakes is Lake Hańcza (8.5°C), located on the opposite side of the study area (Fig. 1).

The analysis of changes in the annual LSWT showed that in all cases they were characterised by an increasing tendency (Fig. 5) averaging at 0.37°C·dec^{-1}. It was slightly higher than the calculated trend for air temperature (0.36°C·dec^{-1}), with the Pearson correlation coefficient equalling 0.93. In all cases, the first decade of the analysed multiannual showed a decreasing tendency in LSWT (in the years 1971-1980, the trend amounted to -0.12°C·dec^{-1}), and then from the early 1980's successive increase occurred.

Tendencies towards change in monthly water temperatures show that the highest increase was recorded in spring (April 0.51°C·dec^{-1}, May 0.63°C·dec^{-1}) and July (0.57°C·dec^{-1}), while the lowest changes were observed in the winter period (December 0.19°C·dec^{-1}, January 0.16°C·dec^{-1}, February 0.10°C·dec^{-1}, Tab. 4). Results showing the most substantial warming in the period of spring and summer confirm findings by Woolway *et al.* (2017a) concerning recently observed changes among lakes in Central Europe.

Future projections

LSWT anomalies by 2100, calculated against reference period (1971-2005), show a strong dependency on the adopted RCP scenario, and the selected sub-period of the 21st century.

Fig. 7 presents changes in water temperature for

Tab. 4. Directional coefficients of trends of lake surface water temperature in the period 1971-2015. The values are marked with bold font for trends statistically significant at a level of 1 -α=0.05.

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Charzykowskie	0.28	**0.25**	**0.40**	**0.64**	**0.69**	0.28	0.46	**0.38**	**0.36**	0.28	0.27	**0.30**	**0.38**
Gardno	0.15	0.00	0.20	**0.51**	0.48	0.28	0.44	**0.37**	**0.41**	0.29	0.32	0.12	**0.30**
Hańcza	-0.05	-0.02	0.12	**0.41**	**0.86**	**0.70**	0.55	0.38	0.14	0.26	0.01	-0.27	**0.26**
Jeziorak	0.05	0.03	0.12	0.37	0.42	0.29	**0.64**	**0.55**	**0.64**	**0.44**	**0.40**	0.10	**0.34**
Lubie	**0.32**	**0.21**	**0.43**	**0.78**	**1.01**	**0.71**	**0.76**	**0.58**	**0.64**	**0.58**	**0.59**	**0.35**	**0.58**
Mikołajskie	0.15	0.11	0.21	**0.42**	0.50	0.29	**0.56**	**0.49**	**0.40**	0.29	0.31	0.23	**0.33**
Selmęt Wielki	0.23	0.17	0.32	**0.56**	**0.60**	**0.48**	**0.64**	**0.56**	**0.35**	**0.42**	**0.50**	**0.34**	**0.43**
Sępoleńskie	0.13	0.01	0.13	0.36	0.50	0.38	0.50	**0.42**	**0.41**	**0.40**	**0.47**	0.19	**0.33**
Sławskie	0.26	0.14	0.33	**0.48**	**0.71**	**0.40**	**0.58**	**0.49**	**0.41**	**0.42**	**0.50**	0.24	**0.41**
Studzieniczne	0.12	0.10	0.20	**0.53**	0.54	0.31	**0.56**	**0.46**	**0.40**	**0.36**	**0.32**	0.26	**0.35**
Average	0.16	0.10	0.25	**0.51**	**0.63**	**0.41**	**0.57**	**0.47**	**0.42**	**0.37**	**0.37**	0.19	**0.37**

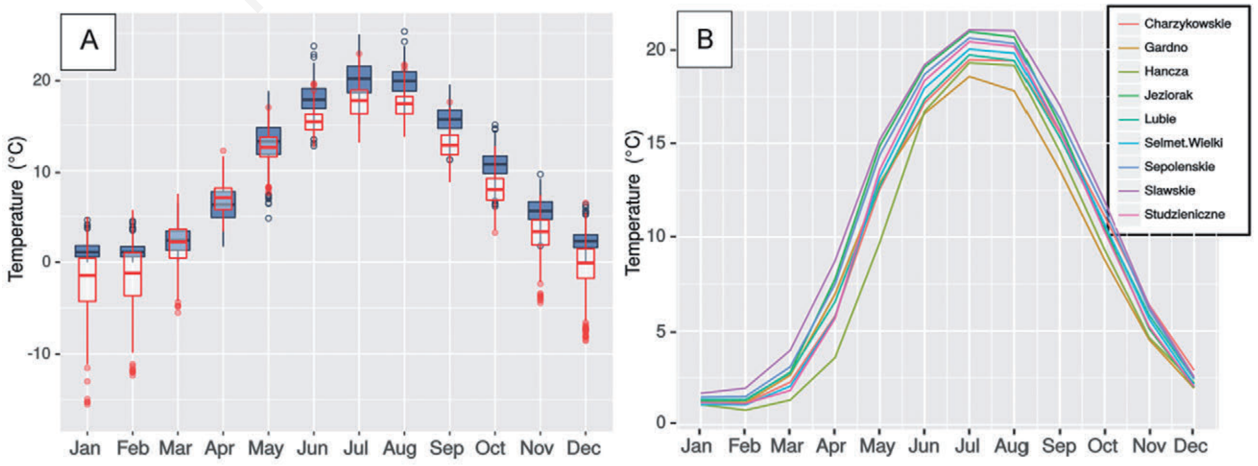

Fig. 6. Monthly distribution of air (red) and water temperature (blue) in lakes (A); monthly course of mean water temperature in particular lakes, 1971-2015 (B).

particular lakes taking into consideration past and future changes. Due to the convergence of future changes regarding the adopted scenarios, an analysis of averages was performed for all the lakes combined (Fig. 8, Tab. 5).

Results obtained by downscaling models based on selected CMIP5 projections show a high accordance among annual trends in the historical period, and assume further continuation of the currently diagnosed changes irrespective of the RCP scenario by approximately 2020. This corresponds to an increase in the mean annual LSWT by 0.8°C, thereby exceeding the value of 10°C (up to 10.3°C). After that period, divergences begin to emerge between particular RCP scenarios. In the period 2021-2040, the highest mean changes are suggested by simulations based on RCP 8.5 (+1.4°C), with the lowest value for RCP 6.0 (+1.1°C). In the years 2041-2060, divergences between the warmest and coldest scenarios already amount to 0.8°C at a change in water temperature for RCP 8.5 equalling +2.2°C, in addition to an evident slowdown of increase for scenario RCP 2.6 (change by +1.4°C). In the second half of the 21st century, considerably greater changes were obtained for RCP 8.5 which, for the periods 2061-2080 and 2081-2100, translate into an increase in the lakes' mean annual water temperature at levels of 3.2 and 4.2°C, respectively (Tab. 2), whereas some of the selected GCMs suggest a substantially lower increase in temperatures, translating into more than 5-degree anomalies around the year 2100 (Fig. 8). Assuming a reduction in greenhouse gas

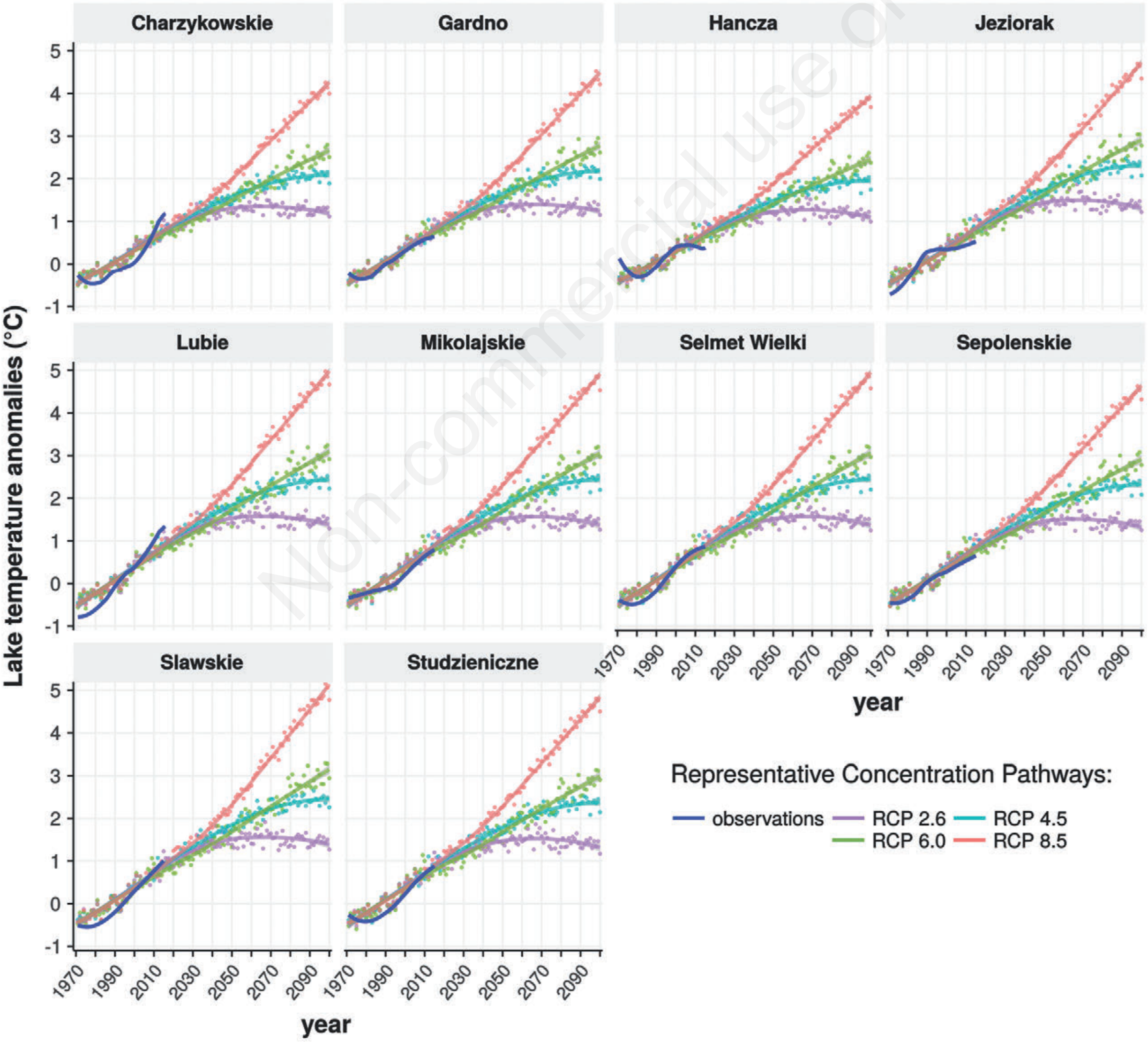

Fig. 7. Projections of changes in mean annual surface water temperature in reference to the period 1971-2005 based on CMIP5 models (points) and their values smoothed by means of locally polynomial function (locally-weighted polynomial regression) for particular lakes.

emission, the RCP scenarios show less drastic changes, and are balanced to the assumed reduction in anthropogenic emission. Due to a relatively long duration of response to changes in radiative forcing, and the additional time needed to obtain equilibrium in the LSWT (Schmid *et al.,* 2014), for the years 2051-2070, scenarios for RCP 4.5 and 6.0 are still quite similar. After this period, divergences between them increase, and in the last two decades, the mean difference between them amounts to 0.4°C (change in anomalies amounts to +2.3 and +2.7°C, respectively). The most optimistic scenario is presented by RCP 2.6. After 2060, a decrease in LSWT and its further stabilisation at the level from the period 2031-2040 is assumed.

General patterns concerning differences in LSWT depending on RCP scenarios in different subperiods of the 21st century are also confirmed in the monthly cycle (Tab. 5, Fig. 9). Also here, the greatest differences between particular RCPs concern the period after 2050, with at warmest RCP of 8.5, followed by 6.0, 4.5, and 2.6. However, it is worth emphasising the uneven increase in water temperature in the annual cycle, and the expanding range of uncertainty trends between particular RCPs. The lowest rate of changes in water temperature by 2100 should be observed in February (2081-2100: RCP 2.6=+0.5°C, RCP 8.6=+1.8°C), and due to a somewhat stronger trend of forecasted changes for January (2081-2100: RCP 2.6=+0.6°C, RCP 8.6=+2.5°C), February will increasingly and frequently be the month with the lowest water temperature. In the historical period (1971-2015), the proportions were 53.3% to 46.7% in favour of January. The lowest increase in water temperature in February is a result of the assumed changes in air temperature occurring in the preceding months, and the importance of the autocorrelation factor in ESD models. In the historical period, air temperature in December, January, and February amounted to -0.4°C, -2.1°C, and

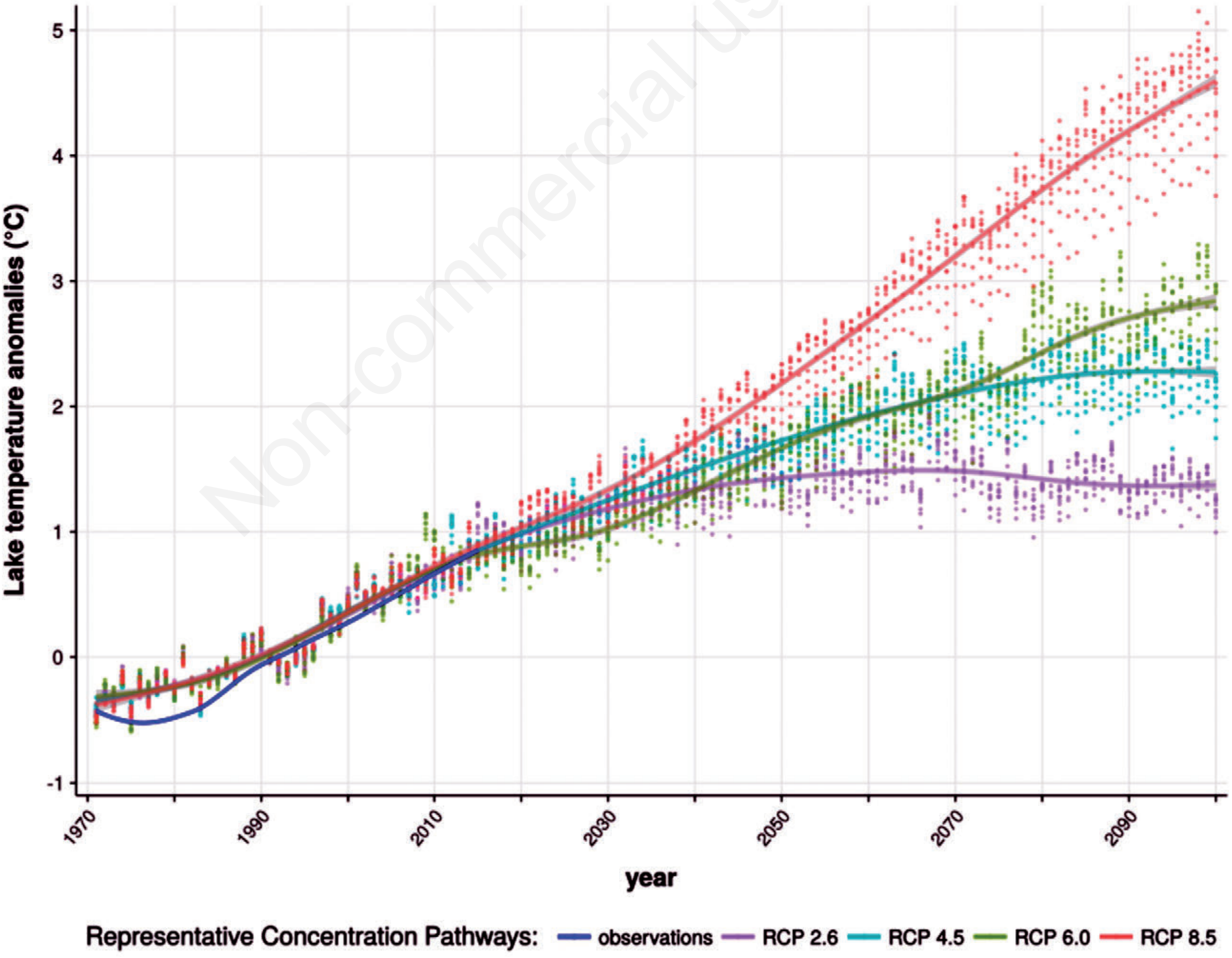

Fig. 8. Projections of changes in mean annual surface water temperature in reference to the period 1971-2005 based on CMIP5 models (points) and their values smoothed by means of locally polynomial function (locally-weighted polynomial regression) - averaged for all lakes.

-1.5°C, respectively. In consequence of the assumed warming, this will favour a delayed occurrence of ice cover, and a reduction in its persistence. Due to negative mean air temperature values in January and February, to be maintained even in the second half of the 21st century, the lowest increases (usually <1-2°C) in lakes' water temperature are assumed for the period from January to March. For comparison, trends of changes at the beginning of the season with ice phenomena show a considerably faster rate of changes. In December, for which air temperature already currently exceeds 0°C, the projected change in water temperature does not differ considerably from the value for November, for which at the end of the 21st century the increases will range from 1.1°C (RCP 2.6) to 4.2°C (RCP 8.5).

The decline in ice cover, beginning in early spring, is accompanied by an accelerating increase in the LSWT. According to scenario RCP 8.5, in the period from May to August, changes will exceed 5°C (even up to 6.0°C in June). The disproportions between the remaining scenarios in this period compared to the remaining seasons have also become more evident. For example, anomalies in such months for RCP 6.0 and 4.5 vary from 2.7 to 3.5°C.

In autumn, the changing signal substantially declines, even though it is on average still less than 1°C higher than the level assumed for the spring period (Fig. 9), due to very strong heating of the water surface in summer. In the extreme scenario RCP 8.5, in such months, an increase in temperatures can reach 3.7-4.8°C at the end of the century, whereas the more optimistic forecast of RCP 2.6 shows changes of approximately +1.5°C only.

DISCUSSION

The results presented in this paper correspond to the global trend in research on changes in the temperature of lake waters within the context of global warming. Studies of this nature concern both historical and current changes in the thermal regime of lakes, even though they also reach into the future by simulating the rate of further transformation. Both approaches were implemented in this study, thereby filling an existing gap for lakes in that central part of Europe adjacent to the Baltic Sea. Referring the obtained results to earlier studies of a similar type from the territory of Poland (which of course investigated the process in another time period) shows that while the tendencies towards change are similar, they have increased remarkably in recent years. Dąbrowski *et al.* (2004), in analysing water temperature fluctuations in the

Tab. 5. Anomalies of lake surface water temperature in particular subperiods of the 21st century and their reference values (1971-2005). Values are given in Celsius degrees.

Time period	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1971-2005		1.2	1.2	2.3	6.1	12.8	17.6	19.6	19.6	15.4	10.4	5.4	2.2	9.5
2006-2020	RCP 2.6	0.3	0.2	0.4	0.8	1.2	1.2	1.1	1.0	0.9	0.9	0.7	0.6	0.8
2021-2040	RCP 2.6	0.5	0.4	0.7	1.2	1.8	1.8	1.6	1.5	1.3	1.3	1.1	1.0	1.2
2041-2060	RCP 2.6	0.6	0.4	0.9	1.6	2.3	2.1	1.9	1.7	1.6	1.6	1.3	1.1	1.4
2061-2080	RCP 2.6	0.6	0.4	0.9	1.6	2.4	2.2	2.0	1.8	1.6	1.6	1.2	1.1	1.5
2081-2100	RCP 2.6	0.6	0.5	0.8	1.5	2.2	2.1	1.8	1.7	1.4	1.5	1.2	1.1	1.4
2006-2020	RCP 4.5	0.3	0.2	0.5	0.8	1.2	1.2	1.0	1.0	0.8	0.8	0.6	0.6	0.8
2021-2040	RCP 4.5	0.6	0.4	0.8	1.4	1.9	1.8	1.6	1.6	1.4	1.4	1.1	1.1	1.3
2041-2060	RCP 4.5	0.8	0.5	1.1	1.8	2.7	2.6	2.3	2.2	1.9	1.9	1.5	1.4	1.7
2061-2080	RCP 4.5	1.0	0.7	1.3	2.1	3.2	3.1	2.8	2.6	2.3	2.3	1.8	1.8	2.1
2081-2100	RCP 4.5	1.2	0.8	1.4	2.4	3.5	3.4	3.0	2.8	2.5	2.5	2.0	2.0	2.3
2006-2020	RCP 6.0	0.2	0.2	0.5	0.8	1.3	1.0	1.0	1.0	0.9	0.8	0.7	0.5	0.8
2021-2040	RCP 6.0	0.4	0.4	0.7	1.2	1.7	1.5	1.5	1.3	1.3	1.3	1.0	0.7	1.1
2041-2060	RCP 6.0	0.8	0.6	1.0	1.8	2.5	2.5	2.4	2.1	1.9	1.9	1.5	1.4	1.7
2061-2080	RCP 6.0	0.9	0.8	1.3	2.2	3.3	3.3	2.9	2.7	2.4	2.4	1.8	1.6	2.1
2081-2100	RCP 6.0	1.3	0.9	1.6	2.7	3.9	3.9	3.5	3.4	3.1	3.1	2.4	2.4	2.7
2006-2020	RCP 8.5	0.3	0.2	0.4	0.8	1.1	1.2	1.2	1.1	1.0	0.9	0.6	0.6	0.8
2021-2040	RCP 8.5	0.6	0.4	0.9	1.4	2.1	2.0	2.0	1.8	1.5	1.5	1.2	1.1	1.4
2041-2060	RCP 8.5	1.0	0.8	1.4	2.2	3.2	3.3	3.0	2.8	2.5	2.5	2.0	1.9	2.2
2061-2080	RCP 8.5	1.9	1.3	2.0	3.2	4.6	4.6	4.2	4.0	3.6	3.6	2.8	3.0	3.2
2081-2100	RCP 8.5	2.5	1.8	2.4	3.9	5.7	6.0	5.6	5.3	4.7	4.8	3.7	4.2	4.2

years 1961-2000 for six lakes in the Lakeland area of Poland, recorded an increasing tendency in all cases. The values, however, were lower than current ones. The highest water temperature increase (0.27°C·dec^{-1}) in the years 1960-2000 was observed for Lake Jeziorak. Based on current data, that value is now higher, amounting to 0.37°C·dec^{-1}. At the regional scale, lakes in Poland show a coherent course of lake water temperature fluctuations in comparison to other parts of central Europe (Pernaravičiute, 2004; Gross-Wittke *et al.,* 2013; Dokulil *et al.,* 2010; Nõges and Nõges, 2014; Schmid and Köster, 2017; Ptak *et al.,* 2017; Woolway *et al.,* 2017a).

Based on Poland's lakes, the analysed increase in temperature for all cases shows low variability. Cases of extreme situations should be associated with the influence of two different types of climate. Lake Lubie (0.5°C·dec^{-1}) is located the furthest to the north-west among the analysed lakes, where warmer marine climate occurs. Lake Hańcza (0.2°C·dec^{-1}) is located in the north-eastern part of the study area, a region dominated by continental climate. The different character of both regions is also manifested in the effect of macroscale atmospheric circulation (North Atlantic Oscillation) on lake water temperature in Poland (Wrzesiński *et al.,* 2015a). Moreover, the unique

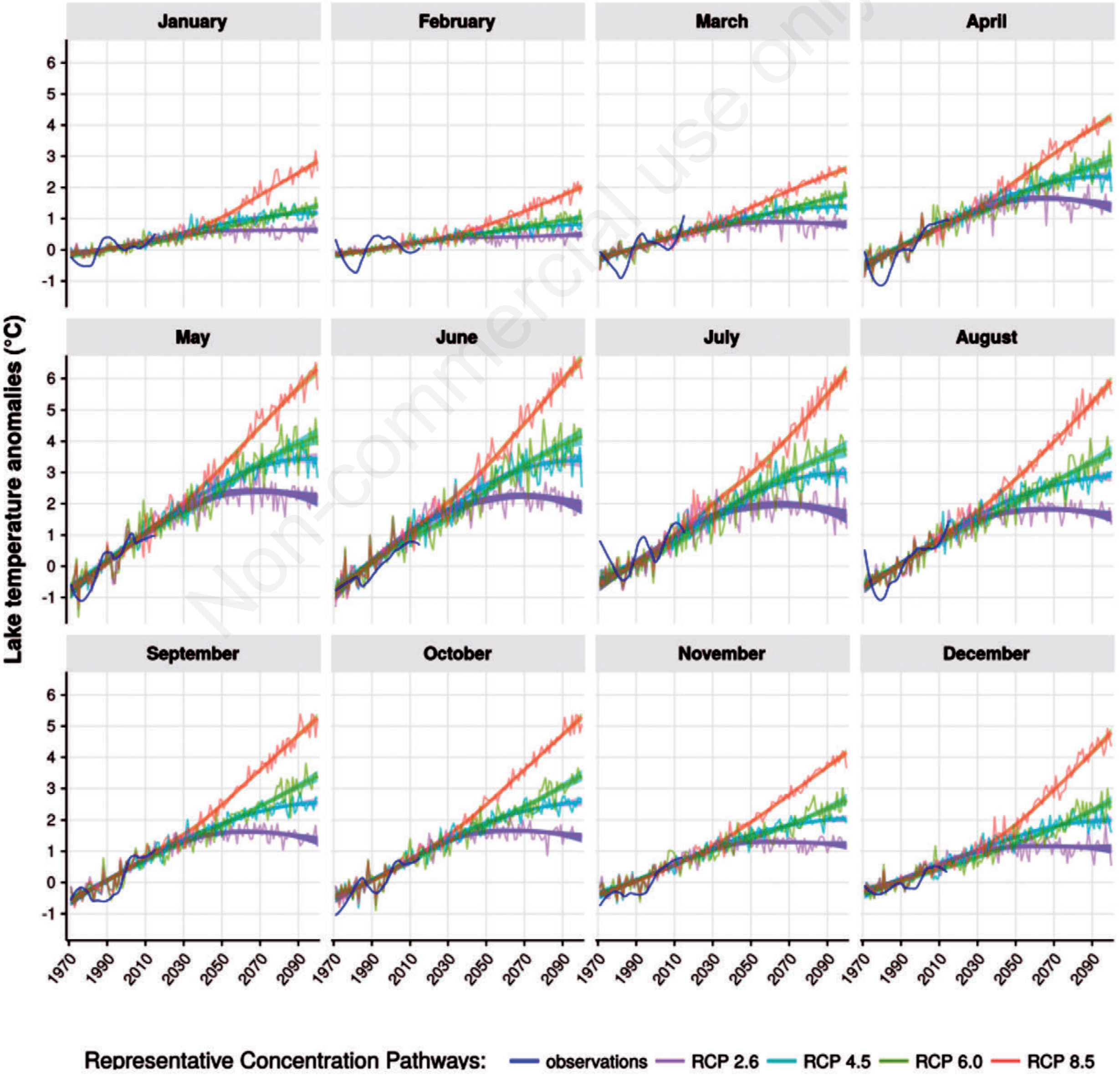

Fig. 9. Projections of mean monthly lake surface water temperature in reference to the period 1971-2005 (combined for all lakes).

morphometric parameters of Lake Hańcza should also be taken into consideration. This is the deepest lake in the central part of the European Lowland. The geological cross-section presented by Pochocka-Szwarc *et al.* (2013) shows that the lake has direct contact with aquifers (sands, gravels) with considerable thickness (reaching up to 50 m). The alimentation of the lake with cooler groundwaters can therefore reduce the effect of climatic factors. The important role of groundwater alimentation in the course of hydrological processes in the lake is pointed out by, among others, Choiński and Ptak (2012) as well as Cieśliński *et al.* (2016).

In the seasonal cycle, the highest temperature increase in spring and summer is related to the climatic conditions and morphometry of lakes. Such a situation, in the case of Lake Lugano with a maximum depth of 288 m (northern basin), has been described by Lepori and Roberts (2015). The highest increase in water temperature in spring and summer (0.6-0.9°C dec^{-1}) was caused by the highest air temperature increase in those seasons of the year. In the period of autumn and winter, the climatic effect on LSWT is obliterated as a result of its vertical circulation. Water mixing can constitute a buffer for surface waters in the context of climate warming (Livingstone, 2003). In morphometric terms, eight out of ten analysed lakes have features of stratified lakes, *i.e.* they also have the situation described above. Further causes of faster water temperature rise in spring involve changes in the ice regime. According to the long-term analysis of ice phenomena for 18 lakes in Poland, the term of disappearance of ice cover successfully occurs earlier, and in the years 1961-2010 amounted to 4.1 days dec^{-1} (Choiński *et al.,* 2015). As a consequence, faster and longer warming of the water occurs. This ice phenomena should also be associated with a considerable increase in water temperature in summer, resulting from the situation occurring in early spring. The entire process was described in detail by Austin and Colman (2007) in the case of Lake Superior in North America. According to their study, in the summer period, water temperature increased by 2.5°C in the years 1979-2006. Such a situation was caused by a shortening of the ice season, resulting in the earlier occurrence of summer stratification, which in turn considerably prolonged the period of water warming. Stratification dynamics also play an important role in the vertical heat exchange (Piccolroaz *et al.,* 2015). Research by Mishra *et al.* (2011), conducted on smaller lakes (0.01-557 km^2) in the area of the Great American Lakes, confirmed that the combined effects of air temperature increase and earlier occurrence of stratification were critical to the rise in the lakes' accumulated heat. In the region, increase in water temperature is higher than that for air temperature. This also accords with the situation recorded in the case of the paper. The effect of earlier thermal stratification on temperature increase in the epilimnion is also described by Rösner *et al.* (2012) based on example from small lakes Plußsee (0.14 km^2) in Germany. As to Poland, Skowron (2011), analysing the vertical distribution of lake water temperature in the years 1970-2009, has also determined the occurrence of substantial changes. Similar to the current response of lake water temperature in Poland, the projected future changes also accord with the majority of studies concerning this same issue in different parts of the world. For example, according to the results obtained in this paper, an LSWT increase in Poland for the period 2081-2100 compared to the period 1971-2005 in the annual cycle can vary from +1.4°C (RCP 2.6) to +4.2°C (RCP 8.5). Depending on the region and the adopted climate change scenario, water temperature increase will oscillate at different levels (Elo *et al.,* 1998; Persson *et al.,* 2005; Trumpickas *et al.,* 2009; Kirillin, 2010; Rao *et al.,* 2012; Ngai *et al.,* 2013).

Consequences of changes in the thermal regime of lakes are currently being thoroughly investigated and even documented in many studies. They cover all functional aspects of such ecosystems. In hydrological terms, they concern, among others, changes in the occurrence of ice cover (Wrzesiński *et al.,* 2015b; Magee *et al.,* 2016), changes in the system of water mixing and stratification (Perroud and Goyette, 2010; Palmer *et al.,* 2014), or changes in the water's physical and chemical properties (North *et al.,* 2014; Bartosiewicz *et al.,* 2016). Any change in the components of a lake's hydrological balance is an important issue. As was mentioned in the introduction, Poland is one of those countries with the scarcest water resources per capita in Europe. An increase in temperature, and as a consequence increase in evaporation, can only contribute to the deterioration of an already unfavourable situation. Choiński *et al.* (2016) investigated changes in water resources in 18 lakes in central Poland. Analysing both anthropogenic and natural factors contributing to the reduction in the amount of water accumulated in those lakes, they determined that in the case of the latter, an increase in evaporation was of critical importance, and not a decrease in precipitation which in the study period was maintained at a constant level. Living organisms in lakes respond to changes in the thermal regime relatively fast. This refers to, among others, transformation in the species' composition, biological parameters, or their abundance (Pełechata *et al.,* 2015; Przytulska, *et al.,* 2015). It is commonly assumed that an increase in water temperature will also lead to an increase in trophic status (Feuchtmayr *et al.,* 2009). The progressing temperature increase will lead to further transformation in lake ecosystems, as confirmed by numerous papers modelling such future changes (Trolle *et al.,* 2015). Komatsu *et al.* (2007) have also predicted that in the Shimajigawa Reservoir (Japan), the surface water temperature will rise by 3.8°C in the years 2091-2100 compared to the decade 1991-2001. This will result in (among others) the prolongation of the stratification period, deepening of the thermocline layer, increase in oxygen demand, higher phosphorus concentration in water, and increase in phytoplankton. In the case of Lake Erken in east Sweden, Blenckner *et al.* (2002) have also observed similar transformations as those presented above, *i.e.* change in the water mixing system, as well as increase in the circulation of nutrients and lake productivity. Possible changes in water quality are also mentioned by Sahoo *et al.* (2016), leading to changes in the duration of thermal stratification in Lake Tahoe. The existing studies have predicted changes in the rate of growth of fish, changes in their habitats, *etc*. (Sharma *et al.,* 2007; Van Zuiden *et al.,* 2016). In the case of Poland, future changes can be reflected in the situation occurring in artificially heated lakes being adapted to energy production. The complex of five lakes (the so-called Koninskie Lakes) in central Poland constitutes an element of the cooling system for nearby power plants. The above situation provides a visual illustration of forecasted changes in the thermal regime of lakes and their potential impacts. According to Záhorská *et al.* (2013), the mean temperature increased from 5 to 7°C, affecting the flora and fauna in the lakes. Substantial changes in the thermal regime of lakes have brought about new living conditions. Gąbka (2002) describes a new species for the Polish flora *Vallisneria spiralis* L which perfectly adapted to life in the Konińskie Lakes as a result of considerable increase in the water temperature. The appearance of the plant has had further consequences for the hydrobiology of the heated lakes. With the appearance of *V. spiralis*, a new thermophilic species of rotifers was also recorded (Ejsmont-Karabin, 2011). Therefore, the described cases clearly show very close relationships between particular components of the lake ecosystems. Due to the complexity of the hydrological and biological processes, the projected substantial increase in water temperature will only lead to more frequently difficult-to-predict transformations. These changes can often be irreversible in character, radically changing the current parameters of lakes. Starkel (2002) emphasises how exceeding the threshold values will disturb the stability of natural environmental systems, which will be continued with progressing climate warming.

CONCLUSIONS

The study results show a substantial increase in the water temperature of Polish lakes. Such a situation may well be expected to continue over the next several decades, resulting in a considerable transformation of the thermal regime of lakes in the study area. It is difficult to determine which of the assumed RCP scenarios is most credible, as it will largely depend on the global strategy applied for the reduction of greenhouse gas emission. Each of the adopted scenarios assumes an increase in lake water temperature. The most optimistic of them all, namely RCP 2.6, shows a discontinuation of the process in the second half of the 21st century, and even a decrease in value. However, the observation of a dynamically changing geopolitical world, not to mention the ever-expanding if not competing economic aspirations of various countries, does not seem to confirm the credibility of this variant. In an extreme prognosis, in approximately 80 years, the mean annual water temperature in Polish lakes will be higher by more than 4°C according to the assumption of the 'business as usual' scenario (RCP 8.5). The diagnosed increasing tendency of LSWT in this part of Europe accords with similar research conducted in different parts of the world. A good fitting of the modelled water temperature to historical data suggests that the values of projected changes in temperature are highly credible and dependent on economic scenarios. This fact alone provides a theoretical basis for further research in many disciplines such as hydrology, ecology, water management, among others. In the case of Poland, issues related to low water resources per capita are particularly important. Studies concerning changes in water resources accumulated in lakes have shown that the natural factor playing the most critical role in their reduction was the rise in temperature. Currently, observed changes in the artificially heated Konińskie Lakes suggest that the response of the thermal regime has many aspects, and particular components of the lakes' ecosystems remain in close mutual relationships, while evidently responding to changes in the others. And so, within the context of theoretical investigation into the effects of lake-water warming irrespective of the discipline, research can and should constitute the basis for activities that can possibly accelerate the development of concepts for mitigating the effects of climate changes.

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