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Effect of North Atlantic Oscillation on the hydrological conditions of Lake Morskie Oko (Carphatian Mountains)

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Abstract. The paper presents the effect of North Atlantic Oscillation of macroscale atmospheric circulation (NAO) on the hydrological conditions of Lake Morskie Oko located at an altitude of 1392.8 m a.s.l. in the highest range of the Carpathians. The paper applied detailed hydrometric information from the years 1971-2010 concerning water level fluctuations, water temperature, terms of the commencement and end of ice phenomena and ice cover, as well as meteorological data concerning air temperature and atmospheric precipitation, and monthly and seasonal NAO indices. The performed analysis suggests that the majority of analysed hydrological characteristics of Lake Morskie Oko was not prone to variability of NAO intensity in its various phases. The situation results from the local conditions, particularly responsible for the course of processes and phenomena in Lake Morskie Oko, simultaneously obscuring the effect of macroscale factors.

Key words:
NAO,
high mountains lake,
hydrological conditions,
Poland

Introduction

In the period of strong human impact on the natural environment, transformations of water relations in protected areas and those with specific environmental conditions, such as high mountain regions, are becoming an interesting issue. Lakes existing in such areas constitute a specific group. They show no evident effects of large-scale human activity (agriculture, industry, etc.). According to Juśkiewicz et al. (2015), the anthropopressure is manifested in among others delivery of pollutants to surface waters, and then their accumulation in bottom sediments in lakes. Detailed investigations of the specificity of high mountain lakes is undertaken by various scientific disciplines (Choiński et al. 2015). The research concerns both the biological (Korbee et al. 2012; Kosolapova 2012; Degefu and Shagerl 2015) as well as physical-chemical and physical and chemical aspects (Tanaka and Tominaga 1994; Rodríguez-Rodríguez et al. 2004; Santolaria et al. 2015).

The functioning of lakes is a resultant of the impact of a complex group of factors showing strong mutual interactions. In general, the course of particular processes and phenomena particularly depends on factors with a global range, followed by regional factors and individual parameters of lakes. Among global factors, climatic conditions are influenced by among others macroscale types of atmospheric circulation. In Europe, North Atlantic Oscillation has the strongest impact on the climate (NAO). North Atlantic Oscillation is a bipolar type of atmosphere circulation with centres over Iceland and the Azores. Numerous studies show that depending on the NAO phase, pluvial and thermal conditions change, and changes may occur in the course of precipitation and air temperature (Bednorz 2002; Przybylak et al. 2003; Kejna et al. 2009; Tomczyk 2015; Tošić et al. 2016). The effect of NAO is reflected in the functioning of particular elements of the hydrosphere, including lakes (Maher et al. 2005; Spears and Jones 2010; Sizova et al. 2013).

Lake Morskie Oko is an exceptional object among all high mountain lakes in Poland in terms of hydrological research. It has the longest coherent sequence of observations permitting various analyses – including those regarding the effect of NAO on its functioning. The objective of the paper is the analysis of changes in hydrological processes (including water level fluctuations, thermal conditions, and ice conditions) depending on changes in the intensity of NAO. The assumed objective should provide the answer to whether and at what scale NAO determines the hydrological regime of the high mountain lake in this part of Europe.

Research object and data

The object of the study is high mountain Lake Morskie Oko (1,392.8 m a.s.l.) located in Poland in the Tatra Mountains (Fig. 1) – the highest range of the Carpathians. Its area amounts to 33.5 ha. Its volume equals 9,935.0 thousand m^3, and maximum depth 51.8 m. It is an ultraoligotrophic lake. The lake constitutes one of the greatest tourist attractions of the Tatra Mountains National Park where it is located.

The paper uses data of the Institute of Meteorology and Water Management - National Research Institute (IMGW-PIB) from the years 1971-2010. They include among others water temperature, water level fluctuations, and course of ice phenomena. Water temperature was subject to point measurements at a depth of 0.4 m. Water stages were read from a water

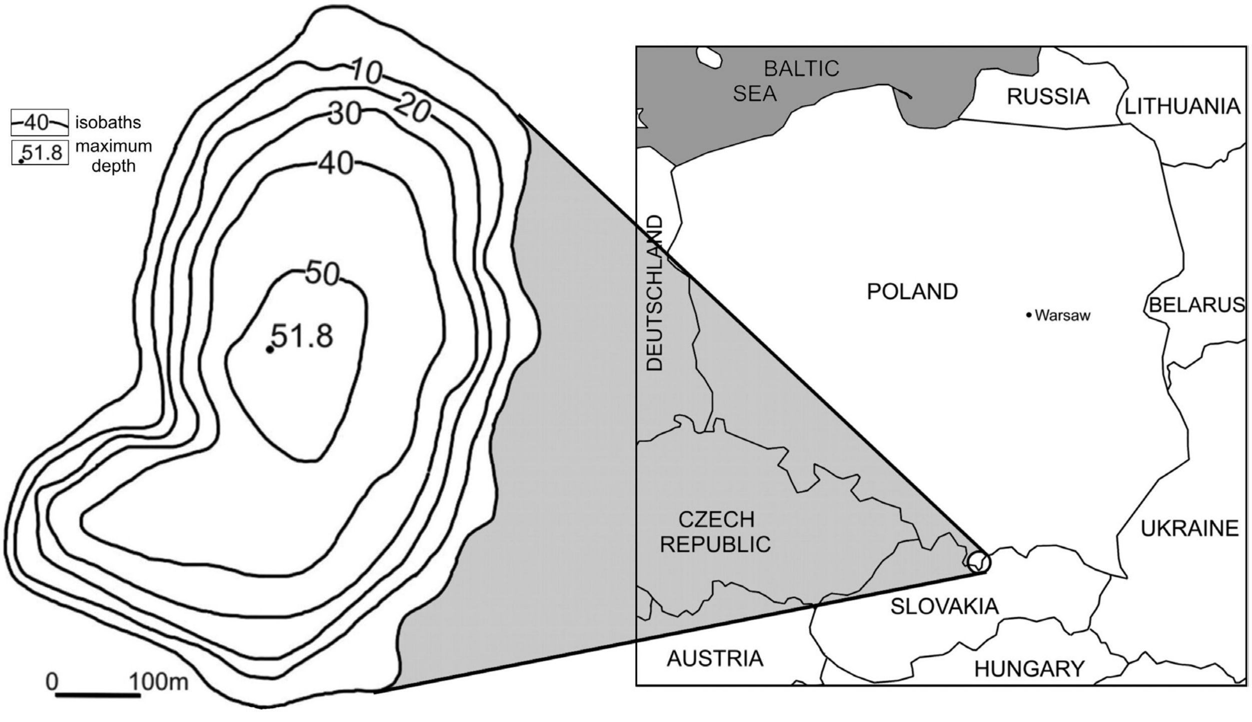

Fig. 1. Location of the study object

gauge located at the outflow from the lake. Information on the ice phenomena includes: the term of appearance of ice phenomena (i.e. ice in any form, e.g. shore ice), term of appearance of ice cover (when the entire surface of the lake is covered with ice), term of the end of ice phenomena and ice cover, and ice thickness (subject to point measurements). Meteorological data from the same period concerned air temperature (station Kasprowy Wierch) and atmospheric precipitation (station Morskie Oko). The paper also applied values of seasonal NAO indices (for three consecutive months), and winter NAO index according to Hurrell (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based).

Methods

For the purpose of determination of correlations between water stages and water temperature in the lake, as well as air temperature and atmospheric precipitation and intensity of North Atlantic Oscillation, Pearson coefficients of linear correlation were calculated between standardised monthly and seasonal values of parameters of the regime of the lakes and meteorological parameters (from three consecutive months) and seasonal NAO indices.

The calculations of correlation coefficients concerned synchronic and asynchronic series, e.g. index NAO_{OND} was correlated with variables from November to October, index NAO_{NDJ} with monthly variables from December to October, and variables from November were correlated with index NA_{ONDJ} from the preceding year, etc. The statistical assessment of significance of correlation coefficients was performed by means of statistic t. The results of the correlation analysis were presented in a graphic form as a matrix of 159 correlation coefficients.

Changes in the parameters of the lake's regime and meteorological elements in various phases of NAO_{DJFM} were determined based on differences of such parameters in the positive and negative phase of NAO_{DJFM} in relation to average values from the years 1971-2010. Similar methodology was applied in earlier studies on the effect of NAO on ice phenomena in Poland (Wrzesiński et al. 2015a). The positive phase was considered as years with high (NAO_{DJFM} > 2.52), and negative phase with low (NAO_{DJFM} < -0.41) values of winter index NAO_{DJFM}. The figures correspond with the first and third quartile from the entire set of index NAO_{DJFM} in the years 1971-2010. The statistical significance of such differences was analysed by means of T test for correlated samples. Each time, the hypothesis $H_0: \mu = \mu_0$ with equality of expected values was tested against $H_1: \mu \neq \mu_0$. The rejection of the hypothesis suggests significant differences between mean parameters

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

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

observed in various phases of NAO_{DJFM} and mean values. For the purpose of verification of the hypothesis, a test for a small sample was applied based on t-Student distribution at n-1 degrees of freedom.

Results and discussion

Because water stages and thermal dynamics of the lake are strongly affected by meteorological elements, the effect of changes in the intensity of North Atlantic Oscillation on meteorological elements was analysed first, namely on air temperature and atmospheric precipitation amount at stations in the vicinity of the lake. The matrix of coefficients of correlation of seasonal NAO indices with monthly air temperatures at station Kasprowy Wierch shows no statistically significant correlations – Figure 2. The situation is different in the case of atmospheric precipitation recorded at station Morskie Oko. Precipitation from May to August shows statistically significant correlations with seasonal indices NAO_{DJF}, NAO_{JFM}, NAO_{FMA}, and NAO_{MAM} (p<0,05) – Figure 3.

Because the strongest effect of NAO is observed in the winter-spring season, the next stage involved the analysis of deviations of mean air tem-

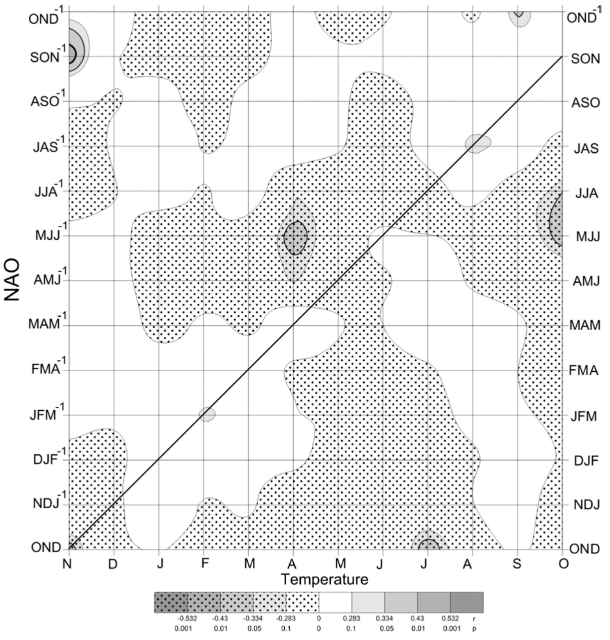

Fig. 2. Matrix of coefficients of correlation of seasonal NAO indices and monthly air temperatures for station Kasprowy Wierch (indices: OND…SON the current year, indices: NDJ^{-1}…OND^{-1} – indices NAO the previous year)

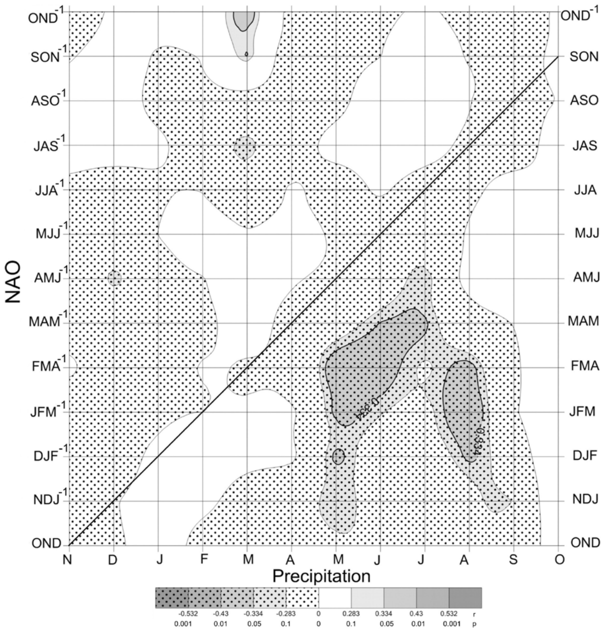

Fig. 3. Matrix of coefficients of correlation of monthly atmospheric precipitation for station Morskie Oko and water stages in Lake Morskie Oko (indices: OND…SON the current year, indices: NDJ^{-1}…OND^{-1} – indices NAO the previous year)

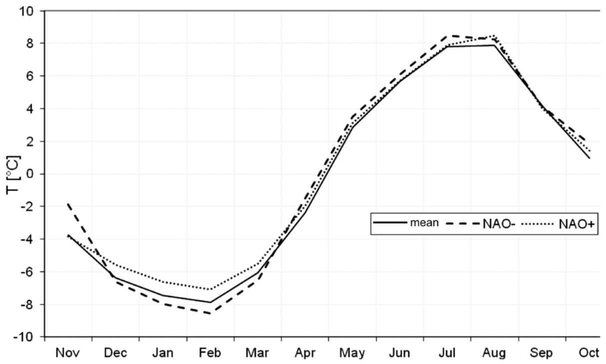

Fig. 4. Changes in air temperature at station Kasprowy Wierch in the average conditions and various phases of NAO_{DJFM}

peratures and atmospheric precipitation values from those observed in the positive and negative phase of NAO_{DJFM}. In the positive phase of NAO_{DJFM}, air temperatures are higher than average in the winter season (e.g. in February by 1.5°C), but the differences are not statistically significant – Figure 4.

More significant changes concern atmospheric precipitation amounts. Atmospheric precipitation in the negative phase of NAO in August are higher by 52 mm, and in October lower by 40 mm than the average, and the observed differences are statistically significant ($p<0.05$) – Figure 5. In the positive phase of NAO_{DJFM}, significant differences in precipitation amounts are recorded in March, when they are higher by 20 mm than the average, and in May and August, when they are lower by 40-50 mm than the average in the entire analysed multiannual.

The analysis of the matrix of coefficients of correlation of seasonal NAO indices with monthly water stages and temperature in the lake shows that the effect of the intensity of North Atlantic Oscillation on water stages and temperatures in the lake is inconsiderable – Figures 6 and 7. Only index NAO_{MJJ} is statistically significantly correlated with water stages in the lake in August.

Water stages in the lake in August can also be affected by the rate of index NAO_{DJFM}. In the negative phase of NAO_{DJFM}, water stages in the lake are lower than average from January to March. The observed differences, however, are statistically insignificant. In the positive phase of NAO_{DJFM}, water stages in the lake are lower than average from June to October, and in August deviations of water stages from the mean values reach 5 cm (Fig. 8) and are statistically significant ($p<0.05$) – Figure 9. A similar pattern is observed in the case of atmospheric precipitation. This confirms that an increase in water stages in August in the positive phase of NAO_{DJFM} is determined by an increase in atmospheric precipitation. In the case of temperatures of the lake's waters in both of the NAO phases (Fig. 10), no statistically significant differences from mean values were recorded – Figure 11.

In various phases of NAO_{DJFM}, parameters of ice phenomena and ice cover inconsiderably differ from the mean values. In the negative NAO phase,

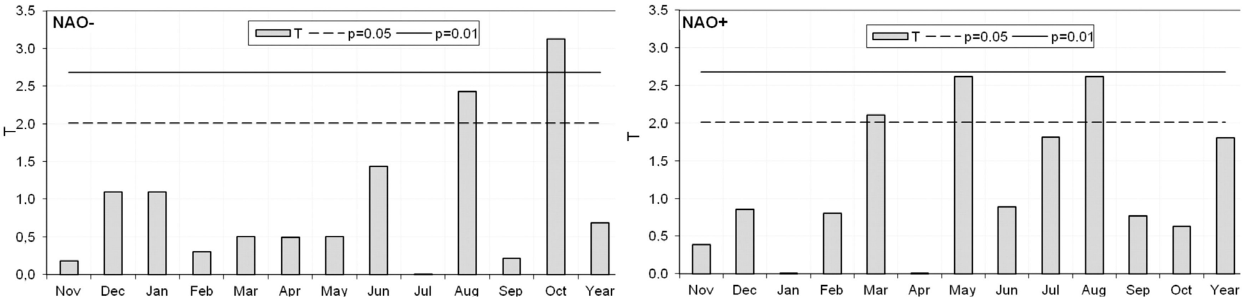

Fig. 5. Test of significance of difference in atmospheric precipitation in the negative (NAO-) and positive (NAO+) phase of NAO_{DJFM} from average values

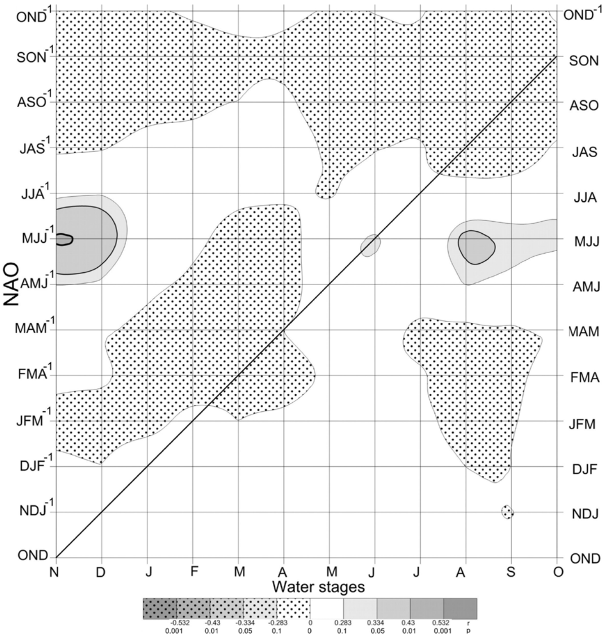

Fig. 6. Matrix of coefficients of correlation of NAO indices and monthly water stages in Lake Morskie Oko. (indices: OND…SON the current year, indices: NDJ^{-1}…OND^{-1} – indices NAO the previous year)

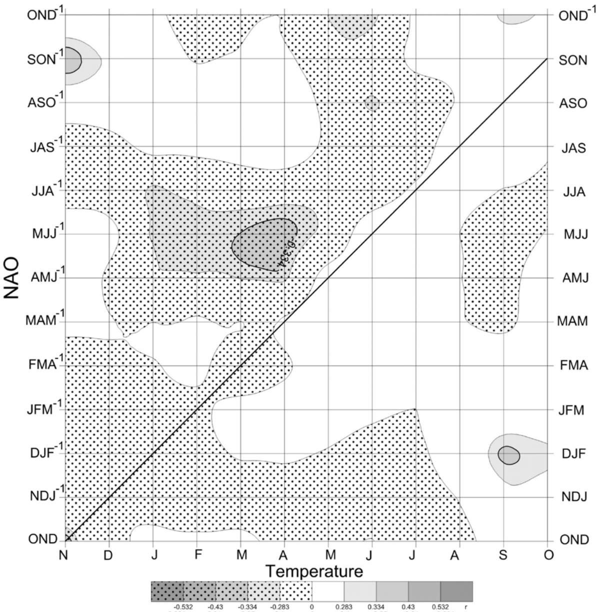

Fig. 7. Matrix of coefficients of correlation of seasonal NAO indices and monthly water temperatures in Lake Morskie Oko. (indices: OND…SON the current year, indices: NDJ^{-1}…OND^{-1} – indices NAO the previous year)

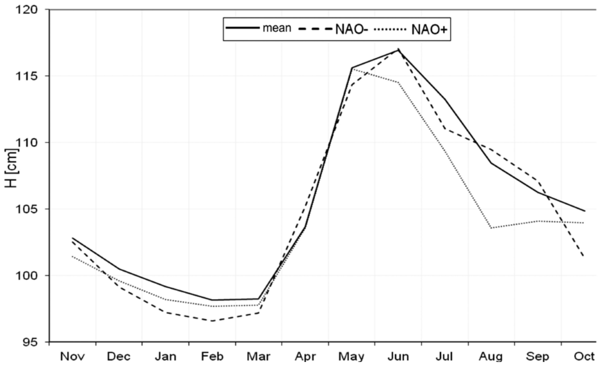

Fig. 8. Changes in water stages in Lake Morskie Oko in average conditions and in various phases of NAO_{DJFM}

the commencement of ice phenomena and ice cover is usually later by 2-3 days, similarly as their ceasing. Only in the positive phase, ceasing of ice phenomena is earlier by one week, their duration is one week shorter than on the average (Fig. 12), and the observed differences are statistically significant (p=0.05) – Figure 13.

The above data show that the majority of the analysed hydrological characteristics of Lake Morskie Oko was not prone to NAO variability in its various phases.

Lack of considerable deviations of water stages from mean values in the context of impact of macroscale types of atmospheric circulation requires a more detailed approach in the future. The situation is more complex than the assessment of the effect of NAO on water level fluctuations in lowland areas (Górniak and Piekarski 2002). One of factors obscuring the response of water stages to particular NAO phases may turn out to be its surroundings. Its southern shore is modelled by the deposition of rock debris in the lake, transported in runoffs (Kotarba 2014). Large scree fans adjacent to the lake (Fig. 14) may prove a quite important element in the retention of precipitation and melt waters, successively feeding the lake.

The effect of NAO on thermal-ice conditions is evident in the case of lakes located in the lowland part of Poland (Girjatowicz 2011; Wrzesiński et al. 2015 a, b), where both the temperature conditions and ice phenomena evidently respond to climatic factors considerably more strongly determined by the impact of changes in the intensity of North Atlantic Oscillation. Due to this, a different response of Lake Morskie Oko to changes in atmospheric circulation should also be associated with the environmental conditions and individual parameters of the lake. Livingstone and Dokulil (2001), analysing eight lakes in the pre-Alpine area (perialpine) in Austria, determined that the effect of NAO on surface temperature of water is the highest in lakes located the lowest. Therefore, it can be presumed that the observations confirm a higher role of lo-

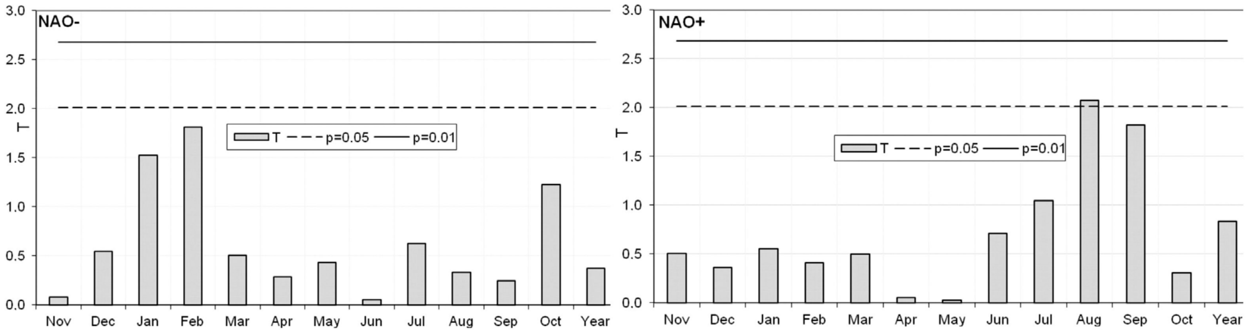

Fig. 9. Test of the significance of difference in water stages in the negative (NAO-) and positive (NAO+) phase of NAO_{DJFM} from mean values

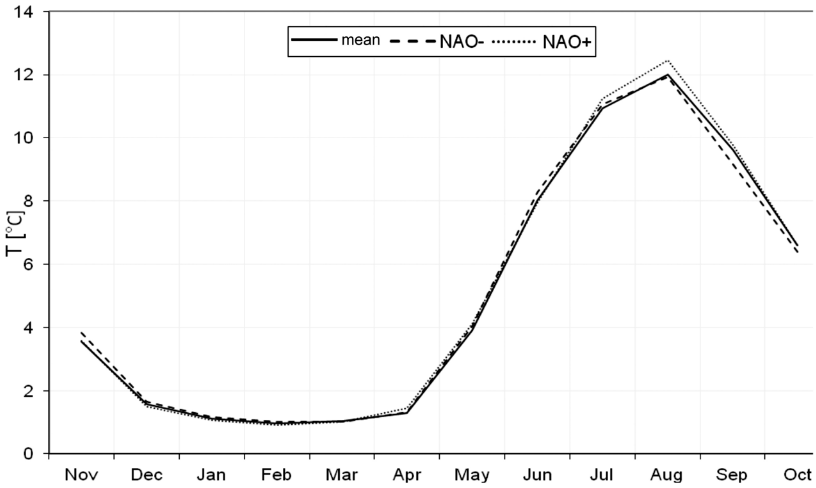

Fig. 10. Changes in water temperature in Lake Morskie Oko in average conditions and in various phases of NAO_{DJFM}

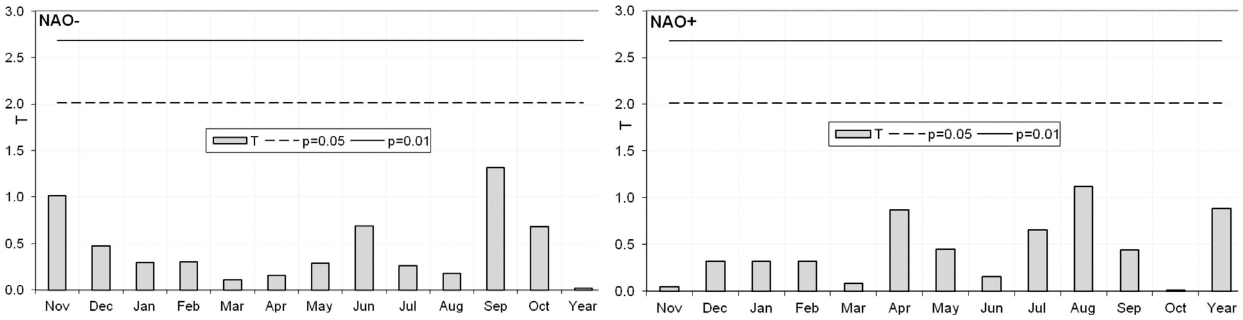

Fig. 11. Test of significance of the difference in water temperatures in the negative (NAO-) and positive (NAO+) phase of NAO_{DJFM} from mean values

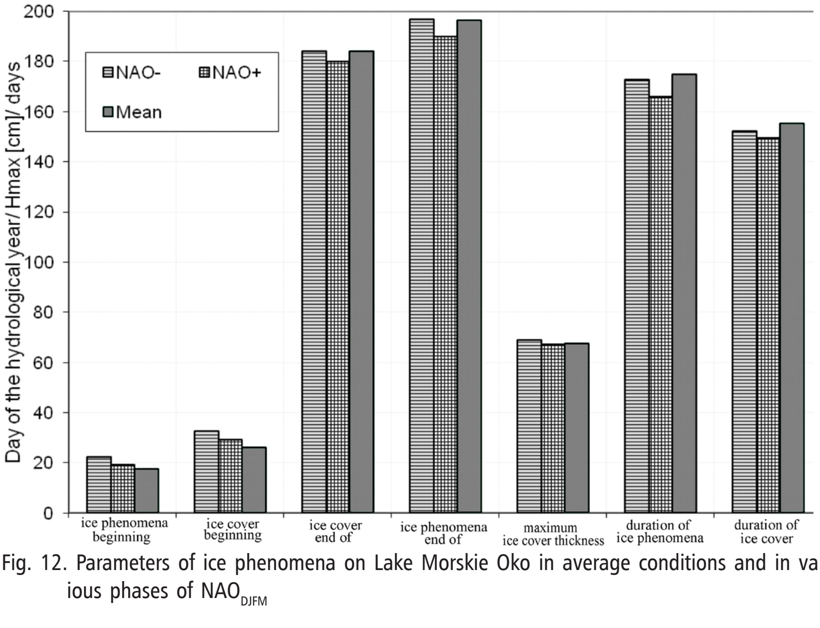

Fig. 12. Parameters of ice phenomena on Lake Morskie Oko in average conditions and in various phases of NAO_{DJFM}

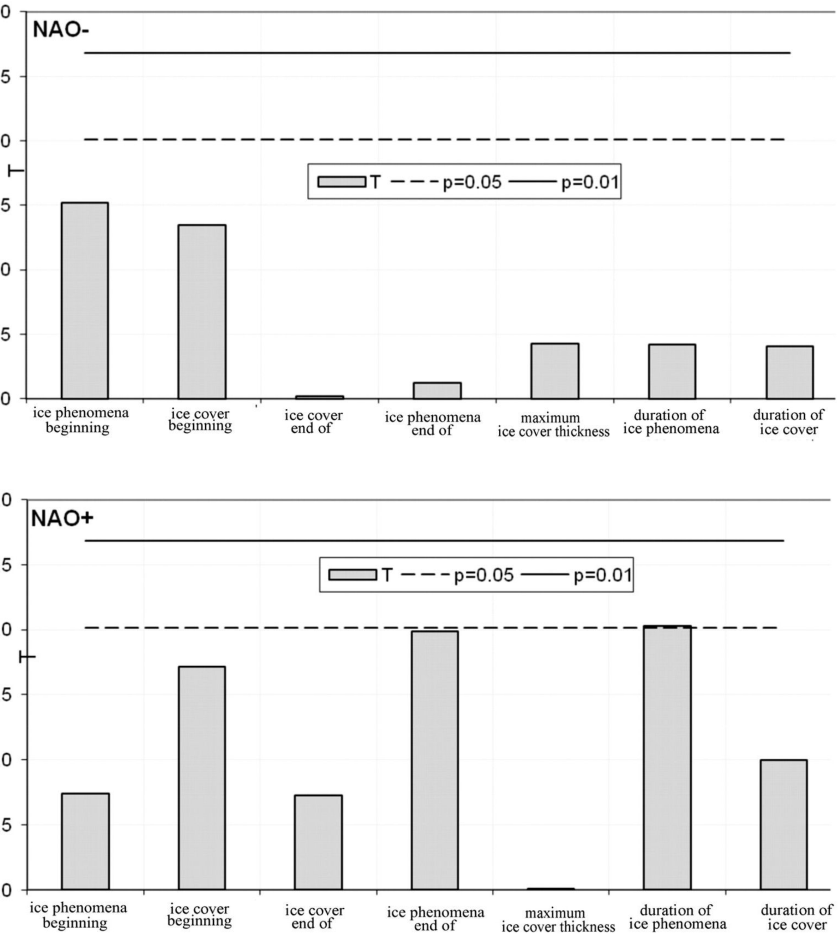

Fig. 13. Test of significance of the difference in parameters of ice phenomena in the negative (NAO-) and positive (NAO+) phase of NAO_{DJFM} from mean values

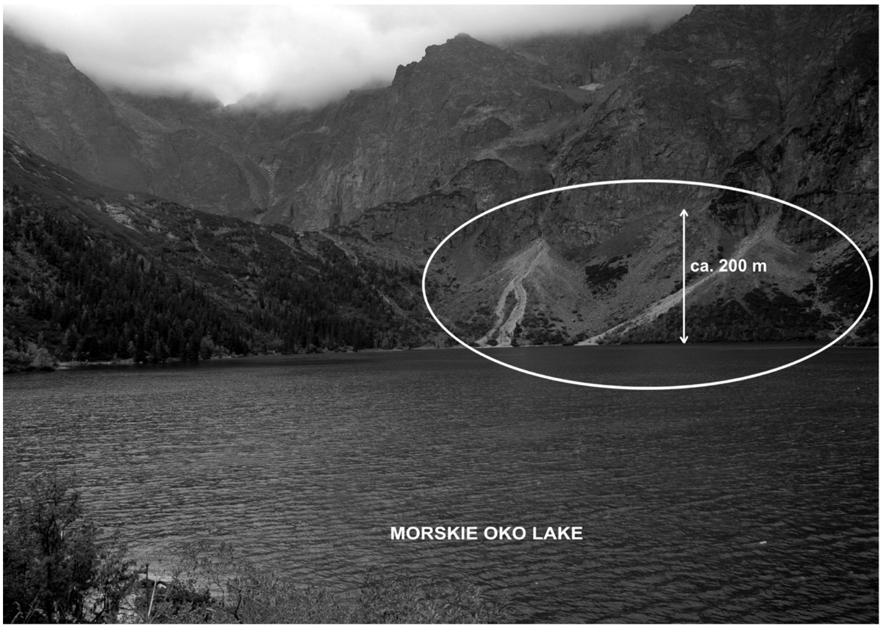

Fig. 14. Scree fans on Morskie Oko Lake

cal parameters, emphasised along with an increase in altitude. Such parameters determining the course of particular components of the thermal regime of Lake Morskie Oko certainly include its surroundings, i.e. peaks of the Tatra Mountains. Due to the orographic conditions, changes in climatic parameters occur, including radiation conditions deserving particular attention. This is particularly evident in reference to ice cover thickness. Based on long-term measurements, Choiński et al. (2013) evidenced that it is highly variable on Lake Morskie Oko, both at the multiannual and seasonal scale. The strong correlation of the exposure of mountain lakes with their thermal dynamics and course of ice conditions is confirmed by other studies, among others from the Alps (Luoto and Nevalainen 2013; Ohlendorf et al. 2000). Sánchez-López et al. (2015), analysing the effect of NAO on ice phenomena on three mountain lakes in Spain, determined its manifestation in the process of degradation of the ice cover. A similar pattern occurs in the scope of Lake Morskie Oko. Evident impact of NAO concerns the term of disappearance and duration of ice phenomena.

Conclusions

In spite of the unquestionable role of NAO in the course of climatic and hydrological conditions in Europe, situations are observed in which its impact on particular elements of the hydrographic network is weak or does not occur. Outside of areas subject to extensive anthropopressure (hydrotechnical development, heated water discharge, etc.), lack of response in the course of hydrological characteristics among others in lakes may result from their individual parameters and local conditions. High mountain lakes are specific in such terms. Based on the example of Lake Morskie Oko, the majority of the analysed hydrological parameters shows statistically non-significant correlations with NAO. The thermal-ice conditions of Lake Morskie Oko are strongly determined by the orographic conditions in its vicinity. The shading effect determining the level of radiation occurring over the lake has been evidenced in earlier studies. The issue of lack of variations of water stages from mean values in various NAO phases is still not clear. The determination of the role of the lake's alimentation with waters retained in screes will require more detailed research in the future. Defining the scale of the alimentation will permit a better understanding of the cycle of water level fluctuations in Lake Morskie Oko.

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