An investigation of water level fluctuations in Polish lakes in various phases of the winter North Atlantic Oscillation

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Received: 25.01.2017; accepted: 19.06.2017

Abstract: The North Atlantic Oscillation is a macroscale type of circulation determining climate and hydrological conditions in Europe. The paper presents water level fluctuations in 19 Polish lakes in various phases of NAO of the winter season in the years 1976–2010. Correlations of the winter NAO index with monthly, seasonal, maximum, and minimum water stages, and annual water level amplitudes in lakes were calculated. Approximately 20% of the performed tests showed statistical significance. Lakes were recorded where the correlations were significant in a major part of the year, as well as lakes showing no significant correlations in any month. Deviations of mean water stages in the positive and negative phase of NAO from mean water stages were calculated for each of the lakes. This permitted classifying the lakes into two groups by Ward's method based on deviations of water stages in the positive and negative phase of NAO_{DJFM} from average values. This resulted in the designation of 4 and 5 typological classes of lakes, respectively. Deviations of water stages in lakes in various phases of NAO_{DJFM} from mean values were determined to even exceed 20 cm. The study results can find practical applications in reference to water retention. In view of the observed environmental changes, it is possible that the hydrotechnical infrastructure on lakes will have to be developed in the future. Such a situation will permit the precise control of water level fluctuations for the purpose of the optimal adaptation of lakes for economic purposes.

Keywords: water stages, teleconnection, NAO, lakes, Poland

INTRODUCTION

The North Atlantic Oscillation (NAO) is the primary type of macroscale atmospheric circulation determining weather conditions in the north Atlantic sector. NAO is a bipolar type of atmospheric circulation, with centres over Iceland and the Azores. In Central Europe, the effect of NAO circulation is the most evident in the case of the course of climatic processes, and as a consequence also hydrological processes in the winter season (December-March). The period is associated with winter NAO index (NAO_{DJFM}) (Wrzesiński 2011). Considering climatic processes, air temperature and precipitation fluctuations should be determined (Scaife et al. 2008, Bednorz 2011, Heape et al. 2013, Labudová et al. 2013). In terms of hydrological processes, the effect of NAO was confirmed in reference to river outflows (Trigo et al. 2004, Pociask- Karteczka et al. 2003, Pociask-Karteczka 2006, Pekarova & Pekar 2007), groundwater runoff (Olichwer & Tarka 2015), the thermal regime of lakes (Livingstone & Dokulil 2001, Trusewicz et al. 2009, Girjatowicz 2011, Wrzesiński et. al 2015a), and the ice regime of lakes (Girjatowicz 2003, Bai et al., 2012, Dokulil 2014, Wrzesiński et al. 2015b). This paper constitutes a continuation of research on the effect of NAO_{DJFM} on the functioning of lake

http://dx.doi.org/10.7494/geol.2017.43.2.151 ISSN 2299-8004 | e-ISSN 2353-0790 | Wydawnictwa AGH

ecosystems in this part of Europe. In spite of the determination of certain patterns, it has not been completely investigated to date.

The objective of the paper is to determine water level fluctuations in Polish lakes during various NAO_{DJFM} phases. The paper aims at the determination of deviations from the mean values of water stages in particular NAO_{DJFM} phases, their statistical significance, and patterns in their spatial distribution.

It is difficult to identify the hierarchy of the importance of processes and phenomena occurring in lakes. Those related to water level fluctuations seem to be among the most important and, in certain cases, they may cause the disappearance of an entire lake. Processes responsible for water level fluctuations are of a natural (precipitation, evaporation) and artificial character (water intake, melioration works). Analysing the water level fluctuations of the Dojran Lake, Bonacci et al. (2015) concluded that it is not easy to determine which natural or anthropogenic factors determine such fluctuations. This conclusion is of a very universal character in a period of considerable transformation in the natural environment. The functioning of lakes is affected by natural processes determined by local (e.g. orography) and macroscale factors (e.g. NAO). Anthropogenic changes can be expansive and dynamic. Various examples (Micklin 1988, Ptak et al. 2013) show that the artificial regulation of water relations in a relatively short time may lead to a complete change in the water balance of a lake. Apart from extreme situations, water level fluctuations and therefore changes in the surface area of a lake and volume of retained water are key for a number of physical-chemical (Håkanson et al. 2000, Jeppesen et al. 2015), biological (Pęczuła & Szczurowska 2013, Stefanidis & Papastergiadou 2013, Weiperth et al. 2014), and economic processes (Crase & Gillespie 2008, Dinka 2012).

As a result, any enrichment of knowledge on issues related to water level fluctuations in lakes should be considered valuable – considering elements of macroscale atmospheric circulation, then modified by the local and individual factors of lakes.

MATERIALS AND METHODS

The area of north-east Central Europe is distinguished by a high number of lakes (Heine et al. 2015). According to Choiński (2006), the territory of Poland includes more than 7,000 natural lakes with an area of 1 ha or more. They are mainly located in the northern part of Poland, a fact related to the last glaciation.

This paper is based on the daily water stages of 19 lakes from the period 1976–2010 (Fig. 1) from the collection of the Institute of Meteorology and Water Management-PIB. The data were presented in accordance with the course of the hydrological year, beginning on 1 November, and ending on 31 October of the following year. The basic parameters of the lakes analyzed in the paper are presented in Table 1.

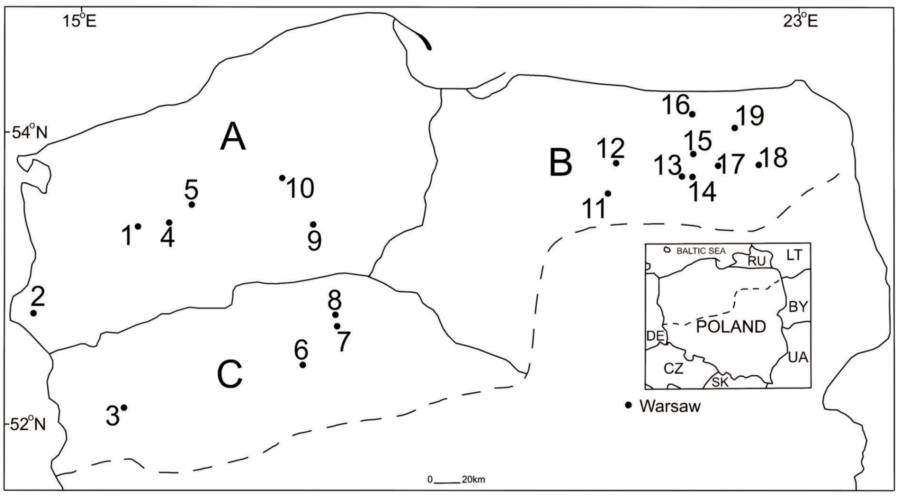

Fig. 1. *Location of the analysed lakes (numeration in accordance with Table 1). The dotted line designates the range of the last glaciations: A – Pomorskie Lakeland, B – Mazurskie Lakeland, C – Wielkopolsko-Kujawskie Lakeland*

Table 1
Morphometric data of the studied lakes

No.	Lake	Area [ha]	Volume [thous m^3]	Average depth [m]
1	Ińsko	529.0	65,182.0	11.0
2	Morzycko	317.5	49,826.9	14.5
3	Niesłysz	526.0	34,457.6	6.9
4	Lubie	1,487.5	169,880.5	11.6
5	Drawsko	1,797.5	331,443.4	17.7
6	Lednica	325.0	24,397.0	7.0
7	Biskupińskie	107.0	6,397,2	5.5
8	Żnińskie Duże	420.5	29,492.6	6.8
9	Sępoleńskie	157.5	7,501.6	4.8
10	Szczytno Wielkie	565.0	51,762.5	8.0
11	Kalwa	561.0	39,468.6	7.0
12	Dadaj	978.0	120,784.2	12.0
13	Mikołajskie	424.0	55,739.7	11.2
14	Śniardwy	1,1487.5	660,211.8	5.8
15	Jagodne	872.5	82,705.2	8.7
16	Mamry	9,851.0	1,003,367.5	9.8
17	Orzysz	1,012.5	75,326.2	6.6
18	Selmęt Wielki	1,207.5	99,463.9	7.8
19	Litygajno	154.5	9,763.9	6.0

For the purpose of the determination of the dependence of water stages in lakes on the intensity of the North Atlantic Oscillation, Pearson's coefficients of linear correlation were calculated between standardised monthly, seasonal, and annual mean water stages and maximum and minimum water stages, as well as annual amplitudes and seasonal NAO indices from the period from December to March. These were retrieved from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based).

Changes in monthly and seasonal water stages in the analysed lakes in various NAO_{DJFM} phases were determined based on differences in the parameters of positive and negative NAO_{DJFM} phase in reference to mean values from the years 1976–2010. Mean values of water stage parameters were calculated for years with high ($NAO_{DJFM} > 2.67$, eight times in the analysed multiannual) and low ($NAO_{DJFM} < -0.41$, eight times in the analysed multiannual) values of winter NAO index. The figures correspond to the first and third quartile from the entire set of NAO index in the years 1976–2010. The statistical significance of the differences was determined by means of a T test for the correlated samples. Each time, the hypothesis $H_0{:}\mu = \mu_0$ was tested with equal expected values, against $H_1{:}\mu \neq \mu_0$. The rejection of the hypothesis permits conclusions to be drawn on the considerable differences between the mean water stages observed in various NAO_{DJFM} phases and their mean values from the years 1976–2010. For the purpose of the verification of the hypothesis, a test for a small sample was applied based on t-Student distribution at n-1 degrees of freedom:

$$t = \left| \frac{\bar{x} - \mu_0}{s} \sqrt{n} \right| \tag{1}$$

where:
n – sample size,
s – standard deviation,
$\bar{x}$ – mean from sample,
μ_0 – mean from population.

Finally, a classification of the studied lakes was performed from the point of view of the differences in monthly water stages in the period with high and low NAO_{DJFM} indices from the values of mean water stages from the years 1976–2010. The classification procedure employed Ward's method of hierarchical grouping. The results of the grouping were presented graphically in the form of a dendrogram, reflecting the structure of the similarity of a given group of lakes, and used for the designation of typological classes. In the paper, the number of classes was determined based on a pattern, i.e. dendrogram geometry and bond distance curve. The mathematical-statistical processing of analysis results involved the application of statistical procedures included in programmes: Excel (Microsoft) and Statistica (StatSoft). The preparation of the graphic representation involved the application of programmes: 10 (Golden Software) and CorelDraw 12 (Corel). The kriging procedure was applied in the construction of isoline maps.

RESULTS

Coefficients of correlation of water stages with NAO_{DJFM} index are listed in Table 2.

Table 2
Coefficients of correlation of water stages in the analysed lakes with NAO index

Lake	Month												Year	Min	Max	Am-pli-tude	Season			
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct					Spr	Sum	Aut	Win
Biskupińskie	−0.3	−0.3	−0.13	−0.15	−0.25	*−0.33*	*−0.37*	*−0.34*	−0.2	−0.28	−0.32	−0.29	−0.28	no data	no data	no data	−0.33	−0.28	*−0.34*	−0.14
Dadaj	−0.08	0.038	*0.414*	***0.57***	***0.479***	0.157	−0.05	−0.29	−0.3	*−0.41*	*−0.36*	−0.26	0.107	−0.13	0.094	0.152	0.263	*−0.37*	−0.27	*0.428*
Drawsko	−0.03	0.012	0.239	*0.395*	0.307	0.227	0.058	−0.05	−0.05	−0.22	−0.23	−0.13	0.116	−0.09	0.199	0.284	0.212	−0.11	−0.15	0.266
Ińsko	0.118	0.106	0.278	*0.346*	*0.347*	0.287	0.173	0.081	0.097	0.043	0.011	0.017	0.208	0.049	0.272	0.273	0.286	0.076	0.033	0.278
Jagodne	−0.19	−0.13	0.204	0.316	0.337	0.139	−0.14	−0.29	−0.25	−0.29	−0.25	−0.23	0.01	0.038	−0.09	−0.13	0.131	−0.3	−0.24	0.21
Kalwa	−0.23	−0.17	*0.423*	***0.497***	***0.455***	0.277	0.007	−0.3	−0.32	***−0.44***	*−0.42*	−0.33	0.03	−0.21	0.198	*0.362*	0.285	*−0.39*	*−0.35*	*0.423*
Lednica	***−0.45***	***−0.44***	−0.18	−0.11	−0.17	−0.27	*−0.34*	*−0.39*	*−0.38*	***−0.45***	***−0.48***	***−0.49***	*−0.34*	*−0.38*	*−0.34*	−0.12	−0.26	*−0.42*	***−0.49***	−0.18
Litygajno	−0.17	−0.05	*0.407*	***0.515***	*0.412*	−0.07	−0.32	−0.31	−0.17	−0.21	−0.27	−0.28	0.01	0.061	−0.06	−0.11	0.1	−0.25	−0.27	*0.361*
Lubie	−0.26	−0.2	0.228	0.3	0.196	0.047	−0.11	0.005	0.064	−0.23	*−0.37*	−0.38	−0.04	−0.21	0.027	0.16	0.062	−0.06	*−0.38*	0.179
Mamry	−0.21	−0.13	0.217	0.306	0.289	0.058	−0.21	*−0.35*	−0.31	*−0.36*	−0.32	−0.28	−0.07	−0.01	−0.1	−0.1	0.059	*−0.36*	−0.29	0.211
Mikołajskie	−0.17	−0.09	0.104	0.189	0.202	0.033	−0.18	−0.29	−0.24	−0.29	−0.24	−0.23	−0.07	0.008	−0.2	−0.22	0.025	−0.29	−0.23	0.12
Morzycko	−0.15	−0.12	−0.19	−0.11	−0.18	−0.23	−0.28	−0.31	−0.27	*−0.38*	*−0.4*	−0.33	−0.33	*−0.38*	−0.21	0.187	−0.24	*−0.34*	*−0.35*	−0.2
Niesłysz	*−0.4*	*−0.34*	−0.03	0.034	−0.02	−0.24	−0.22	−0.22	−0.27	*−0.35*	*−0.41*	***−0.44***	−0.29	*−0.38*	−0.05	*0.378*	−0.17	−0.3	*−0.43*	−0.05
Orzysz	−0.01	0.103	*0.403*	***0.564***	***0.497***	0.034	−0.19	−0.23	−0.13	−0.2	−0.19	−0.16	0.095	0.169	0.018	−0.11	0.148	−0.2	−0.16	*0.396*
Selmęt Wielki	−0.06	0.007	0.322	*0.436*	***0.455***	−0.03	−0.28	−0.27	−0.06	−0.27	−0.15	−0.2	0.036	0.083	−0.07	−0.1	0.192	−0.22	−0.16	0.286
Sępoleńskie	−0.28	−0.26	−0.15	−0.03	−0.24	***−0.54***	***−0.58***	*−0.34*	−0.3	*−0.38*	−0.3	−0.31	*−0.38*	−0.21	−0.31	−0.14	***−0.5***	*−0.36*	−0.3	−0.12
Szczytno Wielkie	0.013	0.065	0.311	*0.352*	*0.396*	0.195	0.095	0.268	0.247	0.223	0.18	0.077	0.281	0.337	0.177	0.055	0.27	0.258	0.067	0.309
Śniardwy	−0.18	−0.12	0.091	0.178	0.193	0.005	−0.2	−0.31	−0.27	−0.32	−0.27	−0.25	−0.09	0.026	−0.22	−0.26	0.003	−0.32	−0.26	0.106
Żnińskie Duże	−0.3	−0.24	0.05	0.025	−0.09	***−0.47***	***−0.56***	***−0.52***	*−0.36*	*−0.42*	*−0.39*	*−0.37*	*−0.43*	***−0.55***	−0.28	0.178	*−0.39*	***−0.46***	*−0.39*	0.002

italic – $p < 0.05$ significance level; ***italic bold*** – $p < 0.01$ significance level; ***italic bold underlining*** – $p < 0.001$ significance level.

The coefficients of correlation of winter NAO_{DJFM} index with monthly and seasonal water stages in the analysed lakes show both temporal and spatial variability. The analysis of the above table shows that statistically significant correlations were revealed by 82 out of 377 performed tests (approximately 20%). Lakes were recorded where the correlations were significant over a major part of the year (e.g. Lake Żnińskie Duże, Lednica), as well as lakes showing no significant correlations in any month (e.g. Lake Śniardwy). The strongest positive coefficients of correlation for the majority of lakes were obtained for water stages in winter months, and weaker for the spring months and spring season. In the period from January to March, the most statistically significant correlations ($p < 0.01$) concern Mazurian lakes (Dadaj, Kalwa, Litygajno, Orzysz, and Selmęt Wielki). Only water stages in five lakes in these months show negative, although statistically non-significant correlations. All of the lakes are located in the southern part of the lakeland belt. They represent the Wielkopolsko-Kujawskie Lakeland (Biskupińskie, Lednica, Niesłysz) and the southern part of the Pomorskie Province (Sępoleńskie, Morzycko). From May, an evident change occurs in the analysed correlations between variables. At that time, water stages in the majority of lakes show negative correlations, but there are not statistically significant correlations with winter NAO index. The strongest negative coefficients of correlation, frequently at a level of $p < 0.01$, distinguish water stages in lakes from April to June (Biskupińskie, Żnińskie, Sępoleńskie), and in months from August to October (Kalwa, Lednica, Niesłysz). A similar situation concerns correlations with seasonal water stages. The majority of lakes show positive coefficients of correlation with water stages in winter and spring, and negative in summer and autumn. Correlations of winter NAO index with the mean maximum and minimum water stages are usually statistically non-significant. In the case of the lakes of the Wielkopolsko-Kujawskie Lakeland, they are usually negative, and in the case of several lakes statistically significant – see Table 2. Also, in the case of extreme amplitudes, both positive and negative coefficients of correlation with NAO_{DJFM} were obtained. Only the amplitudes of Lake Kalwa and Niesłysz are positively and statistically significantly correlated ($p < 0.05$) with winter NAO index.

The determined temporal and spatial variability of the strength of correlations of water stages in Polish lakes with a winter NAO index make the issue of how water stages and their fluctuations develop in the annual cycle in various NAO_{DJFM} phases an interesting one.

The effect of the intensity of the North Atlantic Oscillation (NAO_{DJFM}) on water level fluctuations in Polish lakes shows spatial variability, both in terms of the direction of such changes, and the term of their occurrence (Fig. 2). In the negative NAO_{DJFM} phase in winter months, water stages lower than average are observed in the majority of lakes. In the Mazurian lakes, water stages are usually lower by 10 cm. and in February by even 15–20 cm. In the case of these lakes, the observed differences in water stages are also the most statistically significant ($p < 0.01$). Water stages in the lakes of the Pomorskie Lakeland are also lower, although usually by 5–10 cm, and the differences are significant at a level of $p < 0.05$. Water stages in the lakes of the Wielkopolsko-Kujawskie Lakeland develop in a different way. In years with a low NAO index, water stages in the lakes are not statistically significantly different to those observed in average conditions, and the recorded differences reach up to 5 cm. In the positive NAO_{DJFM} phase, differences in water stages in the majority of lakes are statistically non-significant. In the winter season, the water stages in the lakes of the Pomorskie and Mazurskie Lakelands are slightly higher than average, by approximately 5 cm. Higher differences are observed in the lakes of the Wielkopolsko-Kujawskie Lakeland. There, water stages lower than average by 5–10 cm are recorded (only in the case of Lake Lednica by approximately 20 cm), but the differences are also statistically non-significant.

In the spring season in years with a low NAO index, water stages in lakes of the Wielkopolsko-Kujawskie Lakeland are higher than average, and water stages in lakes of the Mazurskie and Pomorskie Lakelands are slightly lower by approximately 5 cm (Fig. 2).

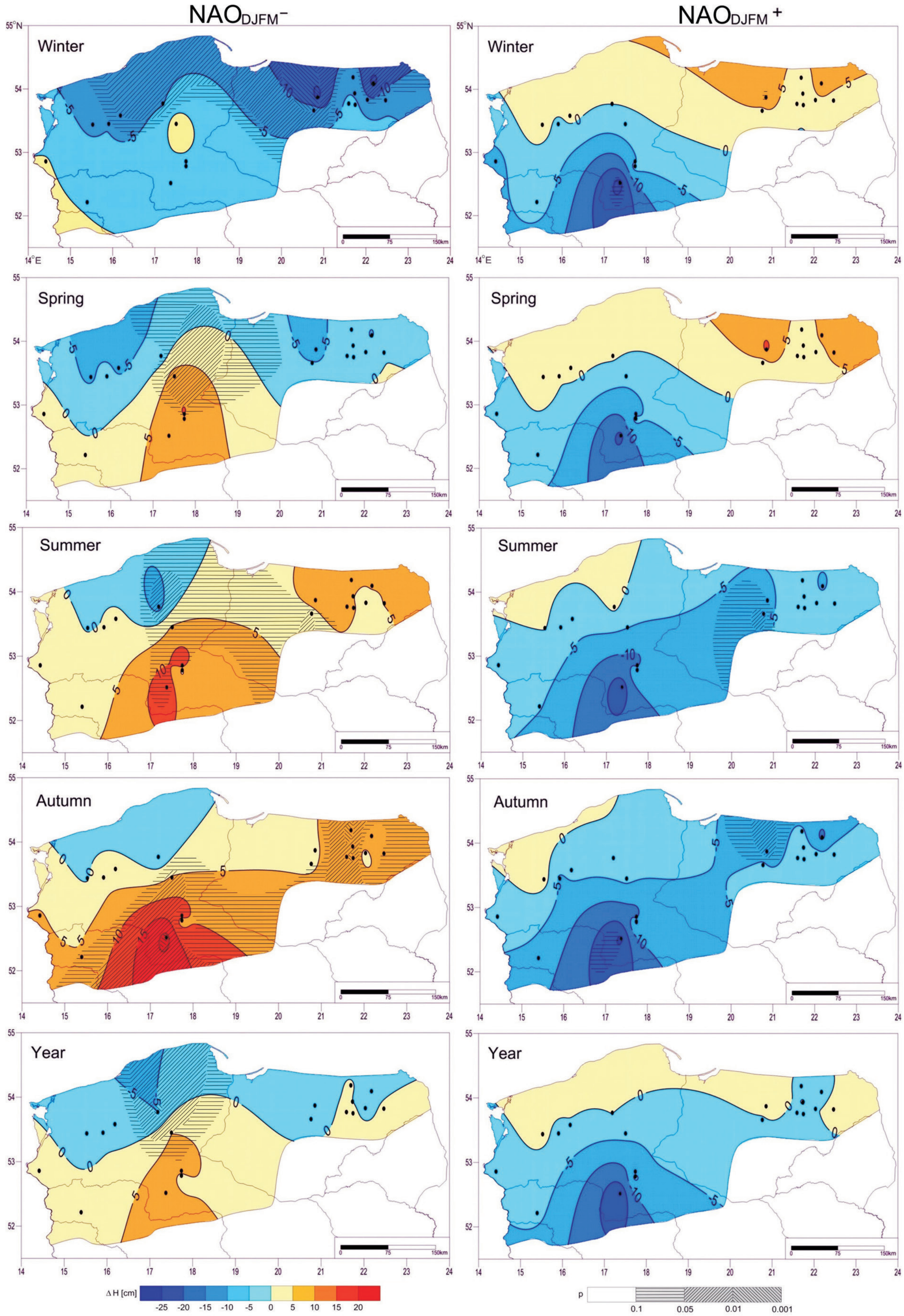

***Fig. 2.** Differences in water stages in lakes in different NAO_{DJFM} phases in comparison to average values (ΔH), and their statistical significance (p)*

Only in the case of Lake Sępoleńskie are water stages lower by 5–10 cm, and the observed differences are statistically significant ($p < 0.05$). Opposite correlations are observed in years with high values in terms of NAO index. Water stages higher by up to 5 cm are observed in the Pomorskie and Mazurskie Lakeland, and lower by up to approximately 10 cm, in the lakes of the Wielkopolsko-Kujawskie Lakeland. The differences, however, are statistically non-significant.

In summer months, the situation changes in the case of Mazurian lakes. Water stages in the lakes, similarly as those in lakes of the Wielkopolsko-Kujawskie Lakeland, are higher in the negative NAO_{DJFM} phase by 5–10 cm than on average, although the differences are usually not statistically significant. A part of lakes of the Pomorskie Lakeland (Ińsko, Szczytno Wielkie) are distinguished in this NAO phase by water stages which are lower than average, and the recorded differences in the case of Lake Szczytno are statistically significant ($p < 0.05$). In the positive NAO_{DJFM} phase, the direction of water level fluctuations in lakes is the opposite. Then, the majority of lakes show water stages lower than average, usually by approximately 5 cm. Only in Lake Lednica and Żnińskie are they lower by more than 10–15 cm. Lakes Ińsko and Szczytno stand out again with their water stages slightly higher (up to 5 cm) than average. No statistically significant differences were observed in any of the cases.

In autumn, the direction of water level fluctuations in lakes is similar to those observed in the summer season. In the negative NAO_{DJFM} phase, higher water stages are observed in the majority of lakes. The highest differences concern water stages in the lakes of the Wielkopolsko-Kujawskie Lakeland. Water stages are locally higher by more than 10 cm (Żnińskie), and even 20 cm (Lednica) than average, and the differences are statistically significant ($p < 0.05$). In years with low NAO indices in the autumn season, water stages in the majority of lakes are lower than average, in the Mazurskie Lakeland by 5–10 cm, and in the Wielkopolsko-Kujawskie Lakeland even by more than 20 cm (Lednica). The lowest fluctuations concern water stages in the lakes of the Pomorskie Lakeland – up to 5 cm.

A TYPOLOGICAL CLASSIFICATION OF LAKES

As a result of grouping of lakes due to standardised differences in monthly water stages in years with low NAO indices from average values from 1976–2010, a division into five groups of lakes was obtained. Their location is quite characteristic (Fig. 3).

The first group is represented by four lakes in the Mazurskie Lakeland (Śniardwy, Mikołajskie, Mamry i Jagodne). They are located within the region of the so-called Great Mazurian Lakes, and represent the same type of water level regime. Also the response of the lakes to changes in the intensity of NAO_{DJFM} is almost identical. In the negative NAO_{DJFM} phase in the winter half-year (from November to April), water stages in the lakes are on average lower by up to 10 cm, and in the period from May to October, higher than average. The most statistically significant differences ($p < 0.05$) are observed in the lakes in September and October (Fig. 4).

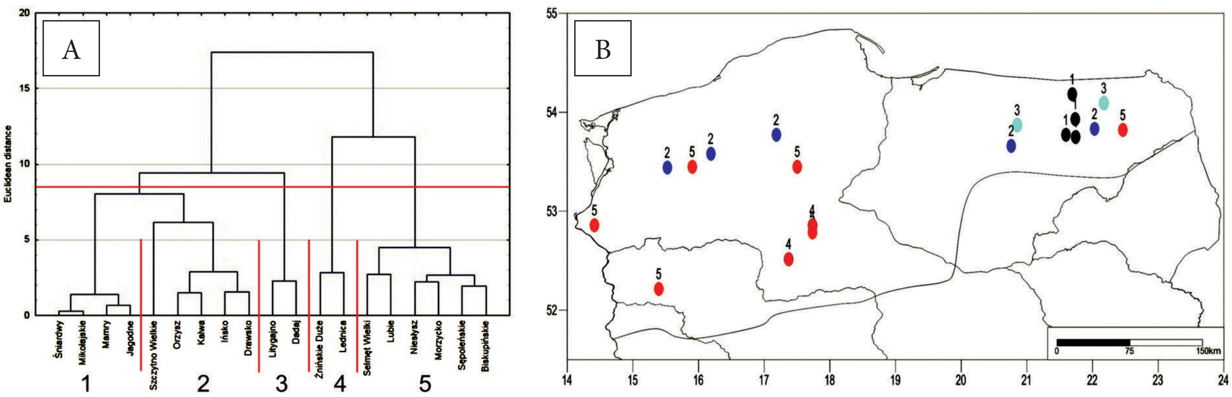

Fig. 3. Dendrogram of grouping of lakes due to differences in water stages in the negative NAO phases from average values (A), and location of the designated groups of lakes (B)

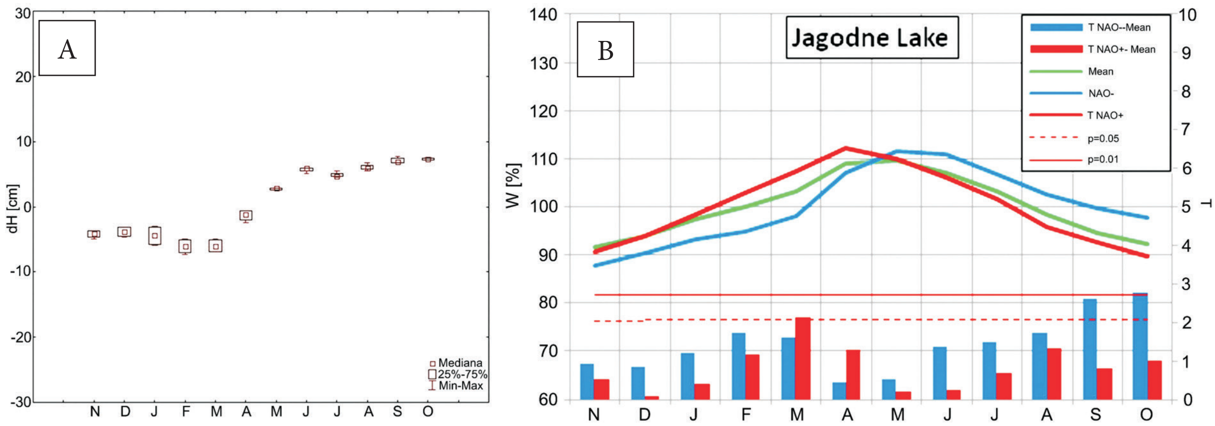

Fig. 4. *The range of the variability of water level fluctuations in the negative NAO phase from the average values for lakes in group I (A), and monthly coefficients of water stages and test of significance of differences (T) – based on the example of Lake Jagodne (B)*

Group 2 is represented by both the lakes of the Pomorskie Lakeland (Ińsko, Drawsko, Szczytno), and Mazurskie Lakeland (Orzysz, Kalwa). The lakes of the group are characterised by similar water level fluctuations to those in group I. In the summer-autumn months, water level deviations from average values are inconsiderable, and in February and March they are slightly higher than in the case of lakes from group I. They differ from the previous group in water stages in winter months (January-February) and March, lower by approximately 10 cm (Fig. 5). The differences from average values observed during that time are statistically significant ($p < 0.05$). In those months, even higher water level fluctuations are observed in lakes from group 3. They include two lakes in the Mazurskie Lakeland (Litygajno i Dadaj). Differences in water levels in the negative $\mathrm{NAO_{DJFM}}$ phase from average values amount to more than 20 cm, and are very statistically significant ($p < 0.01$) (Fig. 6).

A different character of water level fluctuations is represented by lakes from group 4 (Lednica i Żnińskie) in the Wielkopolsko-Kujawskie Lakeland. In the winter months (January-February), their water stages are slightly lower than average values, and from April to October they are considerably higher. The differences vary from 15 to more than 20 cm, and in the period from August to October they are statistically significant ($p < 0.01$) (Fig 7).

Similar responses are observed in the case of lakes from group 5. They include the remaining lakes of the Wielkopolsko-Kujawskie Lakeland (Biskupińskie, Niesłysz), three lakes in the Pomorskie Lakeland (Lubie, Sępoleńskie, Morzycko), and Lake Selmęt Wielki in the Mazurskie Lakeland. Their water stages show the lowest fluctuations in the negative $\mathrm{NAO_{DJFM}}$ phase in comparison to average values among all of the lakes. Their water stages are usually higher in all months with the exception of January, February, and March, although the observed differences are not statistically significant (Fig. 8).

The second typological classification of lakes was performed based on standardised differences in water stages in the positive $\mathrm{NAO_{DJFM}}$ phase from average values from the years 1976–2010. Four groups of lakes were designated (Fig. 9).

The lakes from groups 1 and 4 are typically the lakes of the Wielkopolsko-Kujawskie Lakeland. Water stages in the lakes in all months in a year in the positive $\mathrm{NAO_{DJFM}}$ phase are lower than average. In the case of lakes from group 1 (Lednica, Żnińskie), however, the observed differences are considerably higher, reaching even 20 cm, and in Lake Lednica in December and January statistically significant ($p < 0.05$) (Fig. 10). In the case of lakes from group 4, the differences are inconsiderable, of up to 5 cm, and statistically non-significant. The majority of lakes of the Pomorskie and Mazurskie Lakelands represent groups 2 and 3. They show a similar direction of water level fluctuations. In the positive $\mathrm{NAO_{DJFM}}$ phase, water stages in the lakes are higher from January to May, and in the remaining months lower than average.

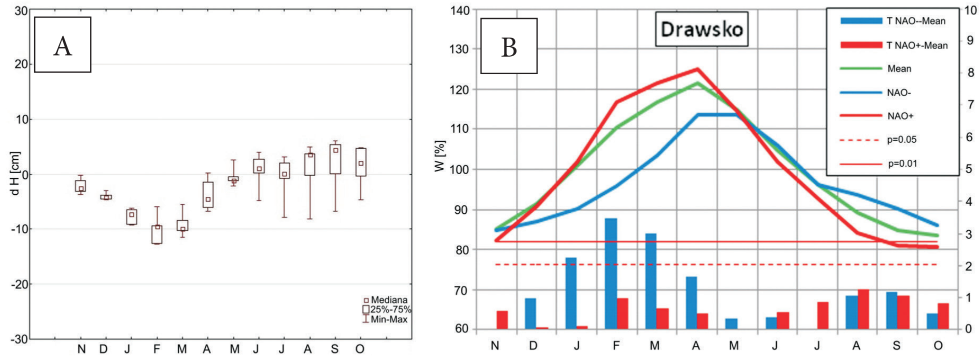

Fig. 5. *Range of variability of water level fluctuations in the negative NAO phase from the average values for lakes in group II (A), and monthly coefficients of water stages and test of significance of differences (T) – based on the example of Lake Drawsko (B)*

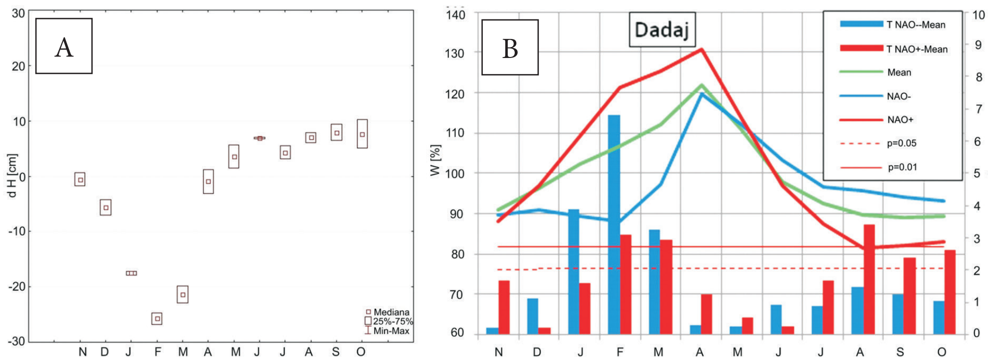

Fig. 6. *Range of variability of water level fluctuations in the negative NAO phase from the average values for lakes in group III (A), and monthly coefficients of water stages and test of significance of differences (T) – based on the example of Lake Dadaj (B)*

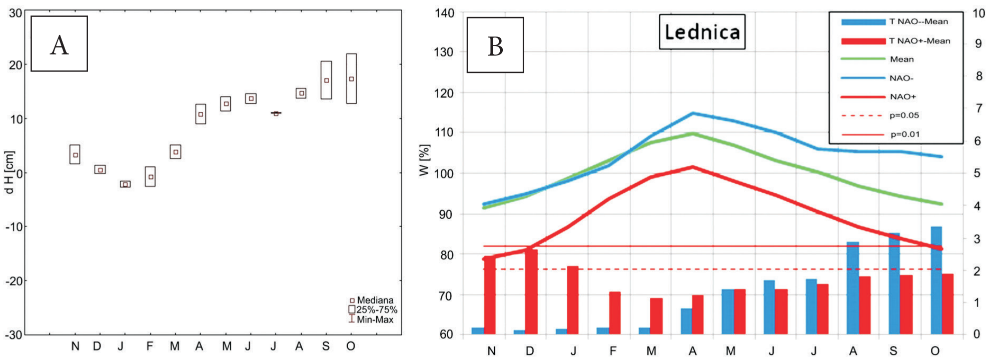

Fig. 7. *Range of variability of water level fluctuations in the negative NAO phase from the average values for lakes in group IV (A), and monthly coefficients of water stages and test of significance of differences (T) – based on the example of Lake Lednica (B)*

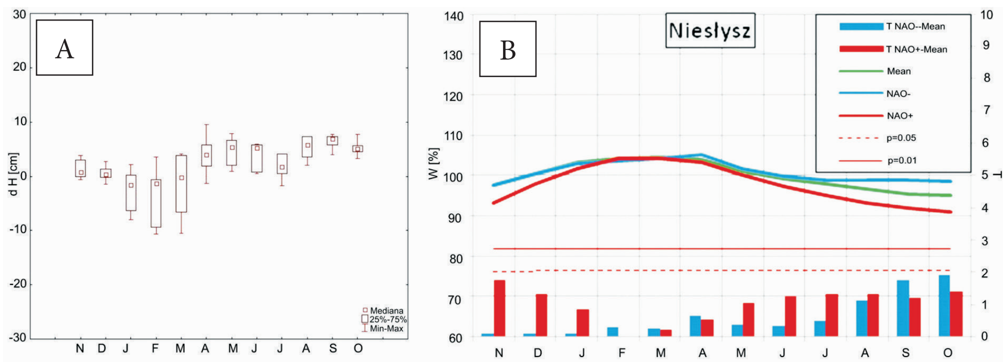

Fig. 8. *Range of variability of water level fluctuations in the negative NAO phase from the average values for lakes in group V (A), and monthly coefficients of water stages and test of significance of differences (T) – based on the example of Lake Niesłysz (B)*

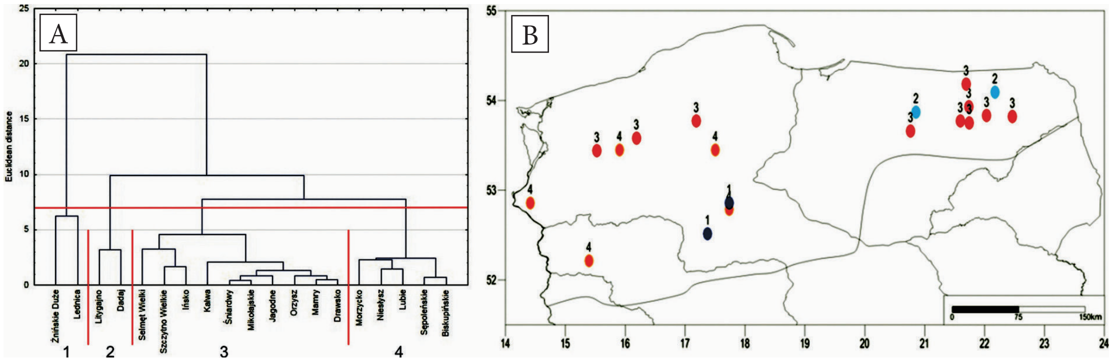

Fig. 9. *Dendrogram of the grouping of lakes due to differences in water stages in the positive phase* NAO_{DJFM} *from average values (A), and location of the designated groups of lakes (B)*

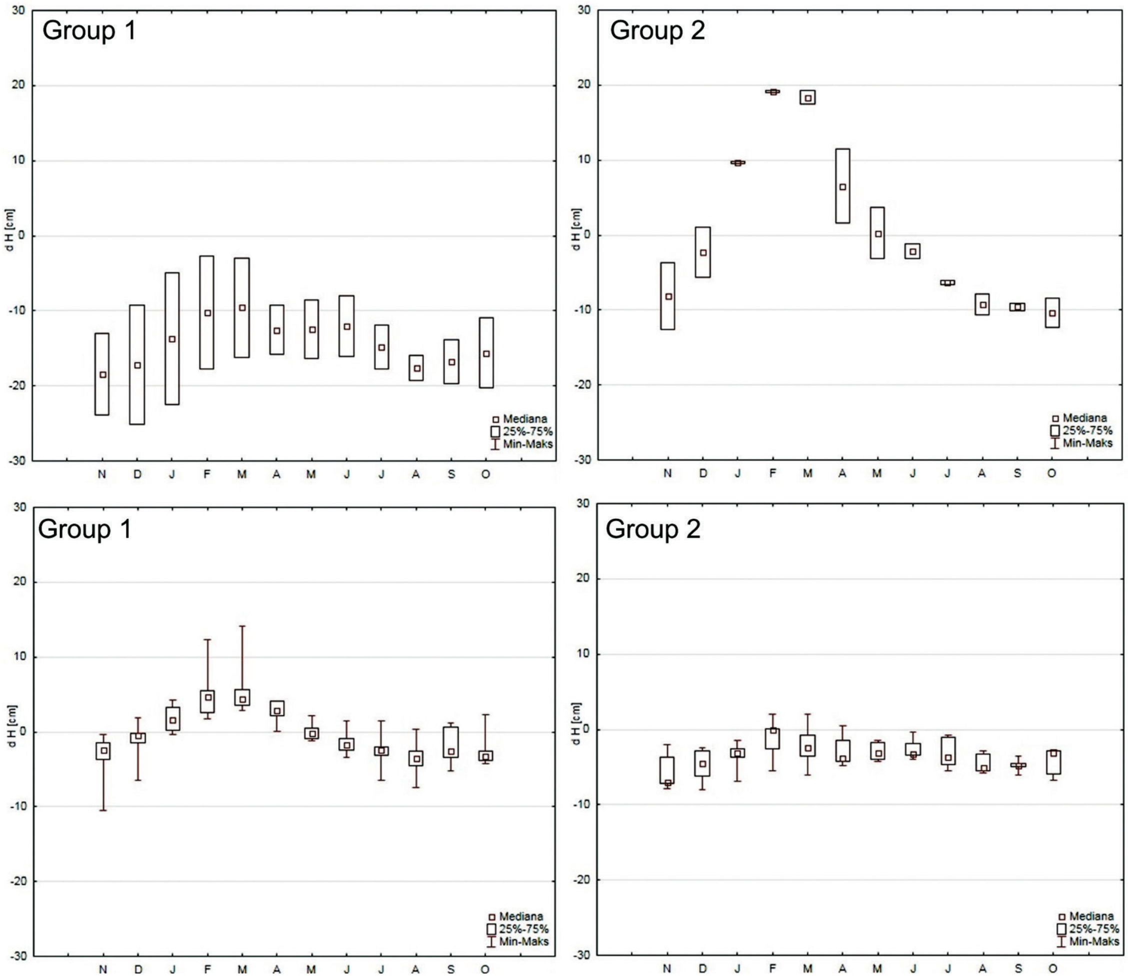

Fig. 10. *Range of variability of differences in water stages in the positive* NAO_{DJFM} *phase from average values in the designated groups of lakes*

A considerably higher deviation from average values is observed in the case of water stages in lakes from group 2 (Litygajno, Dadaj). In February and March, their water stages are approximately 20 cm higher in the positive NAO_{DJFM} phase, and the differences are statistically significant ($p < 0.05$) (Fig. 10). In the case of Lake Dadaj, a statistically significant, but negative deviation from average values is also recorded from August to October. The lakes from group 3 in the positive NAO_{DJFM} phase show no high statistically significant differences in water stages from average values.

DISCUSSION

The issue of the effect of macroscale atmospheric circulation on water levels in lakes is discussed by a number of authors, and depending on the region of the world and type of dominant circulation, it shows varied correlations (Rodinov 1994, LaValle et al. 2000, Jöhnk et al. 2004, Soja et al. 2013, Biron et al. 2014, Jalili et al. 2016), generally associated with air temperature and precipitation fluctuations. Analysing water level fluctuations in selected lakes in the Mazurskie Lakeland in Poland. Górniak & Piekarski (2002) determined that they depend on the amount of precipitation which is in turn determined by the NAO index. Analysing the effect of winter NAO on water stages in Lake Võrtsjärv (Estonia), Nõges et al. (2010) determined that in the positive phase, it is distinguished by higher water stages. This is related to changes in precipitation, air temperature, and term and intensity of snowmelt.

The study results show that the effect of NAO_{DJFM} on water stages in lakes throughout the annual cycle is not uniform, either in reference to particular lakes or selected months. Deviations of water stages from average values in particular NAO phases are varied, and in selected cases considerable – exceeding 20 cm. The response of water stages in Polish lakes to the effect of NAO_{DJFM} is not uniform. Water stages both lower and higher in comparison to average values in the same phases are recorded. Such a situation generally results from the location of lakes in different climatic regions. Within the same regions, however, responses of particular lakes to changes in NAO intensity can differ due to the direct human effect on water stages in lakes, or individual regime parameters resulting from the morphometric properties of the lakes themselves and the lake catchment. Such a situation occurs e.g. in the case of lakes: Lednica, Żnińskie Duże, and Biskupińskie. The regimes of two former ones are characterised by evident periods of spring floods and periods of low water stages in summer and autumn. The water stages in Lake Biskupińskie in the annual cycle are very even. The lake is characterised by very low mean amplitude of annual stages (32 cm), obscuring the effect of NAO on water stages in the lake.

Analysing the effect of NAO on the water stages in seven lakes in Turkey. Küçük et al. (2009) also determined that the correlation is of varied character. In the case of Poland, among the analysed lakes, those located in the Wielkopolsko-Kujawskie Lakeland and in the southern part of the Pomorskie Lakeland are distinctive. They generally respond differently than the remaining lakes to the effect of macroscale atmospheric circulation. This is confirmed by the grouping of lakes due to standardised differences in monthly water stages in lakes, in both the negative and positive NAO_{DJFM} phase. In the case of the negative NAO phase, no evident deviations in water stages from average values are recorded. This may be surprising, particularly in the winter period. The negative NAO_{DJFM} phase in this part of Europe is characterised by inflow of cold and dry air. Therefore, as a result of lower precipitation and conditions favourable for longer water retention, lower water stages should be expected. Such a situation, however, is overcome by the climate conditions of particular regions. The difference in water stages in lakes in the cold season should be associated with winter snowmelts. According to Czarnecka & Nidzgorska (2013), the mean number of days with snowmelt in the period from December to February decreases eastwards, and the differences amount to several days. The highest frequency of snowmelts was recorded in the western and northwestern part of the country. Similarly to the case of lakes, a different effect of NAO_{DJFM} on discharge in rivers is observed in this part of Poland. Analysing river runoff in the region, Wrzesiński (2011) determined that in the negative NAO_{DJFM} phase, the rivers show higher water stages and runoff. Winter snowmelts result in higher water supply to lakes (due to frozen ground and no infiltration as well as low evaporation), as manifested as slight deviations from average values.

Detailed knowledge on the manner of response of particular elements of the hydrosphere – in this case a lake, to the effect of macroscale climate factors can be of an applicable character in the future. Unfortunately, the obtained results are ambiguous. Due to this, further research in the scope is required, particularly based on more uniform hydrometric material, for lakes with a quasi-natural regime of water stages.

CONCLUSIONS

The obtained results are in accordance with current studies concerning the effect of macroscale atmospheric circulation on water level fluctuations in lakes. Using detailed data, the paper supplements information concerning the phenomenon for lakes in this part of Europe, based not on a single case, but on a larger group of objects. The obtained study results show that the effect of North Atlantic Oscillation was limited to selected months and selected lakes. Moreover, differences were observed in the response of water stages to the effect of NAO in spite of relatively small distances between the analysed lakes. The observed correlations were particularly determined by their location in various regions with different climate. The considerable effect of regional factors is evidenced by the grouping of lakes by Ward's method performed in the paper. In the majority of cases, the designated groups include lakes from similar physicogeographic regions.

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