J. Hydrol. Hydromech., 68, 2020, 1, 38–50
DOI: 10.2478/johh-2019-0025
ISSN 1338-4333

sciendo Journal of Hydrology and Hydromechanics

The variability of ice phenomena on the rivers of the Baltic coastal zone in the Northern Poland

Jan Tadeusz Łukaszewicz*, Renata Graf

Department of Hydrology and Water Management, Institute of Physical Geography and Environmental Planning. Faculty Geographical and Geological Sciences, Adam Mickiewicz University in Poznań, 61-680 Poznań, Poland.
*Corresponding author. Tel.: (+48) 693 627 497. E-mail: janluk@amu.edu.pl

Abstract: The main purpose of the research was to determine the conditions affecting ice phenomena, including the three-phase cycle of ice: expansion, retention and decay of the ice cover on selected rivers of the Baltic coastal zone in the Northern Poland (Przymorze region). The analysis has been elaborated for the years 1951–2010 against the backdrop of currently occurring climatic changes, with particular emphasis on the development and phase variability of the NAO. The article presents the impact of the variability in atmospheric circulation which has manifested in an increase in air temperature, over the last 20 years, on thermal conditions during winter periods in the South Baltic Coastal Strip. The increase in air temperature has contributed to an increase in the temperature of river waters, thus leading to a shortening of the duration of ice phenomena on rivers in the Przymorze region. The article also brings to light an increased occurrence of winter seasons classified as cool, and a disruption in the occurrence of periods classified as normal over the last 30 observed years. The research has demonstrated a significant dependence between the seasonal change in air temperature and the variability of thermal conditions of water, which has a direct impact on the variability of the icing cycle of rivers in the Przymorze region. The authors also show that the variability in forms of ice phenomena for individual river sections is determined by the local factors, i.e. anthropogenic activity, impact of urbanized areas or inflow of pollutants.

Keywords: Ice phenomena; Rivers; Coastal zone; Air temperature; NAO; Water temperature.

INTRODUCTION

Ice phenomena are an inseparable element of river regime in temperate climate zones (Kreft, 2013; Prowse and Beltaos, 2002). They also play a key role in shaping this regime by modifying river flow (Klavins et. al., 2009; Majewski, 2009). The intensity and frequency of occurrence for ice phenomena depends, in particular, on the predominant climatic conditions for a given area (Agafonova and Frolova, 2007; Frolova and Alekseevskiy, 2010). The primary factor determining the form and duration of ice phenomena on rivers is air temperature (Łukaszewicz, 2017b), the variability of which depends on atmospheric circulation (Girjatowicz et al., 2002; Graf and Tomczyk 2018; Kożuchowski and Degirmendžic, 2002; Łukaszewicz, 2017a; Marsz and Styszyńska, 2001; Niedźwiedź, 2002; Przybylak et al., 2003). Air temperature fluctuations determine the variability in thermal conditions for waters in a given catchment area (Graf, 2015; Jurgelėnaitė et al., 2012; Klavins et al., 2009; Łukaszewicz, 2017c; Webb and Nobilis, 2007), and consequently have a direct impact on the formation of various ice forms on rivers and water reservoirs (Ptak et al., 2016).

Significant influence on the occurrence and development of ice phenomena on rivers is also exerted by local environmental factors, such as the structure of the river bed, the river gradient, its autochthonous or allochthonous characteristics (Hester and Doyle, 2011; Kreft, 2013; Łukaszewicz, 2017b), and the percentage of underground water supplying the rivers (Graf, 2015). The conditions in which ice phenomena form on rivers are also significantly affected by anthropogenic factors, for example the channeling and regulation of rivers and the erection of dams and hydropower plants. The channeling of a section of a river helps clear the flow of ice floats and limits the formation of embacles and ice covers (Majewski, 2009), thus eliminating the serious risk of flooding caused by embacles that may arise when broken ice accumulates. Research has shown that for more than 60% of the rivers in the Northern Hemisphere, seasonal effects on the occurrence of ice phenomena can be observed. It is assumed that extreme hydrological phenomena, such as floods and low river waters in winter, are mainly the result of the occurrence and disappearance of ice phenomena (Majewski, 2009). Ice phenomena significantly influence the functioning of the fluvial system and the water ecosystem, but also on the life cycles of water organisms (Allan, 1998).

The broad scope of the impact ice phenomena has on river regimes and living organisms has become the topic of a great number of studies. Some of the research focuses on the effect of weather anomalies (Bednorz and Kossowski, 2004; Filipiak, 2004; Kożuchowski, 2000), particularly the recently registered rise in air temperature (Graf, 2018; Graf and Tomczyk, 2018; IPCC, 2007; Russak, 2009; Tylkowski, 2013), on changes in thermal conditions of waters and the development and duration of icing on rivers. One of the most important aspects of the macroscale changes in climatic conditions is the impact of the North Atlantic Oscillation's (NAO) influence on changes in individual elements of river regimes, not only because individual catchments can be compared on a regional basis, but also because this type of research captures the problem in relation to a series of long-term measurements. The influence of the variability of the NAO on hydrological phenomena, including river regime, changes in the flow rate and the thermal and ice regime of rivers and lakes, has been described, among others, by Yoo and D'Odorico (2002) and Klavins et al. (2009). Due to the strong climatic factors that determine the formation of ice phenomena on rivers, the phenomena can be used as a significant indicator of climatic changes.

Records from the last two centuries regarding the dates for the disappearance of ice cover on rivers of the Northern Hemisphere provide consistent evidence indicating their subsequent freezing and earlier disappearance of ice phenomena (Magnuson et al., 2000). The results of reports and studies carried out over the last 40 years on European rivers show a decrease in the frequency and appearance of ice phenomena, especially ice sheets (EEA Report No. 12/2012). This is a result of the impact of climate change, especially the increase in the incidence of warmer winters. The observed tendency is also confirmed by studies on changes in river thermo-waves, which have been determined to have increased by about 1–3°C over the last century. Analyses of long-term trends in changes in river congestion have shown that the surface water ice regime in Northern Europe is linked to changes in the NAO, having features that confirm long-term climate change (Klavins et al., 2009; Kuusisto and Elo, 1998; Yoo and D'Odorico, 2002). Changes in the ice melting regime are also observed in the Baltic region, where the direct impact of the sea is the factor influencing the structure and duration of ice phenomena. It is pointed out that the duration for the ice cover on the rivers of the Baltic region during the last decades, even centuries, has shortened. Periods of interruption in the observation of ice phenomena in particular years and periodic changes in the intensity of ice formation have been increasingly observed. These tendencies are confirmed by the observed trend of air temperature increase of coastal areas during the winter season (Hagen and Feistel, 2005), which translates into an increase in the temperature of river waters and a hinderance in the occurrence of ice phenomena (Klavins et al., 2002, 2009; Lizuma et al., 2007).

The main purpose of the research was to determine the conditions affecting ice phenomena, including the three-phase cycle of ice (the phases of expansion, retention and decay of the ice cover) on selected rivers of the Przymorze area in Northern Poland for the years 1951–2010. These rivers flow into the Baltic Sea, which directly impacts their hydrologic and thermic conditions. The analysis has been elaborated against the backdrop of currently occurring climatic changes, with particular emphasis on the winter periods, which are dependent on the development and phase variability of the NAO. The work also takes into consideration changes in thermal conditions of river waters and local environmental factors impacting catchments, including the level of anthropogenic impact.

The research has been undertaken to answer the following questions:

- what has been the frequency and duration of the ice phenomena on rivers in the Baltic Coastal Zone over a multi-year period?
- how have the trends in air temperature changes affected water thermal conditions in rivers and characteristics of the ice phenomena, i.e. duration of ice and individual forms of the ice phenomena?
- how does the historical data base influence the future data base and how does it facilitate forecasting?

The results will be useful in monitoring the temporal and spatial changes of ice on rivers in the temperate zone, especially in areas that are impacted by the Baltic Sea.

TEST AREA

According to the physico-geographical division of Poland (Kondracki, 2009), the Przymorze region is located in the Southern Baltic Coastal macro-region, which is characterized by considerable variability in weather conditions (Fig. 1). The region is located in the temperate climate zone and is affected by Atlantic Ocean climate factors, the Baltic Sea – with which it is in direct contact - and certain elements of the Eastern European continental climate. The North Atlantic is considered as the main climate forming zone of Poland (Marsz and Styszyńska, 2001), and therefore it also plays a significant role in shaping the thermal conditions of the Southern Baltic Coastal Strip.

Near the sea, winters are less frosty than in other regions of the country (Woś, 2010). To a large extent, the Baltic Sea determines the annual range of air temperature, particularly through the reduction of daily values, annual amplitudes and fluctuations in temperature distribution primarily during the winter periods (Woś, 2010). The thermal impact of the Baltic Sea also lengthens and shifts the duration of transient seasons (Niedźwiedź, 2002).

Changes in air temperature in the Baltic coastal zone are also impacted by anemometric factors and cloud cover. Westerly winds influence the occurrence of positive thermic anomalies in the winter season. Winds from the northern sector bring warmer air, whereas easterly winds bring cooler weather. Cloud cover is also of considerable importance in relation to air temperature changes in Pomerania. Increased cloud cover is related to a decrease in the value of temperature amplitude and an increase in extreme temperatures (Filipiak, 2004).

The test area covers the catchment area of 5 rivers in the Przymorze hydrographical region – Rega, Parsęta, Wieprza, Słupia and Łupawa – which flow into the Baltic Sea (Fig. 1). The analyzed rivers are classified as small rivers, i.e. not exceeding 200 km in length and having a drainage area of no more than 10,000 km^2 (Table 1).

Table 1. The selected morphometric parameters of selected rivers from the Przymorze region.

River	Length of the river [km]	Catchment area [km^2]
Słupia	138.6	1310.0
Łupawa	98.7	924.5
Łeba	117.0	1801.2
Wieprza	140.3	2172.7
Rega	167.8	2723.3
Sum	662.4	8931.7

In hydrological terms, the rivers located east of the Parsęta River (Fig. 1) are characterized by a weakly developed nival regime and their average flow in a spring month does not exceed 130% of the average annual flow. In the annual cycle, rivers with such a regime are distinguished by the most even flows and the greatest share of subterranean outflow from the total outflow. The Parsęta River and rivers located west of it (Fig. 1) are characterized by a moderately developed nival regime typical of rivers with an average flow during spring months totaling between 130–180% of the average annual flow. Rivers in northern Poland and in the Wieprza River catchment area are characterized by a high share of subterranean supply (60–80%), which is 40–60% for the other rivers with this type of regime. Temperature stability of subterranean waters may have a considerable influence on the development of the icing cycle of rivers (Graf, 2015; Łukaszewicz, 2017a, b).

The selected rivers are typified by a diverse level of anthropogenic impact. Some of their sections are located in urbanised municipal areas (e.g. the section in Słupsk) (Fig.1), while others flow through land that has retained its natural character, or through areas that have experienced only a slight degree of anthropogenic impact (Łukaszewicz, 2017b). This is particularly visible in the case of the Łupawa River (Fig. 1), for which the headwaters flow through the Słowiński National Park.

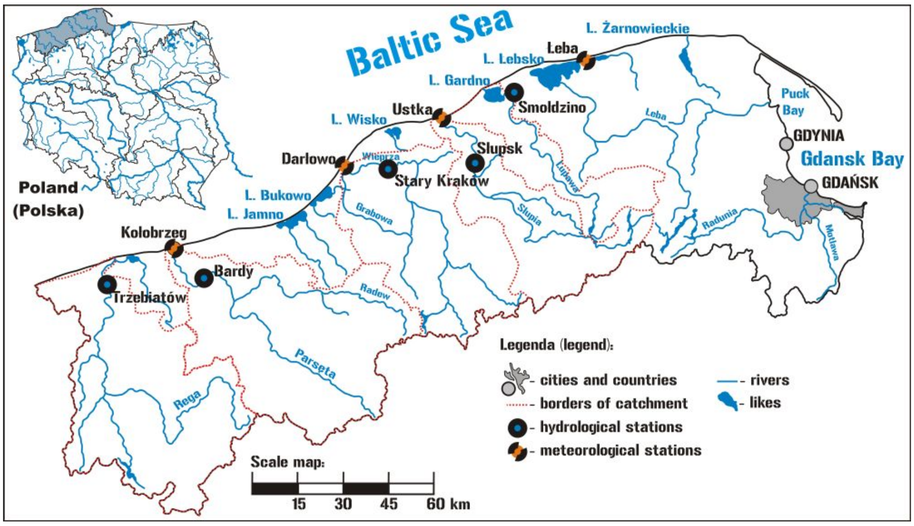

Fig. 1. Location of the test area and arrangement of measuring stations for the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) in the Przymorze hydrographical region.

Table 2. Thermic classification criteria according H. Lorenc (1998).

Class No.	Year evaluation	Values interval calculated according $T_{mpt.\cdot\ year\cdot}$
1	Extremely warm	$T_{mat.\cdot\ year\cdot} > T_{mpt.\cdot\ multiyear\cdot}$ + 2.5 SD
2	Anomalously warm	$T_{mpt.\cdot\ multiyear\cdot}$ +2.0 SD < $T_{mat.\cdot\ year\cdot} \leq T_{mpt.\ multiyear}$ +2.5 SD
3	**Very warm**	$T_{mpt.\cdot\ multiyear\cdot}$ +1.5 SD ≤ $T_{mat.\cdot\ year\cdot} \leq T_{mpt.\ multiyear}$ +2.0 SD
4	**Warm**	$T_{mpt.\cdot\ multiyear\cdot}$ +1.0 SD < $T_{mat.\cdot\ year\cdot} \leq T_{mpt.\ multiyear}$ +1.5 SD
5	**Slightly warm**	$T_{mpt.\cdot\ multiyear\cdot}$ +0.5 SD < $T_{mat.\cdot\ year\cdot} \leq T_{mpt.\ multiyear}$ +1.0 SD
6	**Normal**	$T_{mpt.\cdot\ multiyear\cdot}$ –0.5 SD ≤ $T_{mat.\cdot\ year\cdot} \leq T_{mpt.\ multiyear}$ +0.5 SD
7	**Slightly cold**	$T_{mpt.\cdot\ multiyear\cdot}$ –1.0 SD ≤ $T_{mat.\cdot\ year\cdot} < T_{mpt.\ multiyear}$ –0.5 SD
8	**Cold**	$T_{mpt.\cdot\ multiyear\cdot}$ –1.5 SD ≤ $T_{mat.\cdot\ year\cdot} < T_{mpt.\ multiyear}$ –1.0 SD
9	**Very cold**	$T_{mpt.\cdot\ multiyear\cdot}$ –2.0 SD ≤ $T_{mat.\cdot\ year\cdot} < T_{mpt.\ multiyear}$ –1.5 SD
10	**Anomalously cold**	$T_{mpt.\cdot\ multiyear\cdot}$ –2.5 SD ≤ $T_{mat.\cdot\ year\cdot} < T_{mpt.\ multiyear}$ –2.0 SD
11	Extremely cold	$T_{mat.\cdot\ year\cdot} < T_{mpt.\cdot\ multiyear\cdot}$ –2.5SD

Explanations: ($T_{mpt.\cdot\ multiyear\cdot}$ – average multi-year temperature; $T_{mat.\cdot\ year\cdot}$ – average annual, monthly or seasonal temperature; SD – standard deviation). Classes of winter seasons. distinguished on the basis of data from analyzed meteorological stations. have been marked in bold.

Some of the analyzed rivers, for example the Słupia River, have been significantly transformed in their upper and middle reaches through the modification of the river beds, the erection of numerous dams and a network of hydropower plants (Łukaszewicz, 2016).

SOURCE MATERIALS

The analysis was performed using data from 5 measuring stations which are in the standard observation network of the Institute of Meteorology and Water Management – National Research Institute (IMGW – PIB, Warsaw – Poland): 1) Trzebiatów – the Rega River; 2) Bardy – the Parsęta River; 3) Stary Kraków – the Wieprza River; 4) Słupsk – the Słupia River; and 5) Smołdzino – the Łupawa River (Fig.1). The database contains daily information about the occurrence or non-occurrence of ice phenomena on the rivers studied during the period of 1951-2010. The analyses take into consideration:

- the division of ice phenomena into individual forms: frazil ice; stranded ice; ice cover; ice floe; ice jam; and frazil ice jam.
- the number of days when some of the abovementioned forms occurred simultaneously, e.g. stranded ice and frazil ice, stranded ice and ice floe.
- in addition, daily water temperature values were analyzed for each of the rivers.

The authors have also utilized meteorological data concerning average daily air temperature values from the meteorological stations (IMGW-PIB) in Kołobrzeg, Darłowo, Ustka and Łeba, which are located in close proximity to water-level indicator points for the analyzed rivers of the Przymorze region (Fig. 1). The frequency of occurrence and the course of individual phases of the NAO were determined using the database of the National Weather Service (https://www.weather.gov/). The Jones' Index, which is calculated as the difference in atmospheric pressure between Gibraltar and southwest Iceland, was also used (Niedźwiedź, 2002).

METHODS

The frequency and phasality of ice phenomena on rivers in the Baltic coastal zone was analyzed for the period of 1951–2010. The frequency was defined as the sum total of days with the observed ice phenomenon in the cool half-year period of the hydrological year (November – April), with reference to average air and water temperature values for individual years. In order to evaluate the connection between air temperature and the course of atmospheric circulation, the phase variation of the NAO was also considered. Using the Jones' index helped to determine the percentage of variation in the occurrence of individual NAO phases. A thermic classification (Lorenc, 1998) – (Table 2), on the basis of which distinguished out of the 11 classes of winter seasons, was used to determine the thermic variability of winter periods and distinguish anomalies during the 60-year period under study. This research was conducted utilizing data from selected IMGW-PIB (Institute of Meteorology and Water Management – National Research Institute in Warsaw) meteorological stations located in the Baltic coastal zone (Fig. 1).

The influence of anthropogenic factors on the development of ice phenomena has been determined by comparing the number of days, in which ice forms occurred along selected river sections, taking into consideration any hydrotechnical infrastructure that could modify the nature of a river's icing cycle.

The LOESS (LOcal regrESSion, i.e. locally weighted scatterplot smoothing) method was utilized for analyzing dependence between individual parameters. The method is also known as locally weighted regression or weighted locally polynomial regression (Cleveland and Devlin, 1988; Shumway and Stoffer, 2010) LOESS regression involves the evaluation of separate regression equations for each point (h) in a time series in which observations located closest to the point are of greatest importance, while those that are more distant exert a lesser impact on the result obtained (Cleveland and Devlin, 1988). The equation for LOESS is:

$$h(T) = \alpha_0 + \alpha_{01}(T_i - T) + \mathcal{E}(T) \quad (1)$$

where: coefficients α_0 and α_{01} are calculated separately for each requested T, using the method of locally weighted lesser squares with weights w, while the model itself takes the following form:

$$\sum_{i-1}^{n} w = \left(\frac{(T_i - T)^2}{n}\right) e_i^2 = \sum_{i-1}^{n} w = \left(\frac{(T_i - T)^2}{n}\right)(H_i - a_0 - a_1(T_i - T))^2 = \min \quad (2)$$

where: H – point magnitude of cloud smoothness (T_i and H_i), α_0, α_{01}– regression coefficients used to determine $H(T_i) = \alpha_0$, w – weight function, T – values, for example, of air temperature.

The approximate strength of the trend in changes for the analyzed thermal characteristics and ice phenomena on rivers (assuming linearity) was determined using the modified Mann-Kendall trend test, also referred to as the Yue-Pillon method (Yue et al., 2002). This made it possible to approximate the average monthly change and changes within the entire period. In addition, on the basis of Kendall's non-parametric correlation τ_b, it allowed to quantify the strength of the changes. This is useful due to the interpretation of the τ_b coefficient being purely probabilistic. It determines how much greater/smaller the probability is, for a random selection of observed pairs, of drawing a pair concordant with the observed trend (i.e. for a positive trend, a pair where $\tau_{n+k} \geq \tau_n$). Furthermore, it is possible to determine the level of significance for the τ_b coefficient, which allows us to reliably separate trends that may be merely accidental.

The trend analysis was supplemented with a KPSS test (Kwiatkowski et al., 1992) and an analysis of the time series structure based on the classical ARIMA model (Box and Jenkins, 1983), which has made it possible to answer the question of how historical values determine future values and to what extent this makes forecasting possible. ARIMA model comprises three fundamental elements: the autoregressive process AR (autoregressive), the degree of integration (integrated), and the moving average MA (moving averages). The order determines how many earlier values impact the current value. For the AR (2) and AR (3) processes, the following equations are used, respectively:

$$y_t = \varphi_1 y_{t-1} + \varphi_2 y_{t-2} + \varepsilon_t \quad (3)$$

$$y_t = \varphi_1 y_{t-1} + \varphi_2 y_{t-2} + \varphi_3 y_{t-3} + \varepsilon_t \quad (4)$$

where: y_t – value of the series at moment t, y_{t-1} – value of the series at moment t–1, etc., ε_t – random component, disturbance at moment t, t – successive 24-hour periods/days, φ – a parameter determining the strength of the impact of the previous process value (or successive, older values) on the current value.

In the adopted model, the selection of the degree for individual ARIMA components is made in such a way as to ensure that it minimizes the model's AIC (Akaike Information Criterion). The statistical model may contain various AIC measures, but the one clearly having the lowest measure is preferred (Akaike, 1969). The authors also made use of the SARIMA model, which is the ARIMA model modified into half-year periods.

Additionally, the time series was reconstructed using the GAM (General Additive Model) forecasting model, thus allowing to determine periods with clear trend changes (Taylor and Letham, 2017). This allowed us to more precisely model the trend as a linear function, however with a directional coefficient that may be variable over time. GAM constitutes one of the most universal procedures for non-parametric regression models and has the form of:

$$E(Yi|xi1, xi2, ..., xiP) = \alpha + f1(xi1) + f2(xi2) + ... + fP(xiP) \quad (5)$$

where: Y – explained variable, x – explaining variables, α – constant, fj – the additive function, where j = 1, 2, ..., P – unknown functions of j explaining variable, estimated through unknown functions determined by means a multiple fitting algorithm, $E(Y|X)$ – the average of explained variable Y conditioned by explaining variables.

In the GAM model, the unknown functions (P) are estimated through local polynomial regression, regimented, for example, by the LOESS (stats) function, which fits locally smoothed polynomials to the second degree. Estimation of the fj functions takes place jointly for j = 1, 2, ..., and for P using the iterative backfitting algorithm procedure, known as the Multiple Fitting Algorithm (Koronacki and Cwik, 2005).

The dispersion (diversity) of the annual distributions of ice phenomena has been expressed by means of Shannon's entropy index (Shannon and Weaver, 1949). Usage of the index was necessary when analyzing data having considerable diversity of distribution (the duration of phenomena differs significantly among the various phenomena, in both individual years and months) and a non-stationary nature for the time series. This allowed to compare and determine the impact of the variability of individual parameters, for example, water temperature, on the variability of the trend throughout the duration of ice phenomena.

The analysis was supplemented with the basic descriptive statistics of the distributions of air and river water temperatures for various time-resolution levels. Due to the large quantity of data, the normality of distributions in individual periods was assessed based on histograms and quantile charts. Using the selected statistical methods, it was possible to distinguish the longest periods of occurrence of ice phenomena on individual river sections and the tendencies appearing in the change in occurrence and duration of these phenomena.

The analyses and calculations were performed in the R calculation environment, version 3.4.0 (2017–04–21). R Suite is both a programming language and a programming environment and is available as "Free Software Foundation's GNU – General Public License", functioning in the UNIX/Linux, Windows and MacOS systems. The results of the applied statistical significance tests were assessed with reference to the adopted level of $\alpha = 0.05$.

RESULTS

In the first three observed decades, there was recorded an increased number of days with ice phenomena on rivers and a greater differentiation of ice forms – irrespective of the river section along which research was conducted (Fig. 2) In the last two decades, frazil ice and border ice were the predominant ice forms observed in the first phase of the freezing over of rivers. The exception is the Parsęta River, for which, in recently observed years, the occurrence of ice cover was recorded, however the number of days observed with this form decreased by nearly one half in comparison to preceding years, i.e. the period 1951–1980.

Due to the shortening of the duration of ice phenomena over the last decade, practically no ice forms characteristic of the final, third phase of the river freezing cycle, i.e. ice floe and frazil ice, have been observed other than on river sections with only slight traces of anthropogenic impact, i.e. places where the river bed was not regulated by the erection of damming systems or the shortening of river course (the Rega and Parsęta Rivers). The frequency of occurrence of forms characteristic of the second and third phase of the icing cycle is decidedly greater along sections of rivers typified by a moderately developed rival regime and located in the western part of the test area (Figs. 2–3).

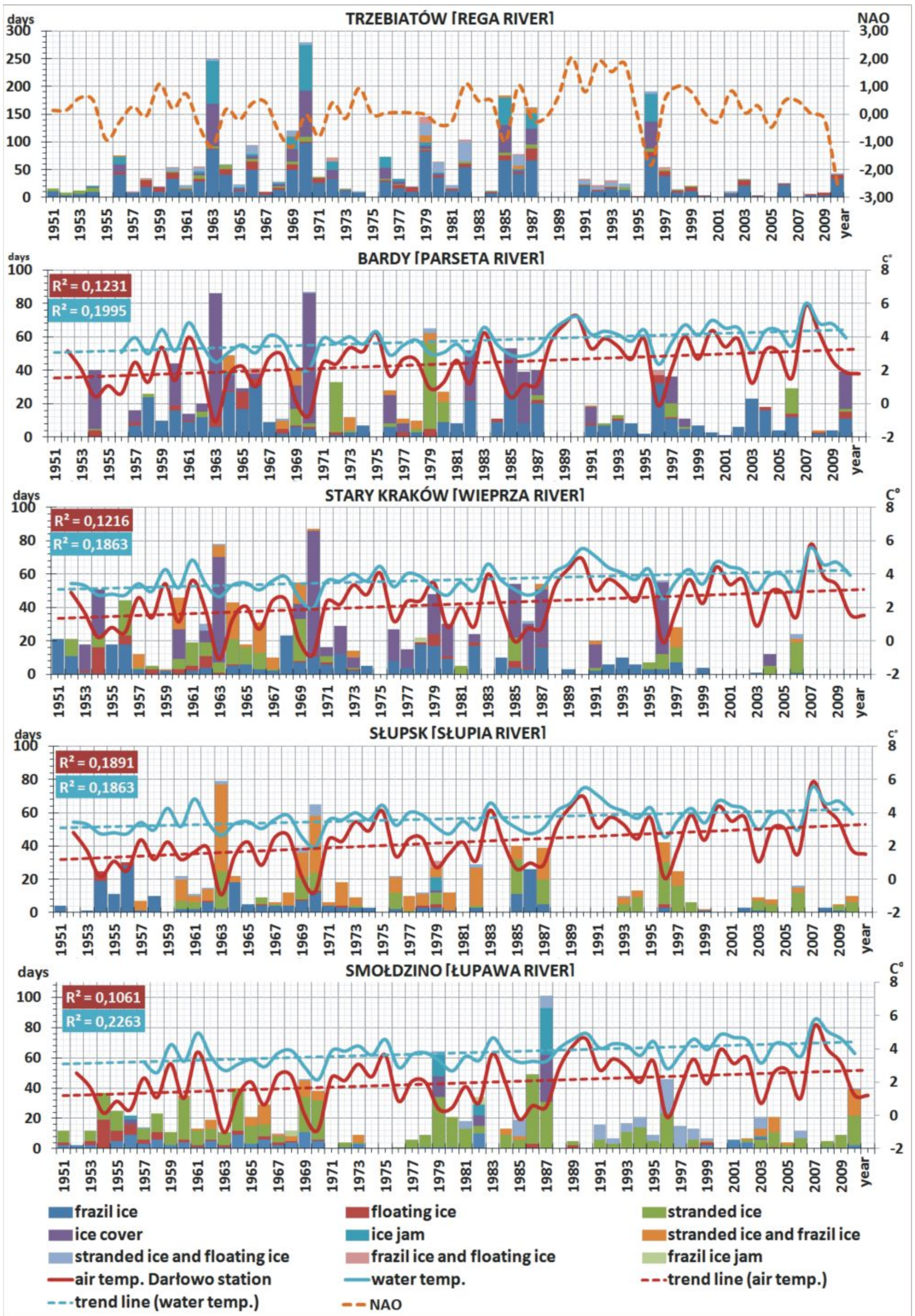

Fig. 2. Frequency of ice phenomena occurrence on Przymorze region rivers during the years 1951–2010, taking into consideration the individual types, the variability of the NAO and the variability of air and water temperature.

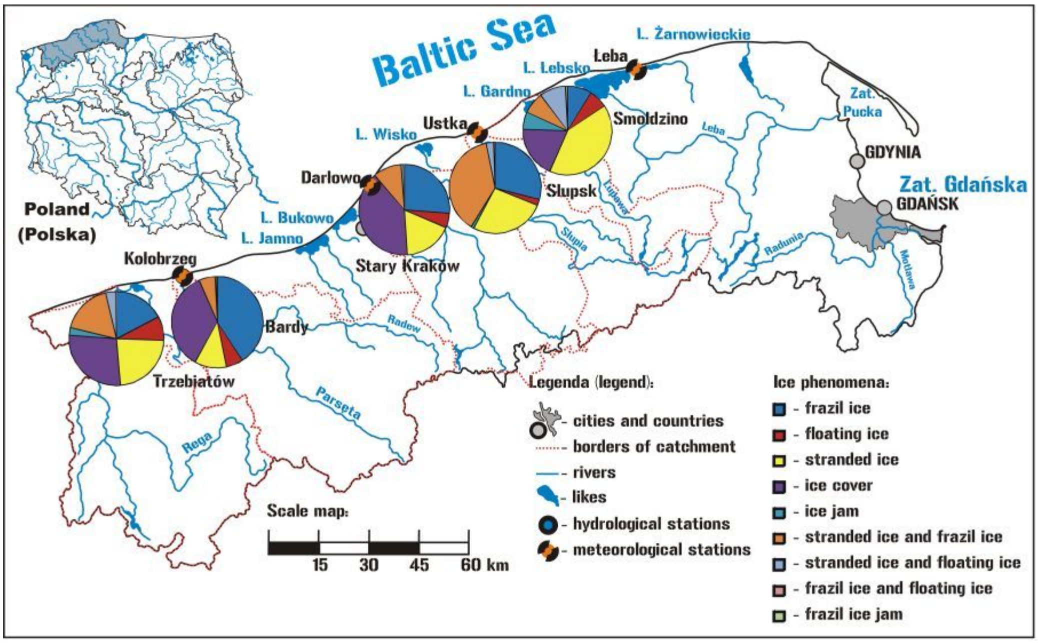

Fig. 3. Frequency (%) of occurrence of individual types of ice phenomena on rivers of the Przymorze region in the years 1951–2010.

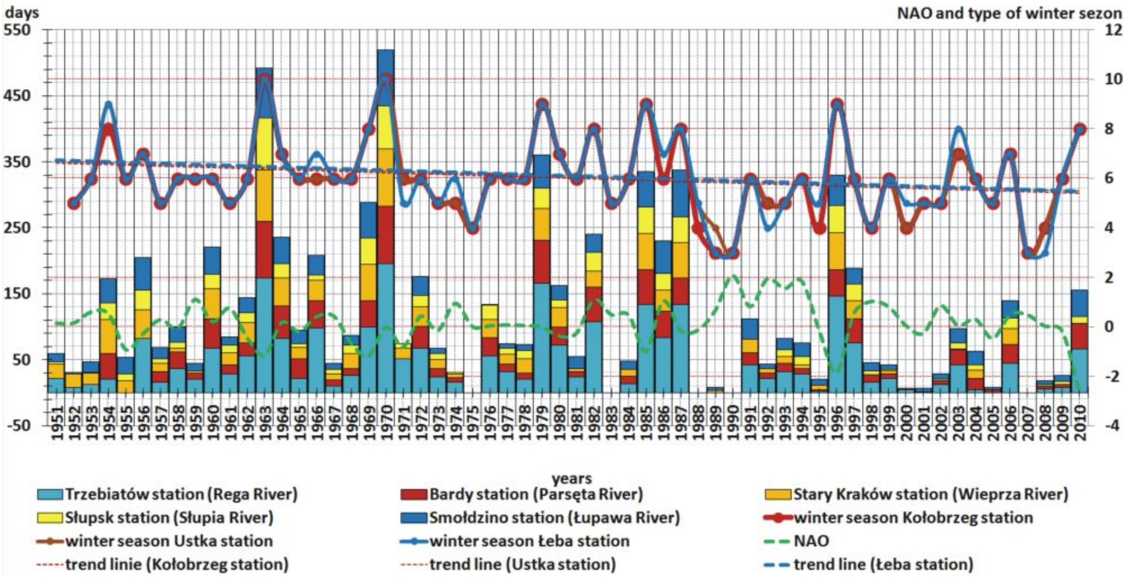

Fig. 4. Number of days with ice phenomena on rivers of the Przymorze region in relation to the variability of thermal conditions in winter periods and the North Atlantic Oscillation (NAO) index. Explanations – classification of winter seasons: 1 – extremely warm; 2 – anomalously warm; 3 – very warm; 4 – warm; 5 – slightly warm; 6 – normal; 7 – slightly cool; 8 – cool; 9 – very cool; 10 – anomalously cool; 11 – extremely cool.

In the first half of the researched period, 1951–1980, the greatest number of days with ice phenomena, as well as the greatest diversity of their forms, on rivers of the Przymorze region was observed, (Figs. 2 and 4). Since 1987, there has been a clear and on-going reduction in the number of days with a single recorded ice phenomenon. This is linked to the increase in Jones' index during the positive phase of the NAO, as shown in the present work. The increase in the index coincides with an increase in average air temperature during winter periods, which in turn impacts the thermal conditions of river waters. Changes in thermal conditions of waters impact the variable frequency of occurrence of ice phenomena and icing forms observed on rivers. The coefficient of correlation between air and water temperature is statistically significant and assumes values within the range of 0.74 to 0.83 at individual stations.

Research demonstrated the considerable impact of the variability of the North Atlantic Oscillation index phases on the increase in air temperature, particularly in the cool half-year period of the hydrological year. This translates directly into an increase in the temperature of waters and the disappearance of ice phenomena in the analyzed region. In the years 1951–2010, the positive phase of the NAO occurred more frequently (57.6%) than the negative phase (42.4%) in the winter season (hydrological year). Taking the winter months into consideration, we may state that the positive phase occurred most frequently in January (64.4%), followed by February (61.0%), while the negative phase was most frequent in December (50.8%). However, the percentage difference between the phases in December was decidedly smaller than in the remaining months of the winter period (Fig. 5).

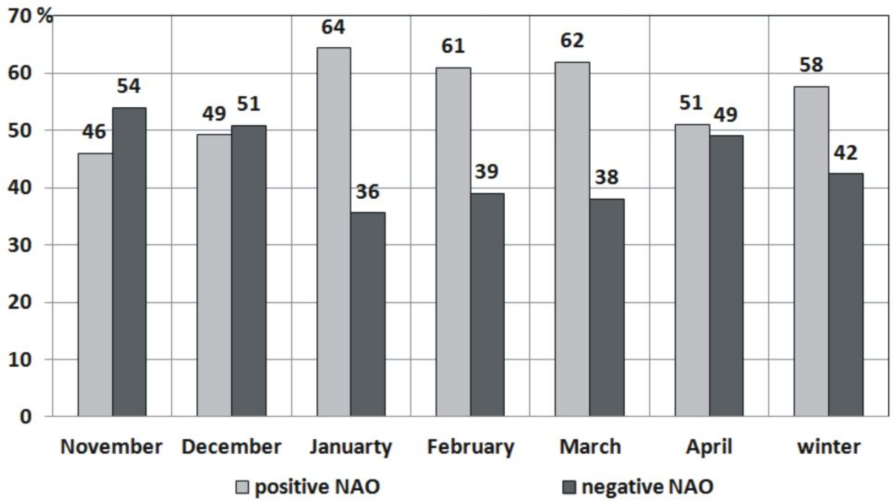

Fig. 5. Frequency [%] of occurrence of the positive and the negative phases of the North Atlantic Oscillation (NAO) in the winter season of the hydrological year (November – April) in the Baltic coastal zone during the years 1951–2010.

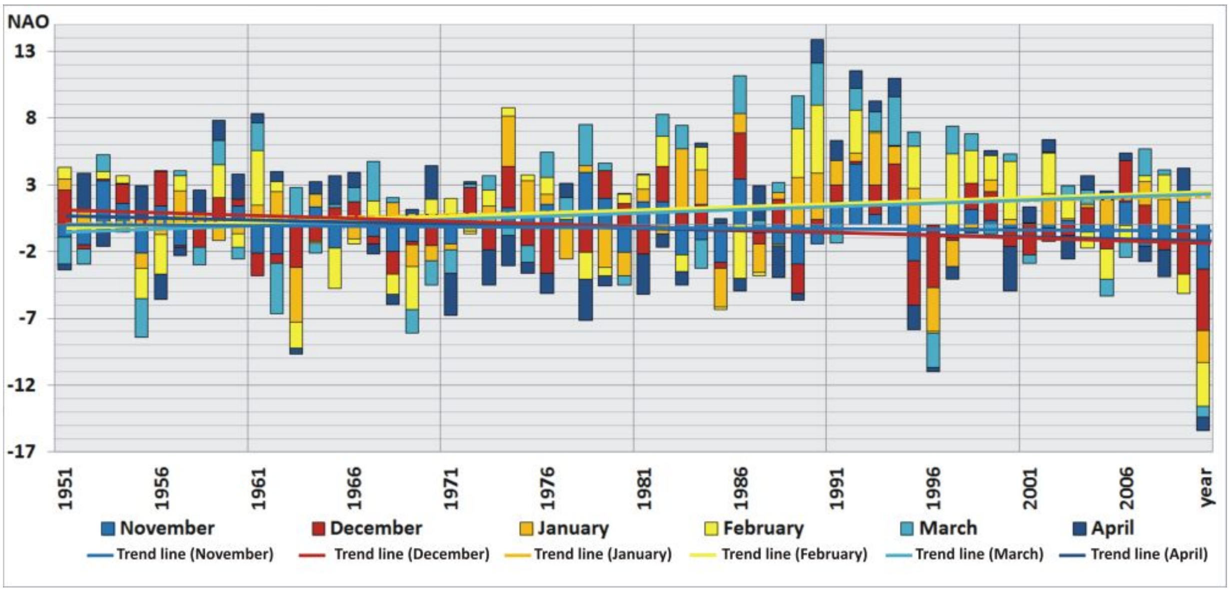

Fig. 6. Progression of positive and negative NAO phases for the winter months of 1951–2010, taking into account the linear trend for individual months.

The predominance of the negative phase over the positive phase (54.0%) was also observed in November, the beginning of the hydrological year, similar to December, whereas in March the positive phase (62.0%) was clearly predominant over the negative phase. A similar tendency was noted in April (51%) – (Figs. 5–6). Based on the results obtained, it was determined that during the last 30 years the frequency of occurrence of the positive phase of the NAO has increased, and this is particularly evident during the winter months.

Research has also shown a clear increase in anomalous winter periods, which exceed the range of calculation values and during which ($T_{mpt., multiyear}$) is in the range ($T_{mpt., multiyear}$, –0.5 SD ≤ $T_{mat., year}$, ≤ +0.5 SD), and therefore classified as normal seasons. This is particularly evident for the last two observed decades (Fig. 4). Such a situation is brought about by the increase in thermal anomalies in the cool half-year period of the hydrological year, to which the rise in the frequency of occurrence of the positive NAO contributes (Figs. 2, 5–6). The high values of Jones' index (Fig. 6) point to an increase in cyclonic activity and its impact on the Baltic coastal zone, in particular for the last twenty observed years, during which the influence of Atlantic oceanic climatic factors grew in significance, resulting in less severe winters. The meteorological stations in Łeba, Ustka and Kołobrzeg (Fig. 1) recorded only two winter seasons that were classified as anomalously cool, which account for no more than 3.3% of all observed seasons. Both seasons occurred in the first half of the researched period, i.e. in the years 1951–1980 (Figs. 2, 4).

Throughout the researched period there were 4 winter seasons that were classified as very warm (class 3), all recorded after 1987, and 7 winter seasons classified as warm (class 4). The first warm winter season was observed in the first observed 30-year period, in the years 1974/1975. The remaining warm winter seasons were recorded only after 1987 (Fig. 4). The largest number of seasons have been classified as normal. Throughout the entire observed period there was not a single extremely cool or extremely warm season. This could have been the result of specific climatic conditions. During the period from 1951 to 1987, no clear differences were observed in changes in thermal conditions, nor in the course of winter periods between individual meteorological stations, indicating a certainty of stationarity of measurement cycles. This stationarity was also confirmed by KPSS tests performed on measurement series. After 1987, there was a clear increase in the occurrence of periods exceeding the value boundary, where ($T_{mpt., multiyear}$, -0.5 SD $\leq T_{mat., year}$, $\leq +0.5$ SD), resulting in normal classification (Fig. 4) and distorting the stationarity of the entire observed period. Research also allowed us to observe a certain regularity in the characteristics of periods where ($T_{mpt., multiyear}$) is within the range below the value boundary ($T_{mpt., multiyear}$, -0.5 SD $\leq T_{mat., year}$, $\leq +0.5$ SD), that is periods classified as normal, i.e. the following periods: slightly cool (class 7), cool (class 8), very cool (class 9) and anomalously cool (class 10). The regularity in the characteristics of these periods manifests itself in a certain regularity of their occurrence. The winter seasons classified in these value ranges occur in 6- or 7-year periods. The observed fact points to the occurrence of a certain phasality of cool winter cycles in the researched period, which is fully dependent on the variability of atmospheric circulation (Fig. 4). In the last two observed decades there was noted a clear increase in winter seasons classified as slightly warm (class 5), warm (class 4) and very warm (class 3). Their occurrence coincides with that of the positive phase of the NAO. Particularly clear is the increase in seasons in which Jones' index adopted the highest values (Figs. 5–6), while the average annual air temperature in the winter period and the cool half-year period of the hydrological year exceeded the boundary value by approximately 4°C (Figs. 2 and 4). The quantitative analysis of winter seasons shows a clear division occurring between periods classified as cool, which are predominant in the first 30 observed years, and periods classified as warm, predominant in the second 30 observed years.

The results obtained have been confirmed by statistical research into time series, conducted on data series. On the basis of a test of time series autocorrelation, performed using the ARIMA model (seasonal SARIMA), it was determined that the series for average half-year values of individual parameters was not stationary for the majority of stations (Fig. 7). The non-stationarity of measurement cycles or the disruption of this stationarity is impacted by the clear increase in air temperature

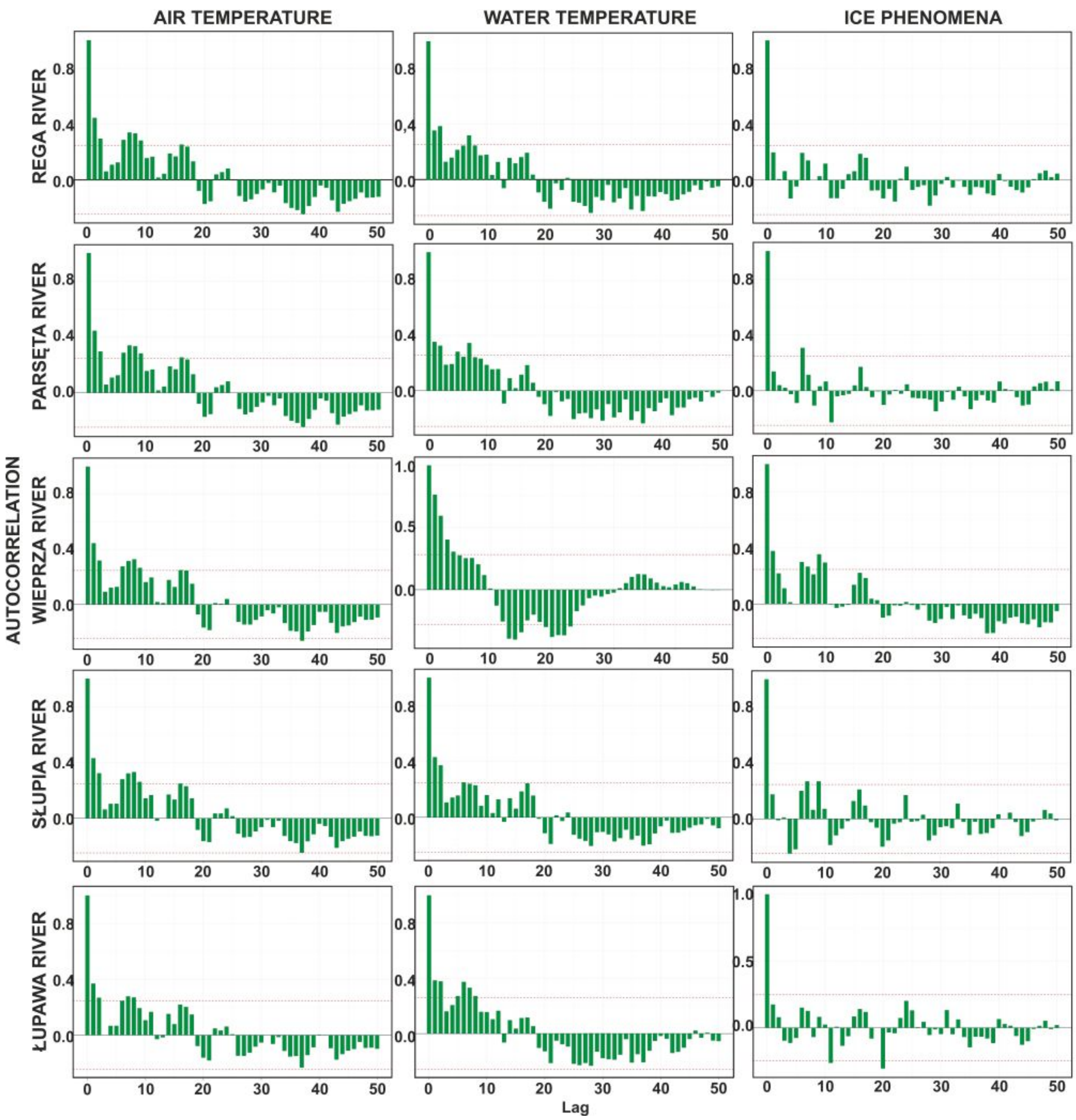

Fig. 7. Results of the autocorrelation test of individual parameters: air and water temperatures and ice phenomena for the years 1951–2010.

and water temperature observed since 1987. The change in the trend has been confirmed by GAM tests. We may therefore assume that the changes in air temperature observed during the last 30 years influenced the periodicity of cool periods and changes in ice phenomena. The number of days with an observed ice phenomenon on rivers is decreasing (Fig. 2), and this is related to the variability of the positive water temperature trend (Fig. 7).

An analysis of the trend using the Yue-Pilon method pointed to the occurrence of a growth trend. Correlation with the monotonic trend was also significantly positive (Fig. 8), meaning that we may talk of a growth trend in data (air and water temperature). A KPSS test performed for the time series associated with the variability in air temperature at meteorological stations and water temperature at water-level indicator points of the IMGW-PIB demonstrated a general non-stationarity of the entire analyzed series for all analyzed stations. At the same time, the KPSS test for the period prior to and including 1980 disclosed a certain stationarity of the data time series, irrespective of random fluctuations, around a solidly stable average value.

The results of tests confirmed our assumptions as to the appearance of a positive trend in the 1980s. Until 1981, the average annual water temperatures fluctuated around a certain average value, while in subsequent years they started to experience a gradual linear increase. The test confirmed our assumptions that a change in the trend occurred after 1987. The annual diversity of ice phenomena during the analyzed period, determined as Shannon's entropy for the distribution of phenomena in a given year, also displays a certain irregularity (Fig. 8). Line fitting to non-parametric regression is also somewhat variable, however this does not necessarily signify the occurrence of a clear actual trend. Even though it was determined, based on analysis of raw data, that the number of days with ice on individual sections of rivers in the Przymorze region had decreased over the past 20 years (calculated using the sum and arithmetic means), an analysis performed with the Yue-Pilon method indicated the lack of a clear linear trend. The monotonic correlation (Kendall's) between entropy and time also did not

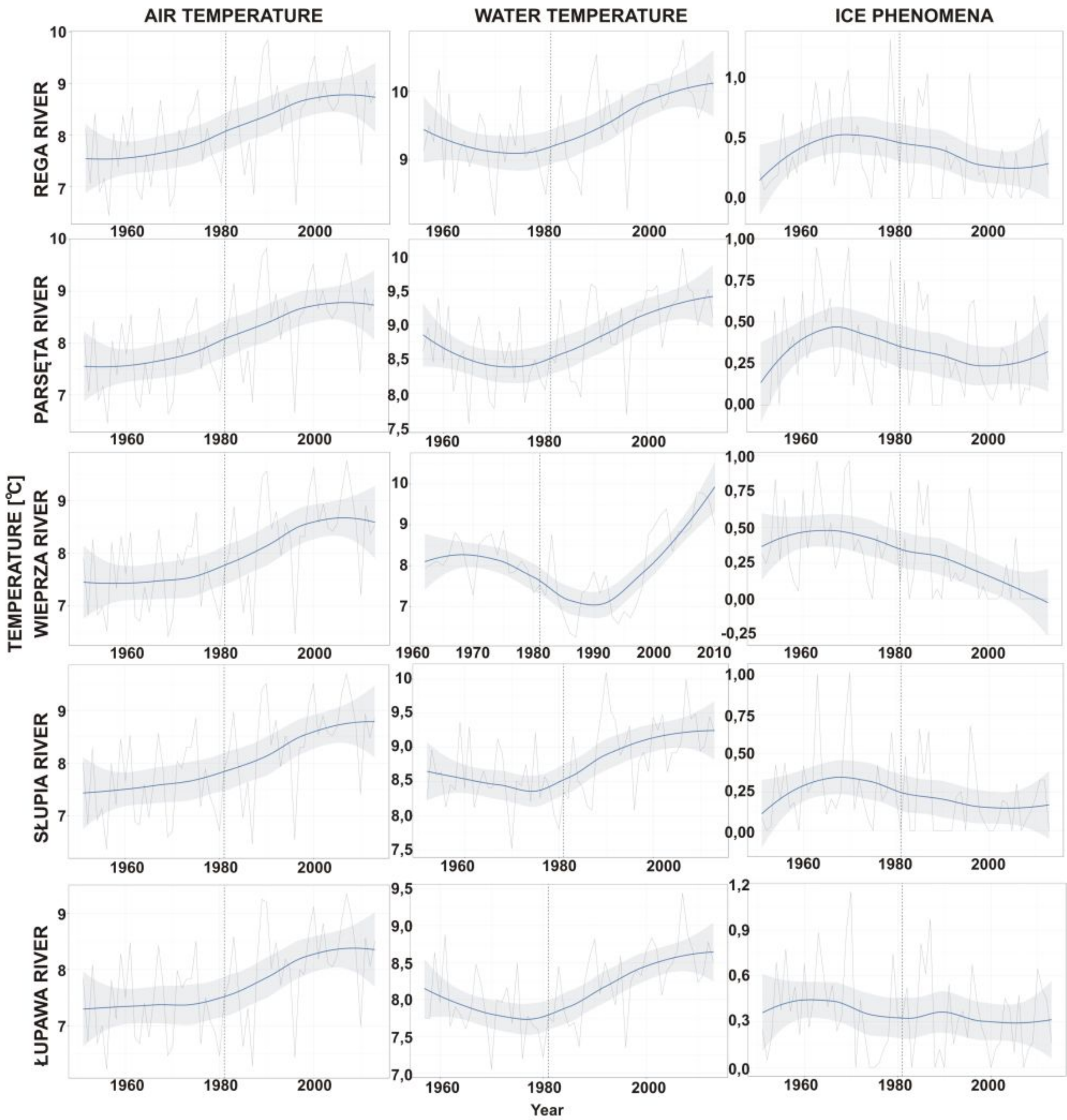

Fig. 8. Analysis results, using the Yue-Pilon method, for air and water temperature trends and ice phenomena for selected sections of Przymorze region rivers during the years 1951–2010.

show any significant trend. This is particularly evident for the rivers located east of Parsęta (Figs. 1, 2, 8), that is rivers characterized by a weakly developed nival regime and those transformed by anthropogenic factors. We may therefore state that the degree of diversity of ice phenomena observed on these rivers has not changed in any systematic way. This was further confirmed by the results of the KPSS test, which displayed a certain stationarity of annual entropy series. This can be the effect of an excessively short series of data. The monotonic trend points to a decrease in the number of ice phenomena, which would be concordant with the assumption adopted that an increase in water temperature in rivers, brought about by an increase in air temperature, leads to the shortening of the duration of phenomena.

The quantile charts elaborated based upon data concerning air and water temperature have shown that their distribution is basically very well fitted to the normal distribution. This points to the quasi-stable development of temperatures during the researched period, which is confirmed, among others, by the charts drawn up for monthly periods (Fig. 9).

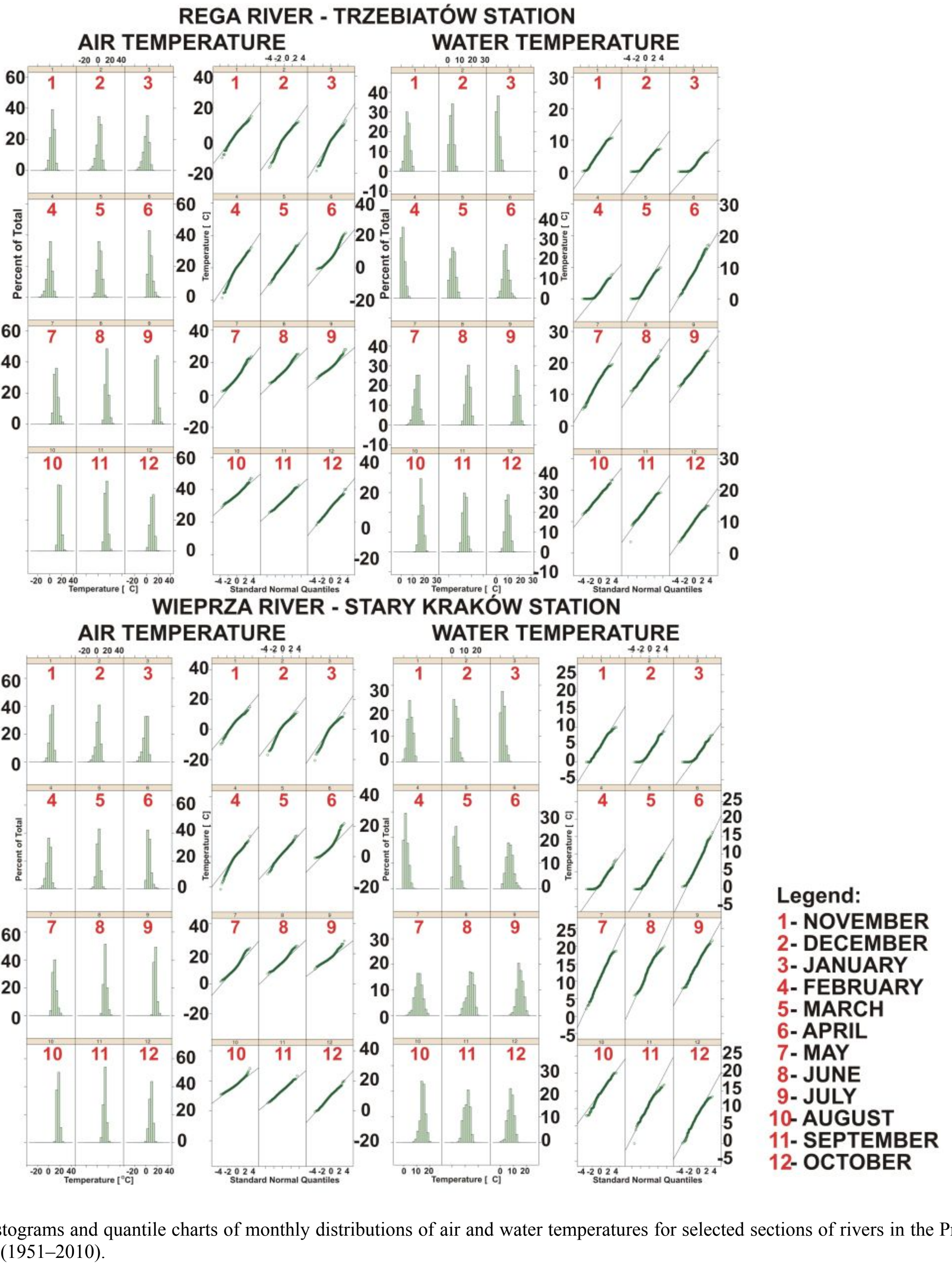

Fig. 9. Histograms and quantile charts of monthly distributions of air and water temperatures for selected sections of rivers in the Przymorze region (1951–2010).

The analyses conducted have proved that the greatest fluctuations caused by the occurrence of low temperatures are in the characteristics of the winter months (the cool half-year period of the hydrological year November – April). A comparative analysis of the frequency of ice phenomena on individual river sections and the types of these phenomena, which takes into consideration the degree of urbanization and the influence of anthropogenic factors, has shown the diversity of their occurrence. This is observed on river sections passing through cities (the station in Słupsk) – (Fig. 1) and on sections with a regulated bed or where the river flow is subject to modification by dumps of water from dammed reservoirs or is regulated by means of dams. This can be observed, for example, on the river section in Słupsk, or in Smołdzino, where there is a lesser diversity in ice phenomena forms (Figs. 2–3). Practically no ice cover – or ice floe, for that matter – have been observed on these sections, whereas on sections with a less transformed bed, or those located outside of urbanized areas, the ice forms observed on rivers are more diversified and the number of days in which they occur is greater, approximately 220 days for the entire researched 60-year period (stations in Trzebiatów, Bardy and Stary Kraków). The results confirm those of research previously conducted on the same aspects of rivers in the Przymorze region (Łukaszewicz, 2016, 2017b).

DISCUSSION AND CONCLUSIONS

The research performed displays a significant variability in the course and frequency of duration of ice phenomena in the rivers of the Przymorze region over the past 60 years. This variability manifests itself in the shortened duration of ice phenomena and a decrease in the diversity of ice forms observed on rivers, and thus in the disruption of the three-phase river icing cycle. Over the past few decades, a clear decrease in the duration of ice forms characteristic of the second and third phases of the icing cycle – such as permanent ice cover, ice jam and ice floe – has been observed. This negative trend is clearly marked after 1987, when the number of days recorded with ice phenomena on rivers fell by nearly one half. In Poland, comparable tendencies have been observed on the Vistula (Gorączko, 2013), the Oder (Kreft, 2013), the River Warta (Graf et al., 2018; Kornaś, 2014), the River Bug (Bączyk and Suchożebrski, 2016), and on rivers in the Przymorze region: Łeba (Łukaszewicz and Jawgiel, 2016), Słupia, Łupawa, Łeba, Reda, Wieprza, Parsęta (Łukaszewicz, 2016, 2017a, b, c; Ptak et al., 2016).

The research conducted has shown that the main cause of this variability was the increase in average annual air temperature observed in the cool half-year period of the hydrological year, which was particularly evident during the last two observed decades. The increase in air temperature was related to an increase in cyclonic activity, caused in part by the percentage growth of the positive phase of the North Atlantic Oscillation (NAO) and the rise in the value of Jones' index. The research has also revealed the significant impact of climatic changes on the variability of the thermal conditions of river waters. A positive trend is now being observed, manifesting itself with an increase in water temperature for all the stations on the Pomorze region rivers and having a statistically significant coefficient for the correlation between the analyzed parameters.

The results obtained pertaining to the increase in air temperature are concordant with research conducted by others authors in the Przymorze region. Kożuchowski (2000) while analysing the course of air temperature in Poland during the years 1959–1968 and 1989–1998, demonstrated that the influence of Atlantic oceanic climatic factors increased, leading to a rise in air temperature and the moderation of winter in the South Baltic Coastal strip. Research performed by Filipiak (2004) also confirmed that in the second half of the 20th century there occurred a positive air temperature trend in the winter season of the Przymorze region. Similar tendencies may be observed in the work of Kirschenstein and Łukaszewicz (2014). These tendencies have also been observed in the results of research concerning other regions of Poland and Europe (Bednorz and Kossowski, 2004; IPCC, 2007; Russak, 2009; Tylkowski, 2013).

The results of the conducted research have shown significant changes in the ice regime during the period of 1951–2010. This has also been confirmed by the results of research conducted on rivers in various parts of the Baltic region (in the northern and western part of the Baltic region). For 10-year increments over the past 30 years, the shortening of the duration of the ice cover on the rivers of the Baltic republics (and Belarus) has been demonstrated by Klavins et al. (2009) to be about 2–6 days per 10-year increment. The duration of the icing and ice-breaking period varies on rivers by more than one month, depending on the distance from the Baltic Sea and the Gulf of Riga, as well as on the characteristics of the river basin. The ice regime on the rivers of the Baltic region is strongly correlated with the North Atlantic NAO index, which is also highlighted by the results of research relating to the Baltic coastal zone in northern Poland. However, observed trends are not consistent between periods that are associated with the occurrence of mild and cold winters. The periodicity of ice phenomena in the Baltic region should be considered as quasi-periodic processes (Klavins et al. 2009).

Positive NAO phases, associated with strong western winds and increased flow of warm and humid air to Western Europe, result in warmer winters, later beginnings to winters and earlier springs (Chen and Hellström, 1999; Hurrell, 1995; Paeth et al., 1999). Over recent decades, a significant increase in air temperature has been detected in the Baltic region, as evidenced by, for example, meteorological observations in Riga (Latvia) and Uppsala (Sweden) (Klavins et al., 2009). At the Riga-University station, over the last 200 years (1795–2002), the average annual air temperature increased by 1.1°C, with its highest increase being observed in the spring season (an increase of 2.1°C). A significant increase in air temperature in the winter and spring season has been observed since the 1970s (Klavins et al., 2002; Lizuma et al., 2007). It has been observed that NAO affects winter precipitation with varying intensity along the Norwegian coast, in northern Sweden and in southern Finland (Uvo, 2003). It should be noted that close links between large-scale NAO enforcement and climate processes occur in the Baltic region on a regional scale (de Rham et al., 2008; Hagen and Feistel, 2005; Marshall et al., 2001). Yoo and D'Odorico (2002), in studying the climate impact during the end of ice phenomena in the Baltic region, showed that the winter NAO index still has a weak but significant effect on the spring temperature regime in the Baltic region, which explains the most important variables embedded in cryophenological records. In their opinion, other climate threats related to regional and global warming (for example, caused by CO_2) influence the appearance of clear trends in the spring temperature regime at the end of the ice season. This is confirmed by Hagen and Feistel (2005), Morse and Hicks (2005), and other research carried out in other regions. In the Baltic region this influence is revealed by the earlier disappearance of ice phenomena in the last few decades.

Research into the so-called spring ice breakup (IBU), conducted on the Aura River in Turku (southwest Finland) over the period of 1749–2018, showed the so-called inter-seasonal trends in the disappearance of ice phenomena. The disappearance of the ice on the river in March, which was extremely rare before 1900, became widespread, while the disappearance in May (previously once every decade) has not occurred since 1881. Over the last 100 years in Finland, there was a statistically significant increase in the average annual air temperature. During the first 50 years of this period, the greatest temperature increases were observed in the spring; however, for the next 50 years the greatest temperature increases took place in the winter season. This influenced the delayed dates for the occurrence of fading on rivers and lakes and accelerated the dates for their disappearance (Kuusisto and Elo, 1998). These results are also confirmed with research conducted on rivers in both the European and Asiatic regions of Russia (Agafonova and Frolova, 2007; Frolova and Alekseevskiy, 2010).

A comparative analysis of individual sections of rivers in the Przymorze region has also demonstrated a certain dependence concordant with research performed by other authors. On sections of regulated rivers that have hydrotechnical structures, the number of ice forms observed is considerably smaller than on sections undisturbed by anthropogenic activity or ones that have experienced only a slight degree of such activity. In order to supplement information about local Przymorze region rivers icing determinants at individual sections of the course, it is recommended to identify and continuous monitoring zones of impact of anthropogenic factors, which contribute to increases in the temperature of waters in the winter season, thereby limiting the formation of ice phenomena, and in particular ice cover. The results obtained are of particular significance for identifying the thermal and circulatory factors determining the appearance of ice phenomena on the rivers of the Baltic coastal zone in the Northern Poland. They are also of potential significance for indicating climate change. Additionally, the results are important for maintaining the economic and ecological functions of the river, including the assessment of the risk of occurrence of extreme thermal and river icing conditions.

Acknowledgements. The present paper is the result of research on ice phenomena occurrence and termal conditions of the river water, carried out as part of the research at the Department of Hydrology and Water Management of the Adam Mickiewicz University in Poznań, Poland.

REFERENCES

Agafonova, S.A., Florova, N.L., 2007. Features of ice regime of Northern Dvina rivers' basin. Water Resources J., 34, 2, 123–131. (In Russian.)

Akaike, H., 1969. Fitting autoregressive models for prediction. Annals of the institute of statistical mathematics, Tokyo, 21, 243–247.

Allan, J.D., 1998. Ecology of Running Water. Polish Scientific Publishers (PWN), Warsaw. (In Polish.)

Bączyk, A., Suchożebrski, J., 2016. Variability of ice phenomena on the Bug River (1903–2012). Inżynieria Ekologiczna, 49, 136–142. (In Polish.)

Bednorz, E., Kossowski, T., 2004. Long-term changes in snow cover depth in eastern Europe. Climate Research, 27, 3, 231–236.

Box, G.E.P., Jenkins, G.M., 1983. Time Series Analysis: Forecasting and Control. PWN, Warszawa. (In Polish.)

Chen, D., Hellström, C., 1999. The influence of the North Atlantic Oscillation on the regional temperature variability in Sweden: spatial and temporal variations. Tellus, 51A, 505–516.

Cleveland, W.S., Devlin, S.J., 1988. Locally-weighted regression: An approach to regression analysis by local fitting. Journal of the American Statistical Association, 83, 403, 596–610.

de Rham, L.P., Prowse, T.D., Bonsal, B.R., 2008. Temporal variations in river-ice break-up over the Mackenzie River Basin, Canada. J Hydrol, 349, 441–454.

EEA Report No. 12/2012. Climate change, impacts and vulnerability in Europe 2012. [online]. http://www.eea.europa.eu/pl/themes

Filipiak, J., 2004. Variability of Air Temperature on the Coast and Pomeranian Lake District in the Second Half of the 20th Century. IMGW, Warszawa. (In Polish.)

Frolova, N.L., Alekseevskiy, N.I., 2010. Influence of ice regime on hydroecological safety under climate change: the chasse study in the north of European part of Russia. In: Servat, E., Demuth, S., Deztter, A., Daniell, T. (Eds.): Proc. 6th Word FRIEND Conf. Global Change: Facing Risk and Threats to Water Resources. IAHS Publ. No. 340. IAHS Press, Wallingford, UK, pp. 40–46.

Girjatowicz, J.P., Świątek, M., Olechwir, T., 2002. The relationships of the North Atlantic Oscillation with ice conditions at the Polish Baltic coast. In: Marsz, A., Styszyńska, A. (Eds.): North Atlantic Oscillation and its Inflow on Variability of Climatic and Hydrologic Conditions of Poland. Maritime Academy, Gdynia, pp. 191–203. (In Polish.)

Gorączko, M., 2013. Variability of ice phenomena on the Vistula River in the vicinity of Bydgoszcz. Prz. Nauk. Inż. Środ., 62, 382–388. (In Polish.)

Graf, R., 2015. Variations of the thermal conditions of the Warta in the profile connecting the Urstromtal and gorge sections of the valley (Nowa Wieś Podgórna – Śrem – Poznań. In: Absalon, D., Matysik, M., Ruman, M. (Eds.): Nowoczesne metody i rozwiązania w hydrologii i gospodarce wodnej. Komisja Hydrologiczna PTG, PTG Oddział Katowice, pp. 177–194. (In Polish.)

Graf, R., 2018. Distribution properties of a measurement series of river water temperature at different time resolution levels (Based on the example of the Lowland River Noteć, Poland). Water, 10, 2, 203.

Graf, R., Tomczyk, A.M., 2018. The impact of cumulative negative air temperature degree-days on the appearance of ice cover on a river in relation to atmospheric circulation. Atmosphere, 9, 6, 204.

Graf, R., Łukaszewicz, J.T., Jawgiel, K., 2018. The analysis of the structure and duration of ice phenomena on the Warta river in relation to thermic conditions in the years 1991–2010. Woda-Środowisko-Obszary Wiejskie, 18, 4, 64, 5–28. (In Polish.)

Hagen, E., Feistel R., 2005. Climatic turning pints and regime shifts in the Baltic Sea region: the Baltic winter index (WIBIX) 1659–2002. Boreal Environ Res., 10, 211–224.

Hester, E.T., Doyle, M.W., 2011. Human impacts to river temperature and their effects of biological process: A quantitative synthesis. Journal of the American Water Resources Association, 47, 3, 571–587.

Hurrell, J.W., 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. Science, 269, 5224, 676–679.

IPCC, 2007. International Panel on Climate Change Fourth Assessment Report: Climate Change 2007. Cambridge University Press, Cambridge.

Jurgelėnaitė, A., Kriaučiūnienė, J., Šarauskienė, D., 2012. Spatial and temporal variation in the water temperature of Lithuanian rivers. Baltica, 25, 1, 65–76.

Kirschenstein, M.C., Łukaszewicz, J.T., 2014. Ekologiczeskie problemy osobo ochranjaemich pryrodnich territorii. Charakterystyka temperatury wozducha i atmosfericznych osadkow, a takze anomalii temperatury i osadkow w Koszalinie. In: Proc. Conf. Aktualnyje naucznо-techniczeskie i ekologiczeskie problemy sochranienia sredy obntanija. [Current scientific technical and ecological problems of the environmental resources protection]. Brest, pp. 119–128. (In Russian.)

Klavins, M., Briede, A., Rodinov, V., Kokorite, I., Frisk, T., 2002. Long-term changes of the river runoff in Latvia. Boreal Environ Res., 7, 447–456.

Klavins, M., Briede, A., Rodinov, V., 2009. Long term changes in ice and discharge regime of rivers in the Baltic region in relation to climatic variability. Climatic Change, 95, 3–4, 485–498.

Kondracki, J., 2009. Regional Geography of Poland. PWN, Warszawa. (In Polish.)

Kornaś, M., 2014. Ice phenomena in the Warta River in Poznań in 1961–2010. Questiones Geographice, 33, 1, 51–59.

Koronacki, J., Cwik, J., 2005. Statistical Learning Systems. ISBN, Warszawa, pp. 168–179. (In Polish.)

Kożuchowski, K., (Ed.), 2000. Seasons in Poland – Seasonal Changes in the Environment versus Long–Term Climatic Tendencies. IMGW Publisher. (In Polish.)

Kożuchowski, K., Degirmendžic, J., 2002. Circulation indicators and air temperature in Poland. In: Marsz, A., Styszyńska, A. (Eds.): North Atlantic Oscillation and its inflow on variability of climatic and hydrologic conditions of Poland. Akademia Morska w Gdyni, pp. 111–128. (In Polish.)

Kreft, A., 2013. Ice problems in the Odra section of the Oder. Gospodarka Wodna, 6, 1–4. (In Polish.)

Kuusisto, E., Elo, A.R., 1998. Lake and river ice variables as climate indicators in Northern Europe. In: Internationale Vereinigung für Theoretische und Angewandte Limnologie: Verhandlungen, pp. 2761–2764.

Kwiatkowski, D., Philips, P.C.B., Schmidt, P., Shin, Y., 1992. Testing the null hypothesis of stationary against the alternative of a unit root. Journal of Econometrics, 54, 159–178.

Lizuma, L., Klavins, M., Briede, A., Rodinovs, V., 2007. Long-term changes of air temperature in Latvia. In: Klavins, M. (Ed): Climate Change in Latvia. UL Publishing House, Riga, pp. 11–21.

Lorenc, H., 1998. Evaluation of the degree of implementation of the program "meteorological observations and climate studies in the system of integrated environmental monitoring" and synthesis of obtained results for the period 1994-1997. In: Kostrzewski, A. (Ed.): Integrated Monitoring of the Natural Environment. Functioning and development trends of Poland's geo-ecosystems. IX Symposium of the ZMŚP, Biblioteka Monitoringu Środowiska. Warszawa, pp. 113–119. (In Polish.)

Łukaszewicz, J., 2017a. The frequency and nature of the occurrence of ice phenomena in the lower reaches of the Wieprza River in the aspect of climate change, with particular regard to changes in air temperature. Nauki Przyrodnicze. II, 5, 69–74. (In Polish.)

Łukaszewicz, J.T., 2016. The process of the ice phenomenon on the Słupia River in 1960–2013. Słupskie Prace Geograficzne, 12, 5–20. (In Polish.)

Łukaszewicz, J.T., 2017b. The course and the character of the ice phenomena in selected sections of Przymorze Rivers with a high influence of anthropopressure in relation to the climate changes that occur in the coastal zone of the Baltic Sea. Acta Architectura, 16, 1, 93–113. (In Polish.)

Łukaszewicz, J.T., 2017c. Nature and variability of the ice phenomena in lower reaches of the Rega river in the context of the climate changes. In: Zinovyev, E.A., Kitaev, A.B. (Eds): Proc. Int. Conf. Hydrobiology and Ichthyology. Perm State Universisty, Perm, 3, 3, pp. 123–130. (In Russian.)

Łukaszewicz, J.T., Jawgiel, K., 2016. The process of the ice phenomenon on the Łeba River. Badania Fizjograficzne, Seria - A - Geografia Fizyczna, pp. 97–116. (In Polish.)

Magnuson, J.J., Robertson, D.M., Benson, B.J., Wynne, R.H., Livingstone, D.M., Arai, T., Assel, R.A., Barry, R.G., Card, V., Kuusisto, E., Grain, N.G., Prowse, T.D., Stewart, K.M., Vuglinski, V.S., 2000. Historical trends in lake and rivers ice cover in the Northern Hemisphere. Science, 289, 5482, 1743–1746.

Majewski, W., 2009. Flows in open channel and ice phenomena. Acta Geophysica, 55, 1, 11–2. DOI: 10.2478/s11600-006-0041-8.

Marsz, A., Styszyńska, A., 2001. The North Atlantic Oscillation and the Air Temperature over Poland. Wyższa Szkoła Morska, Gdynia. (In Polish.)

Marshall, J., Kushnir, Y., Battisti D., Chang, P., Czaja, A., Dickson, R., Hurrell, J., McCartney, M., Saravanan, R., Visbeck, M., 2001. North Atlantic climate variability: phenomena, impacts and mechanisms. Int. Journal of Climatology, 21, 1863–1898.

Morse, B., Hicks, F., 2005. Advances in river ice hydrology 1999–2003. Hydrol. Process., 19, 1, 247–263.

Niedźwiedź, T., 2002. Relations between NAO and circulation indicators over Poland. In: Marsz, A., Styszyńska, A. (Eds.): North Atlantic Oscillation and its inflow on variability of climatic and hydrologic conditions of Poland. Wyższa Szkoła Morska, Gdynia, pp. 87–97. (In Polish.)

Paeth, H., Hense, A., Glowienka-Hense, R., Voss, R., Cubash, U., 1999. The North Atlantic Oscillation as an indicator for greenhouse-gas induced regional climate change. Clim. Dyn., 15, 953–960.

Prowse, T.D., Beltaos, S., 2002. Climatic control of river-ice hydrology: a review. Hydrol. Process., 16, 805–822, DOI: 10.1002/hyp.369.

Przybylak, R., Wójcik, G., Marciniak, K., 2003. Influence of the North Atlantic Oscillation and Arctic Oscillation on thermal conditions in the cold season in Poland from the 16^{th} to the 20^{th} centuries. Przegl. Geofiz., 48, 61–74. (In Polish.)

Ptak, M., Choiński, A., Kirviel, J., 2016. Long-term water temperature fluctuations in coastal rivers (southern Baltic) in Poland. Bulletin of Geography. Physical Geography Series, 11, 35–42.

Russak, V., 2009. Changes in solar radiation and their influence on temperature trend in Estonia (1955-2007). Journal of Geophysical Research Atmospheres, 114, 1, 114 (D00D01).

Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Urbana.

Shumway, R.H., Stoffer, D.S., 2010. Time Series Analysis and its Applications with R Examples. Springer Science & Business Media.

Taylor, S., Letham, B., 2017. Prophet: Automatic Forecasting Procedure. R package version 0.1.1.

Tylkowski, J., 2013. Temporal and spatial variability of air temperature and precipitation at the Polish coastal zone of the southern Baltic Sea. Baltica, 26, 1, 83–94.

Uvo, C.B., 2003. Analyses and regionalization of Northern Europe winter precipitation based on its relationship with North Atlantic Oscillations. Int. J. Climatol., 23, 1185–1194.

Webb, B.W., Nobilis, F., 2007. Long-term changes in river temperature and the influence of climatic and hydrological factors. Hydrological Sciences Journal, 52, 1, 74–85.

Woś, A., 2010. Climate of Poland in the Second Half of the Twentieth Century. Wydawnictwo Naukowe UAM, Poznan. (In Polish.)

Yoo, J., D'Odorico, P., 2002. Trends and fluctuations in the dates of ice break-up of lakes and rivers in Northern Europe: the effect of the North Atlantic. Journal of Hydrology, 268, 1–4, 100–112.

Yue, S., Pilon, P., Phinney, B., Cavadias, G., 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrological Processes, 16, 9, 1807–1829.

Received 22 January 2019
Accepted 5 June 2019