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VARIATION OF THE NORTH ATLANTIC OSCILLATION ACCORDING TO HURRELL'S NAO_{DJFM} INDEX (1864-2019)

ZMIENNOŚĆ OSCYLACJI PÓŁNOCNOATLANTYCKIEJ NA PODSTAWIE WSKAŹNIKA NAO_{DJFM} HURRELLA (1864-2019)

Introduction

The North Atlantic Oscillation Index (NAO_{DJFM}), prepared by Hurrell (1995), expresses the difference between the standardized deviations from the mean pressure values in Lisbon and Iceland (Stykkishómur + Reykjavik) in the winter season, covering the period from December to March (DJFM). This indicator uses pressure averages and standard deviations determined on the basis of data from 1864-1983. It reflects, like other NAO indices, the changing gradients in the pressure field between the pressure systems which shape the North Atlantic Oscillation – the Azores High and the Icelandic Low. At the same time, it is also a measure of the intensity of the zonal atmospheric circulation over the North Atlantic and Europe. However, the design of the indicator entails the fact that the assessments of the intensity of western circulation at different seasons of the year based on it are not directly comparable (Styszyńska 2019). The Hurrell index is one of the so-called NAO station-based indices; therefore, it cannot precisely characterize the oscillation of pressure gradients between the Azores High and the Icelandic Low in the case of changes in the position of both systems. It should also be noted that there is a distance of more than 10 degrees longitude between Lisbon and Iceland, so the pressure gradient associated with the Hurrell index does not define the exact western direction of circulation – it is rather the WSW direction.

Positive values of the NAO_{DJFM} index mean an above-average intensity of circulation in the Lisbon–Iceland profile, negative indices indicate its weakening which is usually accompanied by the occurrence of meridional types of circulation, blockage situations, or even the flow of air masses from the east. However, it is worth emphasizing that negative NAO phases are not tantamount to the disappearance of the western zonal circulation.

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During the "boreal winter" (DJFM), zonal circulation is the most strongly developed, shows the greatest year-to-year variability, and its impact on climatic conditions becomes the most significant (Visbeck et al. 2001; Iles, Hegerl 2017). The impacts of these changes are most clearly visible in the area of the 55th parallel and extend to Central and Eastern Europe.

The NAO_{DJFM} index is one of the circulation indices most frequently used by climatologists; it allows, among others, to explain much of the observed variation of individual climate elements (especially air temperature) over large mid-latitude areas in the Atlantic-European sector. The Hurrell NAO index has a strong positive correlation with the other "station-based" NAO indices, as well as with the circulation indices created by the method of principal components analysis of the pressure field (Wibig 2019). Hurrell et al. (2003) emphasize the fact that the NAO_{DJFM} index accurately reflects changes in pressure systems over the North Atlantic; it is closely correlated (r = 0.92) with the main component of the pressure field in the area of the NAO activity. Long-term changes in the NAO_{DJFM} Hurrell index turn out to be consistent with the changes in the "new NAO index" which allows for the shape of the pressure field in the vast area of the Atlantic and Europe between 20-90°N as well as 80°W and 30°E (Jianping, Wang 2003).

A significant correlation coefficient (r = 0.61) is characteristic of the values of the NAO_{DJFM} index and the frequency of zonal forms of mid-tropospheric circulation, delimited on the basis of the Vangenheim–Girs classification (Girs 1971, 1974; Degirmendžić, Kożuchowski 2019). A weaker, negative correlation occurs between the NAO_{DJFM} indices and the indices characteristic of the development of meridional types of circulation, such as the SCAND index (r = –0.45), or the frequency of E and C forms according to the Vangenheim–Girs classification (r = –0.38 and r = –0.33). A positive, significant correlation is characteristic of the relationship between the NAO_{DJFM} index and the frequency of zonal types of circulation over Poland and Europe, i.e. type A and type C2D according to the Osuchowska–Klein classification. The correlation coefficients here are r = 0.548 and r = 0.324, respectively (Styszyńska 2002). Bartoszek (2017) found a significant correlation between NAO_{DJFM} and the frequency of circulation types bringing strong western advection in Central and Eastern Europe (r = 0.55). He also noticed that the correlation between the NAO_{DJFM} index and the frequency of intense SW, W and NW advection became closer after 1960, probably as a result of the eastward shift of the baric systems controlling the North Atlantic Oscillation (Johnson et al. 2008; Bartoszek 2017).

Ostermeier and Wallace (2003) pointed to the convergence of the NAO index changes with the hemispheric Arctic Oscillation mode (AO/NAM); the NAO phenomenon was defined as a regional aspect of circulation processes on a hemispheric scale. They also mentioned the stochastic nature of their variation.

Ambaum et al. (2001) using the PCA methods compared NAO and AO variability; they found a negative correlation between zonal flows over the Atlantic and Pacific sectors of the hemisphere and expressed an intrigued conclusion that "*… the NAO paradigm may be more physically relevant and robust for Northern Hemisphere variability than is the AO paradigm*".

Also Visbeck et al. (2001) expressed the view that changes in NAO indices over time are characterized by poor persistence and that the observed long-term fluctuations in NAO can be interpreted as a manifestation of random variation. Stephenson et al. (2000) pointed to the complex, both deterministic and stochastic nature of the NAO variation dominated by short-term 2-5-year fluctuations and with longer, ca 10-year trends appearing. According to Marsz (1999), the spectrum of the NAO_{DJFM} indices includes maxima related to 64- and 44-year cycles, but a cycle with a period of 7.76 years is most clearly visible and present also in the spectrum of various climatic characteristics of the winter season in Europe. Hurrell et al. (2003) presented a spectrum of the NAO_{DJFM} index series according to data from the period 1899-2002 which shows a tendency to quasi-two-year and 8-10-year periodicity and the presence of weak red noise in a time series. Similar spectral assessments were presented by Wunsch (1999): on the basis of a series of the NAO_{DJFM} indices from the years 1864-1996, he showed power maxima related to a periodicity of 2.5 and 8 years and a weak, or actually no persistence of the NAO changes over time (nearly white spectral density).

On the basis of the NAO_{DJFM} index series from 1864-1995, Marsz (1999) distinguished multi-year phases of the NAO changes, i.e. the so-called circulation epochs: an epoch of low NAO_{DJFM} indices lasting until 1899, i.e. of poor zonal circulation, an epoch of zonal circulation lasting until 1930 and again an epoch of weakened zonal circulation lasting until 1970, followed by another "zonal epoch". A characteristic feature of these changes is "the amplitude of the NAO index fluctuations between epochs increasing with time" (Marsz 1999, p. 233). The significant development of positive NAO phases related to changes in the thermohaline circulation in the Atlantic Ocean was presented by Hurrell et al. (2001).

The increase in the NAO indices at the end of 1980s to the maximum $NAO_{DJFM} = +5.08$ in the winter of 1988/1989 can be considered particularly significant. The decline in the NAO index in the winter of 2009/2010 ($NAO_{DJFM} = -4.64$) described by Osborn (2011) was equally rapid. However, the biggest change in the entire series of the NAO_{DJFM} indices beginning in 1864 occurred between the 1994/1995 and 1995/1996 winter seasons, when the NAO_{DJFM} index fell by as much as 7.74 NAO units to –3.78 in the winter of 1995/1996. As noted by Jones et al. (1997), it was a "dramatic switch of the index". It is noteworthy that all those extreme changes occurred in what should be described as the period of intense zonal circulation; the average value of the NAO_{DJFM} index in 1988-2015 was +1.04 (Styszyńska et al. 2019).

The above-mentioned epochs of the NAO changes correlate quite well with the circulation epochs defined by other authors based on various criteria; an overview of these divisions can be found in the articles by Degirmendžić et al. (2000, 2018).

The stochastic form of the variation of the NAO phases does not exclude the existence of factors influencing this variation. The multitude of these factors and their interrelationships as well as the macro-turbulent nature of circulation processes are most likely the reason for the formation of stochastic aspects of the NAO variation[1]. Hurrell et al. (2003) quote the results of analyzes by Feldstein (2000), who estimated that the year-to-year variation (variance) of the NAO indices in the second half of the 20th century was significantly higher than the "stochastic variance", i.e. the level of climate noise. This surplus, reaching ca 60% of the total variance of the NAO indices, would therefore evidence the determination of the NAO fluctuations and the possibility of determining their causes.

A number of researchers point to the thermal interactions of the atmosphere over the Atlantic and the thermohaline circulation of ocean waters shaping the heat flow to the atmosphere, the pressure field and the form of atmospheric circulation (Rodwell et al. 1999; Hurrell et al. 2001; Sutton, Dong 2012; Gastineau, Frankignoul 2015; Marsz 2019). The North Atlantic Oscillation being formed in the atmosphere and its long-term trends may be directly linked to the Atlantic Multidecadal Oscillation (AMO) observed in the ocean (Bekryaev 2019). Wanner et al. (2001) regard the seasonal and short-term fluctuations in the NAO as a form of circulation variation which is entirely formed in the atmosphere, whereas as concerns the changes on a 10-year time scale they write about a likely impact of the processes taking place in the ocean and the amount of ice on its surface. An interesting report on the relationship of the ocean level anomaly with changes in the NAO index was recently presented by Świerczyńska-Chlaścik and Niedzielski (2020).

Threjll et al. (2003) wrote about the relationship between the NAO and the geopotential field in the atmosphere with geomagnetic activity. In a way, they referred to earlier hypotheses that solar activity was a factor shaping the cyclical and quasi-cyclical changes in the climate system (e.g. Bucha 1991).

Although much of the interest in the significance of solar impact on climate variation dates back to the early 20th century, it is still an important topic for research. The paper of Maruyama et al. (2008) represents an advanced form of such investigation. It indicates the relations between the solar activity, the ozone content in stratosphere and the zonality of atmospheric circulation on the basis of fractal analysis of selected time series of measurements. The above-delineated circulation epochs are subject to quasi-cyclical changes over a period of around 60 years which, according to some researchers (Sidorenkov, Orlov 2008), are correlated with the rotation of the Earth and which may be a signal of similar (65-70-year) oscillations in the global climate system (Schlesinger, Ramankutty 1994).

Some researchers, including the aforementioned Ostermeier and Wallace (2003) do not exclude anthropogenic influences on the atmospheric circulation, causing e.g. a significant development of the positive NAO phases observed at the end of the 20th century. A similar view was also expressed by Miętus (2002) according to whom "the statistically significant intensification of the positive NAO phase has extra-natural causes" (Miętus 2002, p. 44).

[1] Lyapunov theorem states that the distribution of a random variable X becomes a normal distribution if this variable is a sum of a large number of independent variables, each of which has only a negligible influence on the variable X (after: Gmurman 1975, p. 147). It is possible that this applies to the NAO index distribution.

The observed variation of the NAO indices is undoubtedly affected by the climate changes in the polar and subpolar regions. Both in the first phase of the warming in the Arctic at the turn of the 20th century and during the present climate change, the positive NAO phases developed with the variation of the NAO indices growing significantly from year to year; the amplitude of their fluctuations increased. Such "variability" can be seen by analyzing the 156-year series of the NAO_{DJFM} index.

Objectives, data and methods of analyzing the index variation

Regardless of the stochastic or quasi-stochastic origin of the analyzed index variation, there are significant anomalies in the index value in the NAO_{DJFM} time series which are grouped in multi-year periods referred to as "circulation epochs". The duration of these "epochs" is sometimes disturbed by often-occurring extreme index values, inconsistent with the general character of the epoch: in the epochs of prevailing zonal circulation, deep minima of the index appear, and *vice versa*, in periods of weakened zonal circulation, high index values occur. Therefore, in this study the thesis was adopted that the duration of a circulation epoch is determined not so much by a significant deviation of the mean value of the circulation index, but by an "anomalous" frequency of high/low index values. The averages and frequencies are obviously correlated, but it seems that speaking of frequency slightly better reflects the actual "nature" of the circulation epochs. A similar approach, highlighting the frequency of "NAO regimes" in the description of the history of the NAO changes, was presented by Hurrell et al. (2003, see Fig. 11).

Moreover, it was assumed that the periods of significantly intensified or weakened zonal circulation do not follow each other directly. They are not the alternating multiannual NAO phases (with positive or negative index values), but the episodic periods of significant concentration of high or low index values. Between these episodes there is an approximately "normal" state of zonal circulation, with its inherent variation between DJFM seasons and an approximately symmetrical distribution of the index values.

The main content of this article is an attempt to delimit the epochs as so defined. Its purpose is to outline the long-term history of the NAO changes on the basis of newly defined criteria, based on the evaluation of the observed distribution of the NAO_{DJFM} index values in individual decades of the multiannual period.

In the analyzes presented in this study, a time series of seasonal (DJFM) mean values of the NAO index according to Hurrell from the period 1864-2019 (the number of the NAO_{DJFM} items is n = 156) were used. The data comes from the collection of Hurrell Station Based DJFM NAO Index (Lisbon-Stykkishómur/Reykjavik-Island)[2].

The analyzes were performed using simple statistical methods: the mean value and standard deviation as well as deciles and quartiles of a series of the NAO_{DJFM} index values were determined. The division of indices according to the D1 and D9 deciles

[2] https://climatedataguide.uncar.edu/sites/default/files/nao_station_djfm.txt

and the Q1, Q2 and Q3 quartiles made it possible to assign each observed NAO_{DJFM} value to an appropriate class (fraction): <D1, <Q1, <Q2, >Q2, >Q3 and >D9.

In search for relationships between the index values in successive DJFM seasons of the multi-year period, a time series of changes in the year-to-year index value was used ($\Delta_i = NAO_{i+1} - NAO_i$). The absolute mean value of these changes ($|\Delta|$) and their variation (dispersion), as well as the frequency of year-to-year changes in the above-mentioned index fractions were calculated. The frequency of changes in the change sign was also considered (as a result of increases/decreases in the index in successive years). The frequency distributions of these changes were assessed based on contingency coefficients. The coefficient of convergence (association) in the form: $A = (ad - bc)/(ad + bc)$ was used, where a and d are the frequencies of succession of the matching index classes in successive years, b and c – the frequencies of successive diverse classes (a version of formula A according to Yule and Kendall, 1940).The contingency coefficient $\Phi = \sqrt{\chi^2/N}$ (where χ^2 is the value of chi-square test, N – number of elements) as well as its modified version known as Cramér's V coefficient were used. The differences between the frequency distributions were also assessed using the Kolmogorov-Smirnov test. The assessment of the persistence of the inter-annual NAO_{DJFM} index changes was performed using the autocorrelation coefficient (r1). A runs test was also used to assess persistence. The numbers of runs were determined based on the frequencies of individual fractions of the index. The specified numbers of runs (R) were compared with the number of runs in a sequence of random numbers (R_0):

$$R_0 = (2n_1 \cdot n_2)/(N+1)$$

where n_1 and n_2 are numbers of elements of two fractions and $N = n_1+n_2 = 156$).

The significance of the difference in the numbers of runs was assessed based on the Z test:

$$Z = (R - R_0)/bsR_0$$

where bsR_0 – standard error of assessment of the number of runs R_0

$$bsR_0 = \sqrt{2n_1 n_2(2n_1 n_2 - N)/(N^2(N-1))} \text{ (according to Norcliffe 1986).}$$

The frequencies of the NAO_{DJFM} indices were analyzed in consecutive 10-year periods, i.e. in 147 decades. The frequency of the NAO_{DJFM} indices was calculated, taking into consideration the classes (fractions) of its values determined by quartiles and the 1st and 9th deciles. Based on the binomial distribution, theoretical probabilities (P) of the frequencies of fractions (k) in 10-year series were determined (Table 1). The known Bernoulli formula was used: $P(k) = C_n^k p^k q^{n-k}$ where $k = 0, 1, 2 \ldots, n$, $n = 10$, $p + q = 1$, C_n^k – coefficients in Newton's binomial expansion formula (after Gmurman 1975).

Attention was drawn to the decades in which the observed frequencies were characterized by a significantly low probability of occurrence ($P < \approx 0.05$). For example, the decades were distinguished in which the number of cases of the $NAO_{DJFM} > Q2$ was significantly high and amounted to $k \geq 8$, and the decades in which the number of cases of the $NAO_{DJFM} > Q2$ was significantly low and was $k \leq 2$. These decades were assigned Z (*zonal*) and M (*meridional*) symbols, respectively. Similarly, decades were distinguished based on the frequency of the $NAO_{DJFM} > Q3$ and $NAO_{DJFM} < Q1$ (here in both cases $k \geq 5$ and $k = 0$) and on the frequency of the $NAO_{DJFM} > D9$ and $NAO_{DJFM} < D1$ (in these cases $k \geq 3$) (see Table 1). The distinction into Z decades and M decades based on the anomalous frequencies of the 5th fraction, i.e. $NAO_{DJFM} > Q2$, $NAO_{DJFM} > Q3$, $NAO_{DJFM} < Q1$, $NAO_{DJFM} < D1$ and $NAO_{DJFM} > D9$ were treated jointly, allowing for the "anomalous" frequency of the 1st, 2nd... or 5th fraction (in most cases the anomalous decade was distinguished by the anomalous frequencies of several fractions). This manner of distinguishing between the Z decades and the M decades is hereinafter referred to as the "F5 method".

Table 1. Probabilities (P) of occurrence of exactly k events with probability p in 10 trials (in a 10-year period).

Tabela 1. Prawdopodobieństwa (P) wystąpienia dokładnie k zdarzeń o prawdopodobieństwie p w 10 próbach (w 10-leciu).

k	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
p = 0.50	**<0.01**	**0.01**	**0.04**	0.12	0.21	0.25	0.21	0.12	**0.04**	**0.01**	**<0.01**
p = 0.25	**0.06**	0.19	0.28	0.25	0.15	**0.06**	**0.02**	**<0.01**	**<0.01**	**<0.01**	**<0.01**
p = 0.10	0.35	0.39	0.19	**0.06**	**0.01**	**<0.01**	**<0.0**	**<0.01**	**<0.01**	**<0.01**	**<0.01**

Furthermore, a second, slightly changed method of assessing the structure of indices in decades was prepared; namely, the frequencies of the NAO_{DJFM} index $> Q1$ (frequency f1), $NAO_{DJFM} > Q2$ (f2) and $NAO_{DJFM} > Q3$ (f3) were used in the construction of the frequency index $\Sigma f = f1 + f2 + f3$. In the case of a decade, the index may assume the values $0 \leq \Sigma f \leq 30$, and the average long-term frequency distribution ($3/4n + 2/4n + 1/4n$) appearing in a decade ($n = 10$) is characterized by the index $\Sigma f = 15$. For the sake of simplicity, the results are presented in the form of the difference $\Sigma df = 15 - \Sigma f$ and the relative measure $\Sigma df/15$. Based on the assessment of the standard deviation of the frequency index, the ranges of significant (at a level of $\alpha = 0.05$) deviations of the index regarding the value of $\Sigma f = 15$ were determined: $\Sigma f \leq 7$ and $\Sigma f \geq 23$. The decades satisfying the condition $\Sigma f \leq 7$ and $\Sigma f \geq 23$ were assigned to class M and class Z, respectively (the "DF" method). Both indices (F5 and DF) provide the data for delimitation of extreme episodes in the course of NAO.

The frequency index was used to describe the long-term fluctuation of the NAO_{DJFM} index, i.e. its changes in successive decades and consecutive 10-year periods. The Σdf indicator is of course correlated with the average value of the NAO_{DJFM} index in decades (correlation coefficient $r = 0.97$); it is, however, a filter allowing to "smooth out" the extreme values of the index, and at the same time satisfying the assumption that the multi-year periods of significant intensification or weakening of zonal circulation, i.e. the "circulation epochs", shaped by significant changes in the frequency of positive and negative NAO phases, reflect the "anomalies" of this frequency. The frequency index turned out to be a stricter criterion for distinguishing significant NAO anomalies than the deviations of the NAO_{DJFM} mean values or the criteria of the F5 method.

The fluctuations of the frequency index were compared with the fluctuations of random numbers. For this purpose, four selected 156-element runs of random numbers from a probability density set of normal distribution u (u) were used, which made it possible to create a series of random distributions of the frequency index in 10-element samples and to compare them with the observed Σdf indices in 10-year periods.

Persistence and year-to-year index variation

The statistics describing the set of the NAO_{DJFM} indices in the multiannual period 1864-2019 are presented in Table 2. The average value of the index in the multiannual period is slightly higher than 0, which results from the predominance of positive NAO phases at the end of the 20th century and the fact that the Hurrell index was defined on the basis of data ending in 1983. Most of the highest index values appeared in the 1980s and later, whereas the lowest indices occurred in the vast majority before 1970. The highest recorded value of the index (NAO_{DJFM} = 5.08) occurred in 1989[3], the lowest (–4.89) in 1969. These numbers indicate a growing tendency and significant fluctuations in the NAO_{DJFM} index in the second half of the 20th century; however, the previous multiple changes of its trends in particular parts of the entire multi-year period 1864-2019 raise doubts as to the existence of a permanent upward trend in the NAO, notably understood as a linear trend.

The amplitude of changes in the index in the multiannual period 1864-2019 is close to the value of 10 NAO units, and the extreme values of the index are distributed approximately symmetrically with respect to the average and satisfy the "three-sigma rule" (3×1.95 = 5.85, see Table 2). The distances between the quartiles and the median and the slight difference between the mean and the median indicate that the observed NAO_{DJFM} distribution is not perfectly symmetrical. However, it also shows no significant differences in comparison with the normal distribution. Using the chi-square test, χ^2 = 9.66 was obtained, which means there are no significant differences in distributions at the level of α = 0.05.

The persistence of the short-term variation of the NAO_{DJFM} was analyzed using a runs test: runs were distinguished in which NAO_{DJFM} year-to-year values continued to remain

[3] In the descriptions of the NAO_{DJFM} series of indices, the date of occurrence of a given value means the year corresponding to the months of JFM; the 1989 index corresponds to season D 1988 / J, F, M 1989, the 1969 index corresponds to season D 1968 / J, F, M 1969, etc.

Table 2. Statistics of a time series of the NAO_{DJFM} index values (1864-2019).

Tabela 2. Statystyki szeregu czasowego wartości indeksów NAO_{DJFM} (1864-2019).

Statistics/Statystyki	NAO_{DJFM}			
mean/średnia	0.23			
difference*/różnica |Δ|	2.03			
stand. dev./odch. stand.	1.95			
1st decile/1. decyl D1	–2.42			
1st quartile/1. kwartyl Q1	–1.03			
median/mediana Q2	0.27			
3rd quartile/3. kwartyl Q3	1.63			
9th decile/9. decyl D9	2.74			
10 highest (max) and 10 lowest (min) values 10 najwyższych (max.) i 10 najniższych (min.) wartości	max.	year/rok	min.	year/rok
	3.87	1882	–3.01	1870
	3.89	1903	–3.80	1881
	3.18	1920	–3.97	1895
	3.42	1983	–3.80	1917
	5.08	1989	–3.86	1936
	3.96	1990	–3.60	1963
	3.28	1992	–2.88	1965
	3.96	1995	**–4.89**	1969
	3.17	2002	–3.78	1996
	3.56	2015	–4.64	2010

*Mean absolute difference between successive index values (= year-to-year change).

*Średnia bezwzględna różnica między kolejnymi wartościami indeksu (= zmiana z roku na rok).

in the ranges determined by deciles and quartiles (below and above the 1st decile, below and above the 1st quartile, etc.).

For the ranges defined by the median (NAO_{DJFM} < Q2 and NAO_{DJMF} > Q2), 72 runs were found in the 156-year sequence of the NAO_{DJFM} values, in which successive indices assumed values below or above the median. The longest run covered 8 consecutive years with the values NAO_{DJFM} > Q2; those were the years 1988-1995. The longest run of the NAO_{DJFM} < Q2 values included 5 consecutive years in the periods 1915-1919 and 1962-1966. Most of the runs were shorter and half were one-year runs (19 + 17 runs, see Table 3).

The number of the NAO_{DJFM} < Q2 and NAO_{DJFM} > Q2 index runs (R = 72) does not differ significantly from the number of runs randomly distributed in time series (R0 = 79 +/- 6.22), which is confirmed by a low value of the runs test (Z = 1.13). We can only speak of a weak, insignificant persistence, causing the index value to remain below or above the median level in several consecutive years. The symptoms of persistence are slightly stronger in the range of the highest index values; the numbers of runs determined according to the thresholds set by the 3rd quartile and the 9th decile can be considered significantly lower than the number of runs in a random series (however, only at the significance level of $\alpha = 0.10$) (Table 3).

Table 3. Number of runs of the NAO_{DJFM} values greater and less than the median (Q2), the 1st and 3rd quartiles (Q1 and Q3) and the 1st and 9th deciles (D1 and D9) by their duration T [number of years].

Tabela 3. Liczba serii wartości NAO_{DJFM} większych i mniejszych od mediany (Q2), 1. i 3. kwartyla (Q1 i Q3) oraz 1. i 9. decyla (D1 i D9) według czasu ich trwania T [liczba lat].

Duration/Czas trwania T*	1	2	3	4	5	6	7	8	Σ no. of runs/ Σ liczba serii	R_0	z test
NAO_{DJFM} > D9	9	3	0	0	0	0	0	0	25	29.1 ±2.2	1.86
NAO_{DJFM} > Q3	18	5	1	2	0	0	0	0	52	59.5 ±4.7	1.60
NAO_{DJFM} > Q2	19	6	5	2	2	1	0	1	72	79.0 ±6.2	1.13
NAO_{DJFM} < Q2	17	5	7	5	2	0	0	0	72	79.0 ±6.2	1.13
NAO_{DJFM} < Q1	23	4	1	0	1	0	0	0	61	59.5 ±4.7	0.32
NAO_{DJFM} < D1	12	0	1	0	0	0	0	0	27	29.1 ±2.2	0.95

* Duration of runs of the NAO_{DJFM} values belonging to a range according to specified inequalities. The total number of runs (Σ) is ≈ twice as high.

* Czas trwania serii wartości NAO_{DJFM} należących do przedziału wg wyszczególnionych nierówności. Łączna liczba serii (Σ) jest ≈ dwukrotnie wyższa.

The weak or even minute signs of persistence of the NAO_{DJFM} indices confirm the frequency distribution of their year-to-year changes (Table 4). The frequency of the index value remaining within a given quartile in consecutive years is not too high; this kind of stability accounts for only about a quarter of all year-to-year changes. High indices (1/3 of repeating values NAO_{DJFM} > Q3 in consecutive years) are the most stable. The most unstable indices belong to the Q2 < NAO_{DJFM} < Q3 range; they repeat themselves in only 15% of changes. Weak persistence also applies to the entire class of indices higher and the class of indices lower than the median (Q2). They are stable only in 54% of changes. The coefficient of convergence of year-to-year changes (A) of the two index classes is only 0.17 and is not statistically significant (z-test = 1.05).

As a whole, the structure of the frequency of year-to-year changes does not differ significantly from the frequencies evenly distributed in a 4×4 array. This is evidenced by a low contingency coefficient (Φ = 0.13) and the insignificant value of the chi-square test (Table 4). However, seeing the data in Table 4, one can notice that the indices belonging to the class of a given quartile tend to change next year, which places them in the class of the adjacent quartile. The tendency results from the magnitude of the average year-to-year change $|\Delta_i|$, which is greater than the distance between quartiles (see Table 2).

The NAO_{DJFM} indices in the period 1864-2019 are characterized by a positive, insignificant, and at the same time unstable autocorrelation of successive values in a time series (the first autocorrelation coefficient r1 = +0.14). In the first part of the analyzed period, until the end of the 19th century, the variation of the indices is described by a significant, negative autocorrelation (r1 = –0.38), which proves the exceptionally great year-to-year variation of the NAO_{DJFM} indices. Positive, but insignificant autocorrelation coefficients in the NAO_{DFJM} time series appear in the second part of the multiannual period, starting from the 1960s (Fig. 1). The coefficients presented herein correspond with the assessments

Table 4. Structure of year-to-year changes (Δ_i) of the NAO_{DJFM} index according to quartiles Q1, Q2, Q3. The ratios* of the observed frequencies to the frequency of average, even distribution of indices in the multiannual period (f = 155/16) and the assessment of the difference between these distributions based on the chi-square test (χ^2) and the contingency coefficient (Φ) are given.

Tabela 4. Struktura zmian indeksu NAO_{DJFM} z roku na rok (Δ_i) według kwartyli Q1, Q2, Q3. Podano stosunki* obserwowanych częstości do częstości średniego, równomiernego rozkładu indeksów w wieloleciu (f = 155/16) oraz ocenę różnicy między tymi rozkładami na podstawie testu chi-kwadrat (χ^2) i współczynnika kontyngencji (Φ).

year/rok		i + 1			
i		1	2	3	4
1	NAO_{DJFM} > Q3	1.16	**1.37**	0.63	0.84
2	Q3 > NAO_{DJFM} > Q2	**1.23**	0.62	**1.23**	0.92
3	Q1 < NAO_{DJFM} < Q2	0.72	0.92	1.13	**1.23**
4	NAO_{DJFM} < Q1	0.92	**1.13**	0.92	1.02
χ^2 = 7.4 Φ = 0.13					

* The highest values of quotients are distinguished in bold.

* Pogrubioną czcionką wyróżniono najwyższe wartości ilorazów.

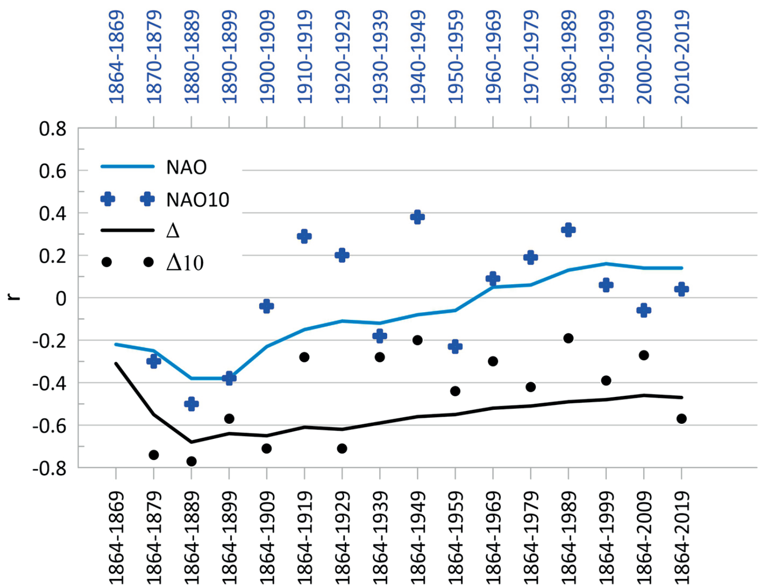

Fig. 1. Autocorrelation in time series of the NAO_{DJFM} index values and year-to-year changes in the index ($\Delta_i = NAO_{i+1} - NAO_i$). First autocorrelation coefficients (r1) in successive decades (NAO10 and Δ10 – signatures • +) and in the period from the beginning of series in 1864 (NAO and Δ – solid lines)

Rys. 1. Autokorelacja w szeregach czasowych wartości indeksu NAO_{DJFM} i zmian z roku na rok indeksu ($\Delta_i = NAO_{i+1} - NAO_i$). Pierwsze współczynniki autokorelacji (r1) w kolejnych dekadach (NAO10 i Δ10 – sygnatury • +) oraz w okresie od początku serii w 1864 r. (NAO i Δ – linie ciągłe).

of Hurrell et al. (2003) who, based on the NAO_{DFJM} series beginning in 1900, determined the autocorrelation coefficient r1 = +0.24.

The insignificant persistence of the NAO_{DJFM} index is accompanied by its intense fluctuations and changes in the signs of year-to-year changes. The mean absolute value of the year-to-year change ($|\Delta_i|$) exceeds the values of standard deviation as well as the difference between quartiles (see Table 2). The standard deviation of year-to-year changes (stdΔ_i = 2.57) is also clearly greater than the standard deviation of the index values (std NAO_{DJFM} = 1.95). The variance of changes Δ_i thus reaches 1.75 times the value of the variance of the NAO_{DJFM} indices and is close to the variance of changes in a random series, where an analogous variance ratio is at a level of ≈ 2.1.

A significant, negative autocorrelation of the values of the NAO_{DJFM} index year-to-year changes was found: the r1 autocorrelation coefficient assumes a value of –0.47. The statistically significant negative autocorrelation in the Δ_i series persists throughout the multiannual period (Fig. 1). Worth noting is also the small difference between the autocorrelation coefficients in the series of observed changes in the index value and autocorrelation in the series of changes in NAO_{DJFM} random values, determined on the basis of the random series of the normal distribution probability density function (r1 ≈ –0.44).

The negative autocorrelation of changes in Δ_i is confirmed by other statistics:

*Nearly 2/3 of the cases of consecutive, comparable differences between indices in a time series (31.8 + 32.5%) are changes with the opposite sign. Only 35.7% are the cases when changes have the same signs in the following year (Table 5).

**There is a significant negative convergence of the directions of year-to-year changes in the NAO_{DJFM} index value. The convergence coefficient A = –0.528 is statistically significant at the level of α = 0.05.

***In the 155-element sequence of annual changes in the value of the NAO_{DJFM} index ($\Delta_i = NAO_{i+1} - NAO_i$), 100 runs were found to contain successive decreases ($\Delta_i < 0$) and successive increases ($\Delta_i > 0$) of indices from year to year. In most cases, the index change sign (increase/decrease) lasted only for 1 or 2 years. The observed number of series of positive and negative values in the time series Δ_i is practically equal to the number

Table 5. The distribution of frequencies [%] of increases and decreases in NAO_{DJFM} indices (Δ_i) in successive years of the period 1865-2019 (i = 1, 2, 3 ..., 154), the coefficient of convergence of sign of changes (A), Z test value as well as autocorrelation coefficient r1 and t test value.

Tabela 5. Rozkład częstości [%] przyrostów i spadków indeksów NAO_{DJFM} (Δ_i) w kolejnych latach okresu 1865-2019 (i = 1, 2, 3 …, 154), współczynnik zbieżności znaku zmian (A) i wartość testu Z oraz współczynnik autokorelacji r1 i wartość testu t.

Year/rok	i + 1	
i	Increases/wzrosty $\Delta_{i+1} > 0$	Decreases/spadki $\Delta_{i+1} < 0$
Increases/wzrosty $\Delta_i > 0$	**17.5**	**31.8**
Decreases/spadki $\Delta_i < 0$	**32.5**	**18.2**
A = –0.528 z = –3.546 r1 = –0.47 t = –6.59		

of series of changes in the series of random numbers formed from the values of the standardized normal distribution. The inter-annual fluctuations, dominated by successive increases and decreases in the NAO_{DJFM} value, are an important feature of the short-term index variation, revealing, as can be assumed, the stochastic aspect of this variation. Changes in the signs of index changes are clearly dominant in comparison with the weak signs of persistence in the NAO_{DJFM} time series.

Long-term changes and circulation epochs

In the assessment of long-term changes in the analyzed index, the distributions of its values in the consecutive 10-year periods of the years 1864-2019 were used. It can be concluded that the decade scale makes it possible to effectively compensate for short-term and probably stochastic fluctuations in the index, and, as a result, to capture the picture of the formation of longer-lasting fluctuations, i.e. the circulation epochs.

Using the "F5" method, the decades representing significantly high indices (Z) were distinguished, as well as the decades including the years with low indices (M) (see description in the part "Objectives, data and methods ..."). The distribution of the distinguished decades in the long-term period is presented in Table 6.

The decades included in the Z and M classes, and thus potentially representing the Z or M circulation epochs, cover over 2/3 of the analyzed long-term period. The remaining 10-year periods should be considered as characterized by the occurrence of average circulation conditions. A certain exception is the Z/M decade (1928-1937), which includes both the years grouped in class Z (1926-1935) and in class M (1928-1937).

Most of the distinguished decades are characterized by significant positive deviations of the mean values of the 10-year NAO_{DJFM} index from the long-term mean (Z* in Table 6) or significant negative deviations (M*). Such deviations clearly increase during the analyzed multiannual period, which proves the growing amplitude of the index fluctuations.

In general, the distribution over time of decades Z and M reflects the occurrence of two waves of increased zonal circulation (Z) and two waves of weak zonal circulation (i.e. developed meridian circulation – M) in the long-term period. These waves roughly correspond to the circulation epochs already known from other reports (Marsz 1999; Degirmendžić et al. 2000; Sidorenkov, Orlov 2008; Degirmendžić, Kożuchowski 2018). They can be assigned the designations M1, Z1, M2, Z2. However, the analysis of the decade distributions of the NAO_{DJFM} clearly shows the unstable nature of these epochs. In each of them, there are series of decades or individual decades representing average circulation conditions. In particular, epoch "M1" is revealed as only 2 "anomalous" 10-year periods (1870-79 and 1886-95) and a long series of years with average circulation conditions dominating. In the "Z" epochs, there are at least two series of decades classified as class Z. The question arises whether each of these series belongs to one epoch?

Table 6. Decades of the period 1864-2019 included in class M and class Z based on anomaly in the frequency of the NAO_{DJFM} index fraction ("F5" method). More explanations in the text.

Tabela 6. Dekady okresu 1864-2019 zaliczone do klasy M i klasy Z na podstawie anomalii częstości frakcji indeksu NAO_{DJFM} (sposób „F5"). Bliższe objaśnienia w tekście.

10-year period/10-lecia	+									
	0	1	2	3	4	5	6	7	8	9
1861-1870	a	b	c	…						**M**
1871-1880										
1881-1890						**M**				
1891-1900										
1901-1910	**Z**	**Z**	**Z***	**Z**	**Z***	**Z**	**Z**			
1911-1920						**Z**	**Z**	**Z**	**Z**	**Z**
1921-1930	**Z**				**Z**	**Z**		**Z/M**		
1931-1940										
1941-1950										**M**
1951-1960	**M**		**M**	**M**	**M***	**M***	**M***	**M***	**M***	**M***
1961-1970	**M***	**M***	**M***	**M***	**M**					
1971-1980										**Z**
1981-1990	**Z***	**Z***	**Z***	**Z***	**Z***	**Z***	**Z***	**Z***	**Z***	**Z***
1991-2000	**Z***	**Z**	**Z**	**Z**						
2001-2010					**Z**	**Z**	**Z**	**Z**	**Z**	**Z**

a, b, c… – successive consecutive 10-year periods: 1861-1870, 1862-1871, 1863-1872, etc.

a, b, c… – kolejne konsekutywne 10-lecia: 1861-1870, 1862-1871, 1863-1872 itd.

(*) mean 10-year index values significantly different from the mean of 1864-2019 (significance level 0.05 according to Cramér's test)

(*) średnie 10-letnie wartości indeksu istotnie różne od średniej 1864-2019 (poziom istotności 0,05, wg testu Cramera).

In search of multi-year periods (over 10 years) significantly different due to the frequency distribution of the NAO_{DJFM}, two such periods can be identified and they cover the years 1951-1971 (M2) and 1980-1995 (Z2).

The frequency of low values of the NAO_{DJFM} index was particularly high in the period 1951-1971 when over 80% of values below the median occurred, including almost ¼ of values below the 1stdecile, with no cases of the NAO_{DJFM} index > D9. On the other hand, the period 1980-1995 represented the highest values of the index, including the maximum of the entire series from 1989 and 6 cases of the NAO_{DJFM} index > D9. The index frequency distributions in the distinguished periods significantly differ from the long-term distribution (n_0) as opposed to the distributions created by indices from other parts of the multiannual period (Table 7). It follows that long-term and significant changes in the structure of the NAO_{DJFM} index value took place in the second half of the 20th century.

The dynamics of development of significant changes in the frequency of individual index fractions is illustrated, to some extent, in the diagram in Figure 2. It presents the pat-

Table 7. Frequency distributions of the NAO_{DJFM} index in selected parts of the period 1864-2019; frequencies [n/10 years] and maximum values of differences of cumulative distributions (DKS) based on the Kolmogorov-Smirnov test.

Tabela 7. Rozkłady częstości indeksu NAO $_{DJFM}$ w wybranych częściach okresu 1864-2019; częstości [n/10lat] i wartości maksymalne wartości różnic skumulowanych rozkładów (D_{KS}) wg testu Kolmogorova-Smirnova.

NAO_{DJFM} Ranges/ Przedziały	n_0	1864-1902	1903-1928	1929-1971	1951-1971	1972-2019	1980-1995
		(M1)	(Z1)	(M2)		(Z2)	
>D9	*1.0*	0.5	0.8	0.0	0.0	2.3	3,8
>Q3	*2.5*	1.5	4.2	0.9	0.5	3.8	5,0
>Q2	*5.0*	3.6	6.2	3.7	1.9	6.7	8,8
<Q2	*5.0*	6.4	3.8	6.3	8.1	3.3	1,3
<Q1	*2.5*	3.3	0.8	3.7	5.7	1.7	0,0
<D1	*1.0*	1.0	0.4	1.9	2.4	0.4	0,0
D_{KS}		0.141	0.173	0.157	0.321*	0.129	0.375*
$D_{0.05}$		0.22	0.27	0.21	0.29	0.20	0.33

* differences significant at the level of $\alpha = 0.05$, $D_{0,05}$ – critical values of the KS test.

* różnice istotne na poziomie $\alpha = 0,05$, $D_{0,05}$ – krytyczne wartości testu KS.

tern of the NAO_{DJFM} index frequency structure (in the ranges < Q1 < Q2 < Q3) in the consecutive 10-year periods of the multiannual period 1864-2019 and in the two decades representing extreme cases of this structure. Changes in the structure of indices in successive decades reflect the most important features of their long-term variation: two "waves" of intensified NAO dominate with the maxima in the years 1900-1920 and 1980-1990, and the depression separating them in 1950-1960. The decade of the 1950s was the only one characterized by the absence of cases of an index higher than the third quartile, whereas in the decade of the 1960s, also exceptionally, most of the NAO_{DJFM} values were within the range below the first quartile. Both decades were characterized by significant, negative deviations of the mean values of the NAO_{DJFM} (see Table 6).

What is interesting and perhaps also significant is the consequence of changes in the index in the analyzed period: in the 1950s there was a reduction in the frequency of the highest indices (>3), and then, in the decade of the 1960s, there was a huge surplus of the lowest indices signaled by a significant decrease in the NAO_{DJFM} in 1961-1962 (Δ_i = –4.18). In the next decades, after a zero frequency of the lowest indices (<Q1) in the 1980s, there was a significant increase in the index in 1988-1989 (Δ_i = +4.36) and an increase in the frequency of high indices (>Q3) in the 1990s.

It can be noticed that the amplitude of frequency fluctuations of the lowest index values over a multiannual period (i.e. NAO_{DJFM} < Q1 values), mainly due to the depression of the 1950s and 1960s, is clearly greater than the frequency amplitude of the highest index values (NAO_{DJFM} > Q3), which in this light again turns out to be a bit more stable. In general, fluctuations in frequency in 10-year periods are characterized by a certain persistence:

the direction (sign) of changes between decades usually persists for 2-4 consecutive decades (see Fig. 2).

The frequencies of successive quartiles of the NAO_{DJFM} distribution do not change in parallel (synchronously); the correlations between changes in individual fractions are obviously negative, but at the same time quite varied. The strongest are the correlations between changes in the NAO_{DJFM} < Q1 and Q2 < NAO_{DJFM} < Q3 (r = –0.41) fractions and the Q1 < NAO_{DJFM} < Q2 and NAO_{DJFM} > Q3 fractions (r = –0.40). Therefore, more unambiguous assessments of the NAO fluctuations result from the use of the frequency index (Σdf) synthetically presenting NAO_{DJFM} fractions and constituting a statistical measure of the index in given time periods (here: in 10-year periods).

The frequency indices in consecutive 10-year periods vary from Σdf = –12 in the decade 1962-1971 to Σdf = +10 in the decade 1986-1995 (Table 8). The frequency distributions of the NAO_{DJFM} index in these extreme (not only due to the values of Σdf) 10-year periods are presented in Table 9. The maximum and minimum of the frequency index occur in the decades distinguished by the highest and the lowest average 10-year value of the index. The frequency distributions themselves are remarkably skewed.

Significant positive values of the frequency index ("Z") occur in the decade 1905-1914 and in decades in the period 1985-2000, and indicate the intensification of zonal circulation in these years, i.e. in epochs Z1 and Z2. Then, significant negative indicators ("M") characterize 10-year periods in the years 1955-1972, i.e. only in the M2 epoch.

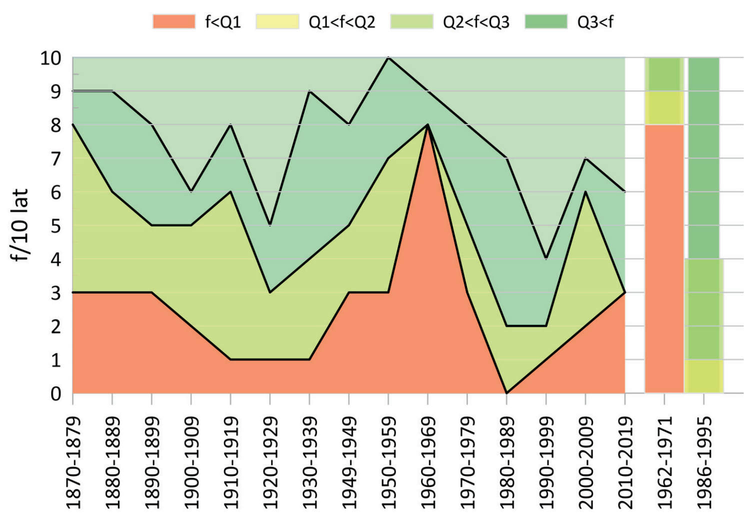

Fig. 2. Frequencies (f) of the NAO_{DJFM} index in successive decades from 1870-1879 to 2010-2019 and frequencies in 10-year periods 1962-1971 and 1986-1995. The following quartile frequencies were considered: f < Q1, Q1 < f < Q2, Q2 < f < Q3 and f > Q3.

Rys. 2. Częstości (f) indeksu NAO_{DJFM} w kolejnych dekadach od 1870-1879 do 2010-2019 oraz częstości w 10-leciach 1962-1971 i 1986-1995. Uwzględniono częstości w przedziałach kwartyli: f < Q1, Q1 < f < Q2, Q2 < f < Q3 i f > Q3.

Table 8. Frequency indices (Σdf) in consecutive decades
of the period 1864-2019 (order of decades as in Table 6).

Tabela 8. Wskaźniki frekwencji (Σdf) w konsekutywnych
dekadach okresu 1864-2019 (kolejność dekad jak w tab. 6).

10-year period/10-lecie	+									
	0	1	2	3	4	5	6	7	8	9
1861-1870				–3	–1	–1	–2	–1	–2	–5
1871-1880	–3	–4	–2	–2	–3	–2	–3	–2	–4	–3
1881-1890	–2	–1	–4	–5	–4	–5	–3	–3	–1	–1
1891-1900	–4	–4	–4	–1	–3	0	1	2	2	2
1901-1910	5	6	7	7	8^{Z}	6	4	1	0	0
1911-1920	0	1	3	3	1	3	3	6	7	7
1921-1930	6	4	2	0	2	1	0	–1	0	1
1931-1940	–1	–2	–2	–1	–1	0	1	–1	–2	–1
1941-1950	1	1	2	1	0	–3	–4	–2	–3	–5
1951-1960	–7	–4	–6	–7	-8^{M}	-8^{M}	-8^{M}	-8^{M}	-10^{M}	-10^{M}
1961-1970	-10^{M}	-12^{M}	-10^{M}	–7	–5	–2	0	–2	–1	–1
1971-1980	1	3	3	3	3	1	1	2	3	6
1981-1990	7	6	7	7	8^{Z}	10^{Z}	8^{Z}	8^{Z}	8^{Z}	8^{Z}
1991-2000	8^{Z}	6	5	3	1	–1	–1	1	2	0
2001-2010	–3	–3	–2	–3	–1	1	3	2	1	3

Symbols "Z" denote significant positive deviations of frequency index from the value 0,
symbols "M" – significant negative deviations (at the level of $p \leq 0.05$). The range
of possible extreme values of frequency index: $-15 \leq \Sigma df \leq +15$.

Symbolami „Z" oznaczono istotne pozytywne odchylenia wskaźnika frekwencji od wartości 0,
symbolami „M" – istotne negatywne odchylenia (na poziomie $p \leq 0{,}05$). Zakres możliwych
skrajnych wartości wskaźnika frekwencji: $-15 \leq \Sigma df \leq +15$.

There is quite a significant number of periods marked by the frequency index $\Sigma df = 0$, which means an approximately uniform frequency distribution of the NAO_{DJFM} indices in a decade, but also indicates the discontinuous nature of anomalies in epochs. The signs of the frequency index, which vary from decade to decade, have a similar meaning; this variation applies especially to the period after 1995 and indicates the variation of relatively high index values at that time.

The observations resulting from the data analysis in Table 8 confirm the thesis that periods of increased and of decreased zonal circulation, i.e. the periods of dominance of positive or negative NAO phases, called circulation epochs, do not form continuous time sequences. There are "neutral" periods between them with average circulation conditions ($\Sigma df \approx 0$ index).

Furthermore, it seems that the delimitation of epochs should be based on the criterion of the significance of the anomalies characteristic of these epochs. The above-presented attempts to find statistically significant anomalies in the NAO_{DJFM} index statistics lead

Table 9. NAO_{DJFM} index frequencies in quartile ranges (f > Q1, f > Q2 and f > Q3), frequency indices (Σdf) and average NAO_{DJFM} index values in selected decades (n = 10) and over the entire period 1864-2019 (n = 156). Index frequencies – number of cases in a 10-year period and the multiannual period 1864-2019.

Tabela 9. Częstości indeksu NAO_{DJFM} w przedziałach według kwartyli (f > Q1, f > Q2 i f > Q3), wskaźniki frekwencji (Σdf) oraz średnie wartości indeksu NAO_{DJFM} w wybranych dekadach (n = 10) i w całym wieloleciu 1864-2019 (n = 156). Częstości indeksu – liczba przypadków w 10-leciu i w wieloleciu 1864-2019.

Period/Okres	NAO_{DJFM} > Q1	NAO_{DJFM} > Q2	NAO_{DJFM} > Q3	Σdf	Σdf/15	Mean/średnia NAO_{DJFM}
1962-1971	2*	1*	0*	–12	–0.80	–2.09*
1986-1995	10*	9*	6*	10	0.67	2.35*
1864-2019	117 (7.5/10 years/lat)	78 (5.0/10 years/lat)	39 (2.5/10 years/lat)	0	-	0.23

* significant deviations from the mean value; see also explanations to Table 8.

* istotne odchylenia od wartości średniej; zob. też objaśnienia w tab. 8.

to the conclusion that in the analyzed multiannual period the most clearly visible significant anomalies (on a 10-year scale) were the 1950s and the 1960s as well as the 1980s and the 1990s, representing the M2 and Z2 epochs. In addition, some criteria also allow to indicate the anomalous nature of circulation conditions in part of the Z1 epoch and trace (short-term) symptoms of anomalies in the M1 epoch at the end of the 19th century (see Table 6 and Table 8).

As a result of the observations made, the following epochs in a strict sense should be distinguished: 1905-1914 (Z1), 1955-1972 (M) and 1985-2000 (Z2). The further presented interpretation of changes in the frequency index, however, prompts to treat this division carefully and to recognize that long-term changes in the NAO_{DJFM} index are fluctuations only slightly different from "random variable walk".

A generalized picture of changes in the frequency index showing the values of Σdf in successive decades (Fig. 3) once more shows four phases of changes in the NAO_{DJFM} index, the last two of which are characterized by significant (at the level of $p \leq 0.05$) deviations in the frequency index. Significant anomalies characterize the decade 1960-1969 (Σdf = –10) and the decade 1990-1999 (Σdf = +8). The previously occurring maximum (1920-1929) and minimum (1870-1879) do not exceed the level of statistical significance. Thus, the graph in Figure 3 shows quasi-cyclical fluctuations with the amplitude increasing with time. In particular, the amplitude of changes in the index resulting from the deep depression of the NAO_{DJFM} in the 1960s, and then a significant increase in the index in the 1980s, deserves to be highlighted as the most significant event in the long history of the NAO changes.

The amplitude of changes in the frequency index Σdf does not fully correspond to the range of specific random variable fluctuations. The depression of the index of the 1960s significantly exceeds the range of probable stochastic changes (Fig. 3).

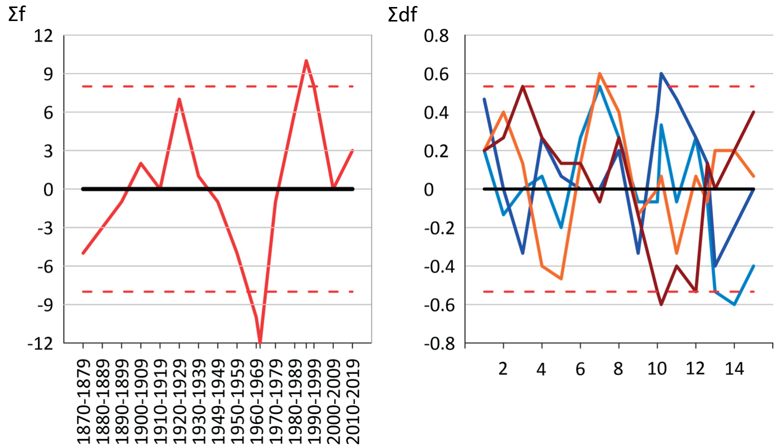

Fig. 3. Frequency index Σdf and its relative values of Σdf/15 in successive decades from 1870-1879 to 2010-2019 (left panel) and 4th random series of index values (right panel).

Rys. 3. Wskaźnik frekwencji Σdf i jego względne wartości Σdf/15 w kolejnych dekadach od 1870-1879 do 2010-2019 (lewy panel) oraz 4 losowe serie wartości wskaźnika (prawy panel).

The standard deviation of the frequency of the observed NAO_{DJFM} values (std. ≈ 4.3) turns out to be slightly greater than the deviation in the series of randomly selected indices (std. = 3.9). Moreover, the observed indices in the successive 10-year periods show a certain persistence; autocorrelation in the 15-element Σdf sequence is positive, statistically insignificant (r1 ≈ 0.42), but clearly higher than close to zero autocorrelation in random sequences. The frequency index shows the occurrence of 7 runs of increases/decreases from decade to decade in the multiannual period, random sequences include 8-10 such runs. As can be seen, the differences between the variation of the observed Σdf index values and the variation of its random values are not great. Nevertheless, it must also be admitted that they are one of the signals of the determined fluctuations of the NAO, especially of the determinants of its changes in the second half of the 20th century. The significant changes in the NAO during this period have already been noticed by many researchers (including Marsz 1999; Feldstein 2000; Ostermeier, Wallace 2003).

Summary

The short-term variation of the NAO_{DJFM} index is dominated by successive increases and decreases from year to year, occurring with statistically significant repeatability and reaching a significant value equaling the magnitude of random changes. The differences between the index values in successive years are characterized by a significant, negative autocorrelation, which means that increases in the index usually follow decreases and *vice versa*, and the series of changes with the same sign occur relatively rarely. It can be assumed that the significant variation and scale of year-to-year changes in the index is due to the nature of the North Atlantic Oscillation, which is characterized by the known negative correlation of pressure in the Icelandic Low and the Azores High. As a result of this correlation, the pressure differences between both systems, and thus the NAO index, increase more than the pressure changes in one or the other system, and the variance of these differences also increases.

The persistence of the NAO_{DJFM} index is of minimal importance. Autocorrelation in the NAO_{DJFM} series is not significant, although it is worth noting that high indices show a tendency to certain stability over time.

Both the year-to-year index variation and the manifestations of persistence are characterized by instability and the dispersion of the index value shows a growing tendency over the multiannual period.

On a decadal scale, there are significant changes in the structure of the index. The series of 10-year periods of significant anomalies in the distribution of the index value make it possible to delimit the following periods in the analyzed period 1864-2019: two epochs of intensified zonal circulation with the domination of high NAO_{DJFM} indices in the periods 1905-1914 (Z1) and 1985-2000 (Z2), and the epoch of decreased zonal circulation with a predominance of negative index values in 1955-1972 (M). The above-mentioned epochs do not satisfy the condition of continuity in time; they are episodes of high/low index values focused in time, and between the periods the indices are at the average level.

The occurrence of a deep negative index anomaly in the M epoch, especially in the decade 1962-1971 and the subsequent increase in the index up to its maximum in 1989 can be considered the most significant events in the long history of the NAO changes. The pattern of the so-called NAO_{DJFM} frequency index (Σdf, Fig. 3) clearly exposes these anomalies.

The variance of the observed frequency index exceeds 120% of the variance in a random series. The scale of changes in the index leading to the formation of anomalies in epochs M and Z2 suggests that they probably have a determined character. On the other hand, the view exposing the stochastic aspects of the NAO variation, especially with regard to short-term (inter-annual) variation, is also not unfounded, although it still remains an open problem.

This study does not resolve this problem. It presents the history of changes in the North Atlantic Oscillation in the light of the 156-year sequence of Hurrell's indices showing long-term changes in the fraction of the index distribution, which were characterized by the frequency index Σdf.

The quite numerous statistical evaluations cited in the study were often considered as signs, symptoms, signals ..., etc., i.e. as not very obvious evidence of hypothetical properties of the analyzed time series. Such doubts may therefore suggest that the forming of the index variation in the long-term pattern has the character of a process referred to as *vacillation*, i.e. a process forming unstable, indecisive fluctuations (Michell 1966). More precisely, the variation of the NAO_{DJFM} index on a short-term (inter-annual) scale analyzed in this study is stochastic, while on a long-term scale it shows significant fluctuations, forming the so-called circulation epochs.

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S t r e s z c z e n i e

Artykuł przedstawia statystyki opisujące zmienność czasową wskaźnika NAO_{DJFM}, w tym zmienność różnic między wskaźnikami w kolejnych latach (Δ_i = NAO $_{DJFMi+1}$ – NAO $_{DJFMi}$). Przedstawiono także zmiany rozkładu częstości indeksów w konsekutywnych 10-leciach okresu 1864-2019.

Analiza krótkoterminowej zmienności wskaźnika NAO_{DJFM} wykazuje, że w jego szeregu czasowym dominuje istotna, negatywna autokorelacja zmian wskaźnika z roku na rok (r1 = –0,47). Przyrosty wskaźnika następują najczęściej po spadkach jego wartości (i odwrotnie), a następstwo znaków zmian między kolejnymi wartościami indeksu (Δ_i) nie różni się znacząco od następstwa zmian w szeregu losowym (tab. 3, 4, 5). Średnia bezwzględna różnica między kolejnymi wartościami indeksu w szeregu czasowym ($|\Delta_i|$) jest większa od odchylenia standardowego w zbiorze wartości NAO $_{DJFM}$, a wariancja zmian (Δ_i) stanowi 1,75 wariancji indeksu NAO_{DJFM}.

Występują śladowe oznaki bezwładności w szeregu wskaźnika: autokorelacja (r1 = 0,14) nie jest statystycznie istotna, przy czym zarówno inercja NAO_{DJFM}, jak i zbieżność przyrostów/ spadków indeksu wykazuje wyraźną niestabilność w ciągu analizowanego okresu (rys. 1). Znaleziono pewne oznaki stabilności najwyższych wartości indeksu NAO_{DJFM} (tab. 3).

W skali dekad występują znaczące zmiany frakcji indeksu, określonych przez kwartyle oraz 1. i 9. decyl rozkładu NAO_{DJFM}: w serii konsekutywnych 10-leci ekstremalnymi rozkładami wyróżniają się okresy 1962-1971 i 1986-1995 (tab. 9). Stosując wskaźnik frekwencji, określony na podstawie kumulowanych częstości indeksu NAO_{DJFM} > Q1 + NAO_{DJFM} > Q2 + NAO_{DJFM} > Q3 (gdzie Q oznacza kwartyle 1. 2. i 3), wyróżniono dekady, w których wskaźnik przyjmuje znacząco wysokie lub znacząco niskie wartości (tab. 8). W analizowanym wieloleciu 1864-2019 wydzielono dwie epoki dominacji wysokich wartości NAO_{DJFM} (epoki nasilonej cyrkulacji strefowej 1905-1914 i 1985-2000) oraz epokę znaczącej przewagi niskich wartości indeksu (epokę rozwoju południkowych form cyrkulacji 1955-1972).

Słowa kluczowe: epoki cyrkulacyjne, autokorelacja, bezwładność, rozkład statystyczny.

A b s t r a c t

The article presents statistics describing the temporal variation of the NAO_{DJFM} index, including the variation of the differences between the indices in successive years ($\Delta_i = NAO_{DJFMi+1} - NAO_{DJFMi}$). Changes in the frequency distribution of indices in consecutive 10-year periods between 1864 and 2019 are also presented.

An analysis of the short-term variation of the NAO_{DJFM} index shows that its time series is dominated by a significant, negative autocorrelation of year-to-year changes in the index (r1 = –0.47). Increments of the index usually follow decreases in its value (and *vice versa*), and the sequence of signs of changes between successive index values (Δ_i) does not differ significantly from the sequence of changes in a random series (Table 3, 4, 5). The mean absolute difference between successive index values in a time series ($|\Delta_i|$) is greater than the standard deviation in the NAO_{DJFM} value set, and the variance of changes (Δ_i) is 1.75 of the NAO_{DJFM} index variance.

There are traces of persistence in the index series: autocorrelation (r1 = 0.14) is not statistically significant, and both the NAO_{DJFM} persistence and the convergence of increases/decreases in the index show clear instability over the analyzed period (Fig. 1). Some signs of stability of the highest values of the NAO_{DJFM} index were found (Table 3).

On a decadal scale, there are significant changes in the index fractions defined by quartiles and the 1st and 9th deciles of the NAO_{DJFM} distribution: in the series of 10 consecutive years, the periods 1962-1971 and 1986-1995 are distinguished by extreme distributions (Table 9). Using the frequency index determined on the basis of the cumulative frequencies of the index NAO_{DJFM} > Q1 + NAO_{DJFM} > Q2 + NAO_{DJFM} > Q3 (where Q stands for quartiles 1,2 and 3), the decades in which the index had significantly high or significantly low values were distinguished (Table 8). In the analyzed multiannual period 1864-2019, two epochs of domination of high NAO_{DJFM} values were distinguished (the epochs of intensified zonal circulation 1905-1914 and 1985-2000) and an epoch of significant predominance of low index values (the epoch of development of meridional forms of circulation 1955-1972).

Key words: circulation epochs, autocorrelation, persistency, statistical distribution.