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THE PROGRESS IN THE STUDY OF THE CAUSES OF CLIMATE CHANGES ON THE EARTH

THE BEGINNINGS OF THE RESEARCH ON THE PERIODICAL CLIMATE CHANGES

The article published by E. Brückner (1890), presenting the idea of the 35-year periods of climate fluctuations, divided into two phases: the warm-and-dry and the cool-and-wet one, stirred high interest among the climatologists.

One of the opponents of this idea, side by side with Wagner (1929), was R. Gumiński (1946), having expressed his view in the paper entitled "The 35-year 'periods' of climatic oscillations of Brückner in the light of contemporary climatology" (in Polish). R. Gumiński considers it "a fact beyond discussion that there is a link between climate fluctuations and the rhythmic changes of the sunspots". He presents interesting results of the research by G. Hellmann (1906), according to whom two minima of precipitation coincide with the dates of the two main maximums of the sunspots. The 35-year rhythm of E. Brückner finds, however, support in the publications of two other authors. Thus, N. Lockyer (1902) identified the rhythm of the length of 34.4 years in the fluctuations of the sunspots, while J. Liznar (1902) — a 33-year rhythm. On the other hand, A. Schuster (1909) found on the basis of the periodogramme of changes in the sunspots for the years 1749 – 1900 three rhythms, of the length of 11.13, 8.32 and 4.76 years, whose interference yields the rhythm of 33.375 years.

Besides, A.F. Doglass (1909), having used the *Weather Calendar* for the years 1392 – 1906 and the annual rings of the yellow pine (*Pinus ponderosa*), found the rhythm of 32.8 years (after Gumiński, 1946).

The estimation of reality of this 35-year cycle does not satisfy the criterion of A. Schuster: $a > 3E$: $E = (2N)^{-0.5}\pi s$, where s is standard deviation, N — number of observations, and a — amplitude.

According to R. Gumiński the frequency distribution of the cycle lengths is too flat. The average length of the Brückner's period is 34.8 years. The individual periods range within a wide interval:

length of period		20	25	30	35	40	45	50
frequency	6	10	12	13	12	8	4	

in which the longest period is 2½ times longer than the shortest one.

The results of the periodogramme analysis of E. Trautman (1926), carried out on the basis of the 90-year observation series from 28 European weather stations (provided in the publication of R. Gumiński) tend to support the proposition of Brückner on the 35-year rhythm of precipitation rather than to reject it. The average amplitudes (in % of total precipitation in the interval of 31 – 40 years) of the sample periods are:

years	31	32	33	34	35	36	37	38	39	40
amplitudes	5.22	5.29	5.27	5.46	5.48	5.58	5.42	5.31	5.31	5.40

Close to the extremum of a sinusoid having quite a long period Θ one should not expect large increments of amplitude a. Similarly, the results of the periodogramme analysis of G. Afzelius (1925), carried out on the basis of the long term precipitation series for Klagenfurt (100 years) and Padova (200 years), can be treated as supportive for the existence of the 35-year periodicity of precipitation. The divergence between the lengths of precipitation rhythms between Klagenfurt (31 years) and Padova (38 years) is not exceedingly large, despite the significant distance between these localities (400 km).

The idea of E. Brückner of one, 35 years long period of climate fluctuations (simultaneous oscillations of temperature and precipitation) is certainly incorrect. Yet, the problem of close-to-35-year periodicity of precipitation is still not resolved.

The close-to-35-year period of precipitation is present in some of the measurement series, i.e. for Cracow (1850 – 1980) — 29.6 years, Colombo (1869 – 1980) — 37.9 years, Nauru (1894 – 1979) — 37 years. The amplitude of these cycles fulfils the criterion of reality of Schuster $a > 3E$ (Boryczka, 1998).

The question of periodicity of precipitation was taken up at the Department of Climatology also by Z. Kaczorowska — as described in her volume *Precipitation in Poland in a long-term perspective* (in Polish), published in 1962.

Harmonic analysis was applied to the measurement series of precipitation from the years 1864 – 1936 (Koszalin, Poznań, Warsaw, Wrocław, Cracow) and from the years 1842 – 1936 (Warsaw, Wrocław), as well as of the Wolf numbers. According to Kaczorowska the largest amplitudes of the first harmonic and the similar phase delays at all the weather stations may constitute the evidence for the existence of the 70-year periodicity of precipitation. The second harmonic component (with the period of 36.5 years) is usually characterised by quite an important amplitude, of 19 – 22 mm. The data from the longer time period (1842 – 1936, i.e. 95 years) imply the periodicity of 95 years.

THE NATURAL CAUSES OF CLIMATE FLUCTUATIONS

In the identification of the causes of fluctuations in the Earth's climate it is important to demonstrate the analogous periodicity of the hypothetical causes, namely the astronomical variables (solar activity, solar constant, parameters of the solar system) and the geological ones (volcanic eruptions

— the dust veil index *DVI*), and the effects — the climatic variables (zonal circulation — the North Atlantic Oscillation index *NAO*, air temperature, precipitation) and the hydrological ones (the level of the Baltic Sea).

The key significance in the explanation of the causes of cooling and warming of climate should be attributed to the 178.9-year period of the parameters of the solar system. Thus, in particular, the diagrams of changes in the acceleration of the Sun with respect to the centre of gravity of the solar system, the resultant force of gravity, the Wolf numbers, and the solar constant, for the periods 1700 – 1879 and 1879 – 1993 (delay of 178.9 years) coincide very closely (Boryczka, 2001). Analogous periods are present in the measurement series of air temperature (the period resulting from the interference of the cycles of solar activity of 102.0 and 187.3 years has 224 years of length), as shown below:

Locality	Winter		Spring		Year	
	Θ	ΔT	Θ	ΔT	Θ	ΔT
Warsaw (1779–1990)	218.3	1.8	208.2	0.3	223.9	1.1
Geneva (1768–1980)	216.6	1.0	147.4	0.7	166.3	0.7
England (1659–1973)	170.2	0.6	220.8	0.4	175.6	0.4

The planetary 178.9-year period is present in the chronological series of the sedimentological variables — the palaeotemperature (the ratio of the quantity of the oxygen isotopes $^{18}O/^{16}O$, Johnsen et al., 1970) and the organic matter, deposited in the lake sediments (Boryczka, Wicik, 1994):

Palaeotemperature $^{18}O/^{16}O$	180
Lake Gościąż (organic substance, calcium carbonate)	206, 180
Lake Wikaryjskie (organic substance, calcium carbonate)	200, 180

The analogous periodicity of the climatological and astronomical variables appears to imply that the extremes of the identified cycles of climate in the 19th and 20th centuries will be repeated in the 21st century. The repetition of the values of solar activity (solar constant) after the period of the planetary cycle of 179 years is a witness to the astronomic causes of a certain part of the progressing warming of the Earth's climate.

The short-term changes in the value of the solar constant do not play any essential role in the shaping of the Earth's climate, since the fluctuations of the air temperature brought about by these cycles do not reach deep. It is close to the maximums of the long cycles, the 102- and the 187-year ones, that large amounts of solar energy are accumulated in the deeper layers of the Earth. The thermal energy "stored" in the oceans exerts a significant influence on the atmospheric circulation.

The upward tendency of the solar activity (and the solar constant) during the last two centuries has been beyond any doubt a cause of a part of the progressing warming of the Earth's climate — through the changes in the general atmospheric circulation.

WARM WINTERS IN EUROPE AND THE RAISING LEVEL OF THE BALTIC SEA

In Europe (and in Poland) it is first of all the winters that are becoming increasingly warm. The tendencies of changes in air temperature in winter, summer, and the entire year, expressed in °C/100 years, are, for instance, as follows:

Locality	Winter	Summer	Year
Warsaw (1779–1990)	1.0	0.1	0.7
Prague (1771–1980)	0.25	-0.25	0.0
Geneva (1768–1980)	0.5	-0.2	0.1

Thus, in Warsaw, winters are becoming warmer by 1°C for 100 years, while summers — only by 0.1°C for 100 years.

The progressing warming of the climate of Europe (and Poland) in the 19th–20th centuries is probably the effect of interference of the natural cycles of temperature synchronous with the cycles of the astronomic and geological variables.

And so, by superimposing, for instance, the four longest cycles of air temperature during the winters in Warsaw (38.3, 66.7, 113.1 and 213.3 years) we obtain the explanation for the increase of the air temperature by 0.9°C per 100 years, out of the total upward tendency of 1.0°C/100 years.

Along with the progressing warming of climate the level of seas and oceans raises. The level of the Baltic Sea, as measured in Świnoujście, has been raising in the years 1811–1990 by 4.5 cm per 100 years on the average:

Spring	Summer	Autumn	Winter	Year
1.4	3.9	6.8	5.8	4.5

A number of cycles have also been identified in the time series of the annual average water levels of the Baltic Sea in Świnoujście, namely of 3.1, 5.5, 6.3, 7.7, 11.1, 15.0, 26.8, and 184 years (Kożuchowski, Boryczka, 1999).

The reconstruction of the ancient coastlines shows that the levels of oceans were much higher during the warmer periods than during the cooler ones (the glacial periods). During the last phase of the Würm glaciation, some 18,000 years ago, the level of the Atlantic Ocean dropped by approximately 135 m, which was accompanied by the increase of the ice cover (Lamb, 1972 – 1977).

The present-day ice cover is equivalent to the difference of the ocean level of 59.1–83.3 m. This cover (the ice of the Arctic and Antarctic, as well as the mountain glaciers) constitutes 43.8–61.7% of the ice mass from 18,000 years ago. The average rate of increase of the ocean level amounted, therefore, to 75 cm per 100 years. The raising of the ocean levels observed during the last century amounts, on the average, to 10–25 cm.

The raising of the sea and ocean levels in the 19th–20th centuries is first of all the effect of the volume expansion of water. The volume of the ocean waters (without separate seas) amounts nowadays to $1370.4 \cdot 10^6$ cu. km, with the average depth of 3,704 m. The increase of water temperature by 1°C (from 4°C to 5°C) corresponds to the increase of ocean levels by 18 cm (admitting the coefficient of volume expansibility of $5.3 \cdot 10^{-5}$).

THE INFLUENCE OF THE ATLANTIC OCEAN ON THE CLIMATE OF EUROPE IN THE YEARS 1825–1997 (INTENSIFYING IN WINTER AND WEAKENING IN SUMMER)

The thermal impact of the waters of the Atlantic Ocean (warming in winter and cooling in summer) on the climate of Western and Central Europe (including the climate of Poland) is conditioned by the meridional gradient of the atmospheric pressure — the zonal circulation.

It was assumed that the zonal circulation is measured with the NAO indicator (North Atlantic Oscillation), as defined by P.D. Jones et al. (1997). This indicator is a normalised difference of air pressures at the sea level between Gibraltar and the south-west Iceland in the years 1825–1997.

The values of the NAO indicator tend to increase in winter and decrease in summer (Fig. 1). In other words, the parallel transport of the air masses from over the Atlantic Ocean in the eastern direction is increasingly big in winter. The progressing warming, especially in winter, is brought about by the intensification of the warming influence of the Atlantic Ocean.

The warmer and warmer winters are associated with the bigger values of the NAO. On the other hand, the slight increasing tendency of air temperature in the summer is caused by the disappearance of the cooling influence of the Atlantic Ocean on the climate of Poland.

It is interesting to compare the spectra of: the air temperature during winters in Warsaw in the years 1780–1990, and of the NAO indicator in the years 1826–1997, in the bands of 2–20 years and 21–130 years (Fig. 2a,b). These spectra are characterised by the analogous periodicity with the dominating period of approximately 7.8 years. A special cognitive significance ought to be assigned the similarity of the spectra of air temperature (for Warsaw, Cracow, and Prague), the NAO indicator, and the acceleration of the Sun (the component oriented towards the centre of mass of the solar system), shown in Fig. 2c. The similarity of these spectra demonstrates that winters in Warsaw are being shaped by the periodical fluctuations of the NAO indicator (of the zonal circulation).

In this manner just one of the links of the distribution of heat in Europe has only been explained. It is still not clear, though, what is the contribution to the phenomenon from the change in solar activity (solar constant) and the volcanic dust, limiting the supply of the solar energy to the Earth's surface.

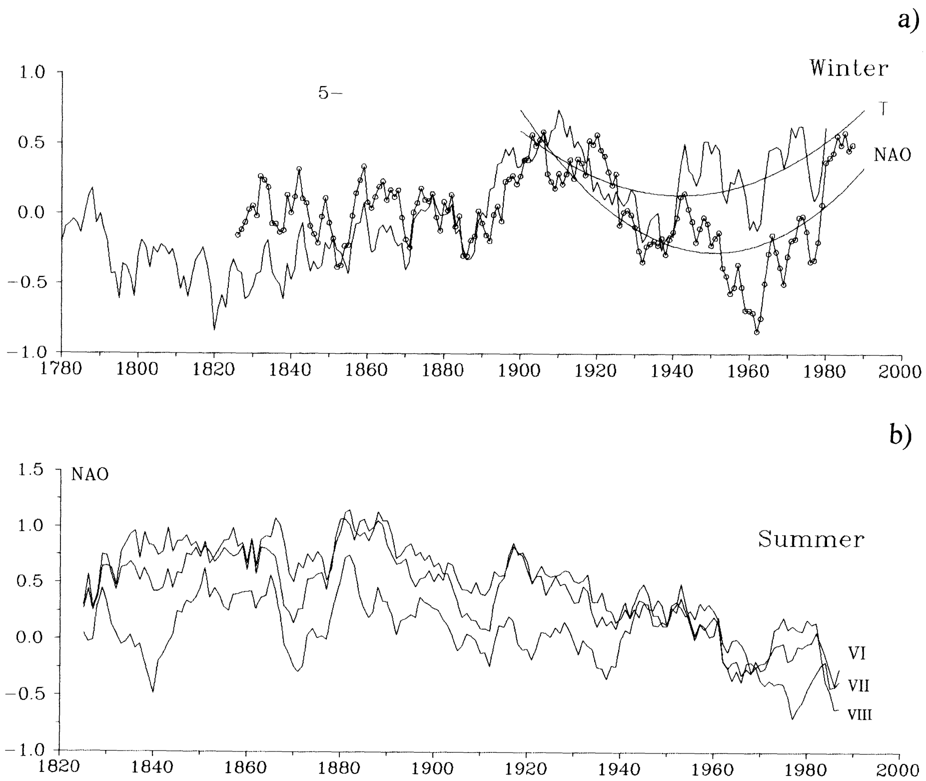

Fig. 1. Changes in the North Atlantic Oscillation (NAO) in winter (a) and in the summer months (b), in 1826–1997, comparison of the consecutive 5-year averages of the NAO values and air temperature during winters in Warsaw.

The influence of solar activity and volcanic dust on the air temperature in winter in Warsaw during the years 1780–1990 is best "legible" for the consecutive 11-year averages. The winters are frosty under very small solar activity, and warm — when the number of sunspots is very high (Boryczka, 2001). Winters are also usually warmer when there is less of volcanic dust in the atmosphere (as measured by log*DVI*).

The dependence of the air temperature in north-western Poland upon the zonal circulation — the North Atlantic Oscillation (the NAO indicators of Rogers and Hurrel) was demonstrated in the work of A.A. Marsz (1999).

The method of J. Boryczka of the "sinusoids of regression" for determining the spectra and the periods

The method used to date to determine the periodicity, namely harmonic analysis, autocorrelation method, and Fourier's transform, have limitations as to their applicability in climatology. These limitations are as follows:

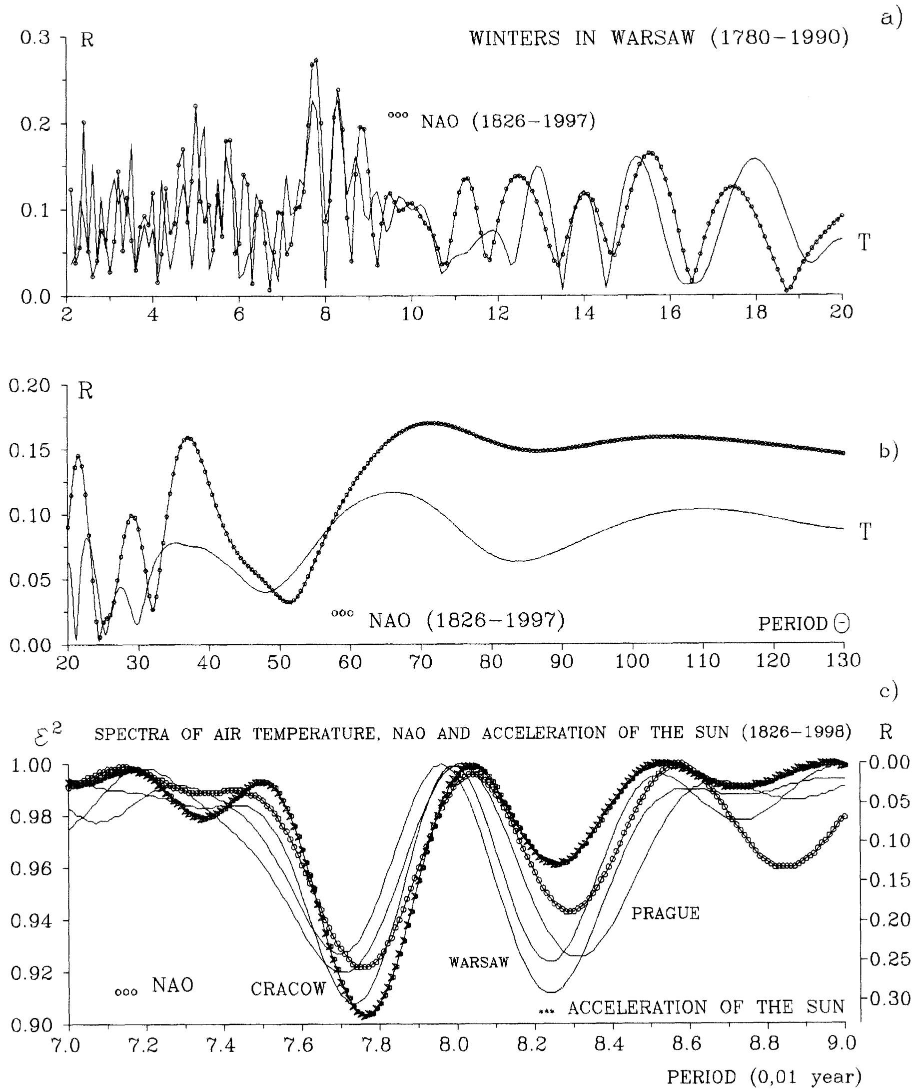

Fig. 2. Comparison of the spectra of a) air temperature in Warsaw (*T*, 1780–1990), b) North Atlantic Oscillation (NAO, 1826–1997) — in the bands of 2.1–20 and 20–130 years, c) air temperature (Warsaw, Cracow, Prague), NAO, and acceleration of the Sun — in the band of 7–9 years.

— the spacing of measurements in the series must be even, Δt = const., the series must be complete, or "complemented";

— only the short-term part of the spectrum can be determined, contained in the interval $0-0.5n$;

— the periods are linked in the explicit manner with the length of the measurement series n (the basic frequency $f = 1/n$).

In the harmonic analysis the periods are being assumed a priori, resulting from the division of the length of the series n into parts: one, two, three, ... The spectrum obtained is too sparse, and the harmonics obtained rarely coincide with the true periods.

Then, in the autocorrelation method a part of the data, $n - k$, is rejected, the number of the rejected observations increasing with the length of the period being determined (the assumption of the n-year period is hidden in the rotational autocorrelation).

The method of J. Boryczka of the "sinusoids of regression", used in the study of periodicity of the natural phenomena, consists in the fitting of the consecutive sinusoids of the hypothesised periods $\Theta = 1, 2, ..., n$ (or 0.1, 0.2, ..., n) to the results of measurements $y_1, y_2, \ldots, y_n$, according to the least squares criterion.

The equation of the sinusoid of regression (this name being given by the author) having period Θ, amplitude b and phase delay c is as follows:

$$y = a + b\sin(\omega t + c), \qquad \omega = 2\pi\Theta^{-1}$$

is being determined by reducing the problem to the one multiple regression of y with respect to the variables $x_1 = \sin\omega t$, $x_2 = \cos\omega t$, i.e.

$$y = a_0 + a_1x_1 + a_2x_2.$$

The amplitude b and the phase delay c are obtained from the inverse transformation, that is, $b = (a_1^2 + a_2^2)^{1/2}$, $\mathrm{tg}\, c = a_2a_1^{-1}$, with due account of the conditions $a_1 = b \cos c$, $a_2 = b \sin c$.

The spectrum of oscillations is the sequence of values of the rest variance ε^2 or of the correlation coefficient $R = (1 - \varepsilon^2 s^{-2})^{1/2}$, corresponding to the supposed periods $\Theta = 0.1, 0.2, ..., n$ (where s^2 is the variance of the variable y). The periods correspond to the local minima of the rest variance ε^2 (the maximums of the correlation coefficient R).

The advantages of the method of the "regression sinusoids" include:

1. The fact that the method can be applied when the time intervals between measurements are not equal (like in the case of volcanic eruptions). 2. It can be applied when the measurement series is not complete — is not "complemented" — and gaps exist. 3. It makes possible the determination of the dense spectrum, not only in the short-term range of $0 - 0.5n$ (like in the other methods), but also in the longer-term range, $0.5n - n$ (i.e. in the entire interval $0 - n$). 4. All the parameters of the cycle are being determined, that is: the period, the amplitude, and the phase delay. 5. The method allows for the comparison of the long-term part of the spectrum of, for instance, the 50-year series, with the short-term part of the spectrum of the 100-year series. 6. It makes possible the direct comparison of the spectra, determined on the basis of the measurement series with different lengths n. 7. The resultant (interference) of just a couple of cycles explains already an important part of variance of a given variable.

THE FORECASTS OF THE NORTH ATLANTIC OSCILLATION (NAO) AND WINTERS IN WARSAW IN THE 21ST CENTURY — INTERFERENCE OF THE CYCLES

We will first present the forecasts of the North Atlantic Oscillation (NAO) indicator for the century of 2001–2100, prepared on the basis of the periodicity identified (interference of cycles). The periods of the NAO indicator for the years 1826–1997 in winter (December–February) are as follows: 2.4, 5.0,

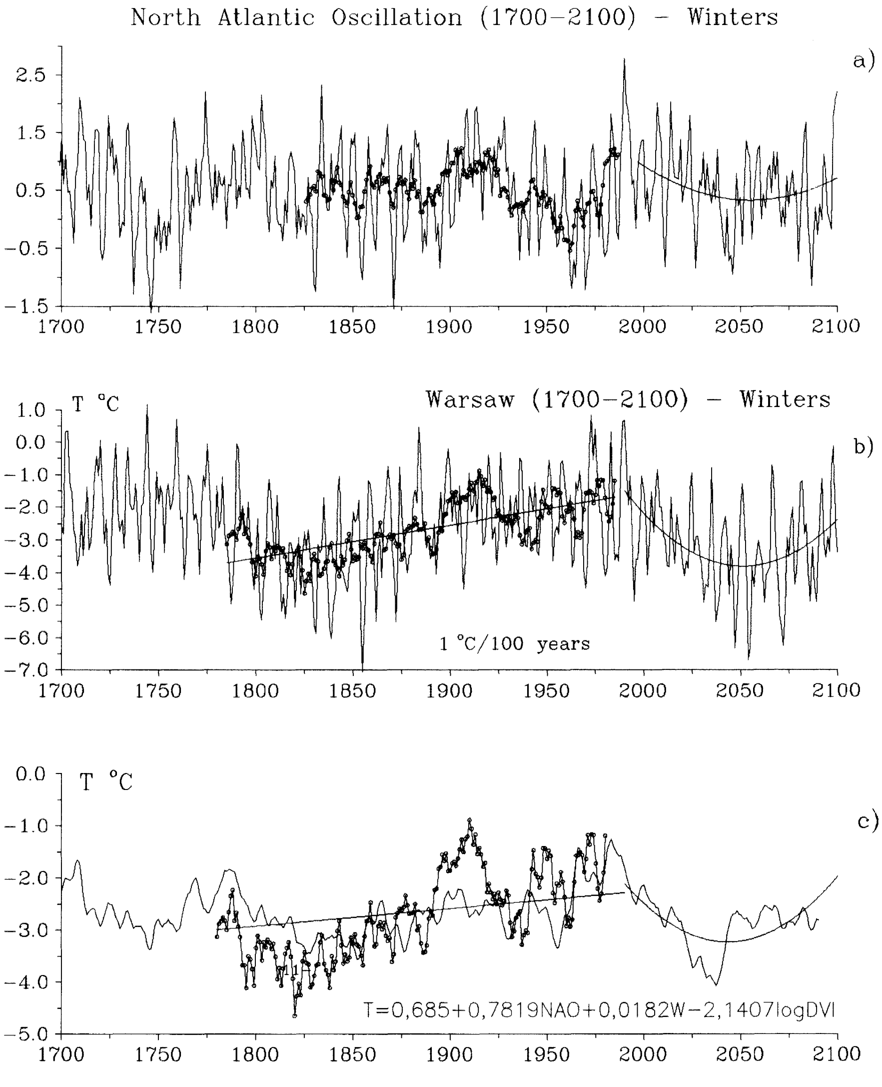

Fig. 3. Forecasts of winters in Warsaw in the 21st century: a) the NAO indicator values, NAO = $f(t)$, b) air temperature according to the interference of cycles, $T = f'(t)$, c) air temperature according to regression, $T = f(\text{NAO}, \log DVI, W)$.

5.8, 7.8, 8.3, 15.5, 21.5, 37.1, 71.5, 105.1 years. During the winters of the period 2001 – 2100 we can expect the decrease of the NAO indicator, that is — the decrease of the zonal circulation, and therefore the weakening of the warming influence of the Atlantic ocean on the climate of Poland (Fig. 3a).

Already these anticipatory forecasts of the NAO indicator value in the 21st century convince of the approaching natural cooling of the climate of Europe. It should also be noted that the longest period accounted for was equal 105.1 years. The diagram presenting the changes of air temperature during winters in Warsaw in the period 1700 – 2100 shows the significant natural cooling of climate in the 21st century (Fig. 3b).

An essential element is constituted by the logical coincidence of the forecasts of the NAO indicator, conditioning the mild or frosty character of the winters in Poland, with the forecasts of the very air temperature in the 21st century.

THE FORECASTS OF THE CLIMATE OF EUROPE IN THE 21ST CENTURY ACCORDING TO THE CHANGES OF THE NORTH ATLANTIC OSCILLATION, THE EMISSION OF VOLCANIC DUST (DUST VEIL INDEX) AND THE WOLF NUMBERS

In the new type of forecasts of the climatic changes in Europe in the 21st century abstraction was made of the cycles of air temperature in Warsaw in the years 1780 – 1990.

The consecutive 11-year averages of the air temperature were forecasted for the period 2001 – 2100 on the basis of the expected values of the North Atlantic Oscillation (NAO), dust veil index (log*DVI*), and the Wolf numbers (*W*).

Linear regression of the air temperature in winter (T) with respect to these three variables, NAO, log*DVI*, *W*, is represented by the formula ($R = 0.70$):

$$T = 0.685 + 0.7819\text{NAO} - 2.1407\ \log DVI + 0.7819W.$$

Conform to these new forecasts we should expect also a natural cooling of climate in the current century (Fig. 3c). A good agreement should be noticed between the consecutive 11-year averages of air temperature in the interval of approximation of 1780 – 1990 (thick lines) obtained according to the temperature cycles, $T = f(t)$, and according to the formula $T = f(\text{NAO}, \log DVI, W)$.

The forecasts were also compared of the Baltic Sea level in winter (Fig. 4) according to periodicity (a) and regression (b):

$$h = 519.95 + 3.08266\ \text{NAO} - 10.6825\ \log DVI + 0.0954\ W.$$

High cognitive importance should be attached to the logical coincidence of the forecasts for the 21st century (parabolas with the minima more or less in the middle of the century) of temperature and the Baltic Sea level obtained according to the periodicity identified (T) and the variables NAO, log*DVI*, and *W*.

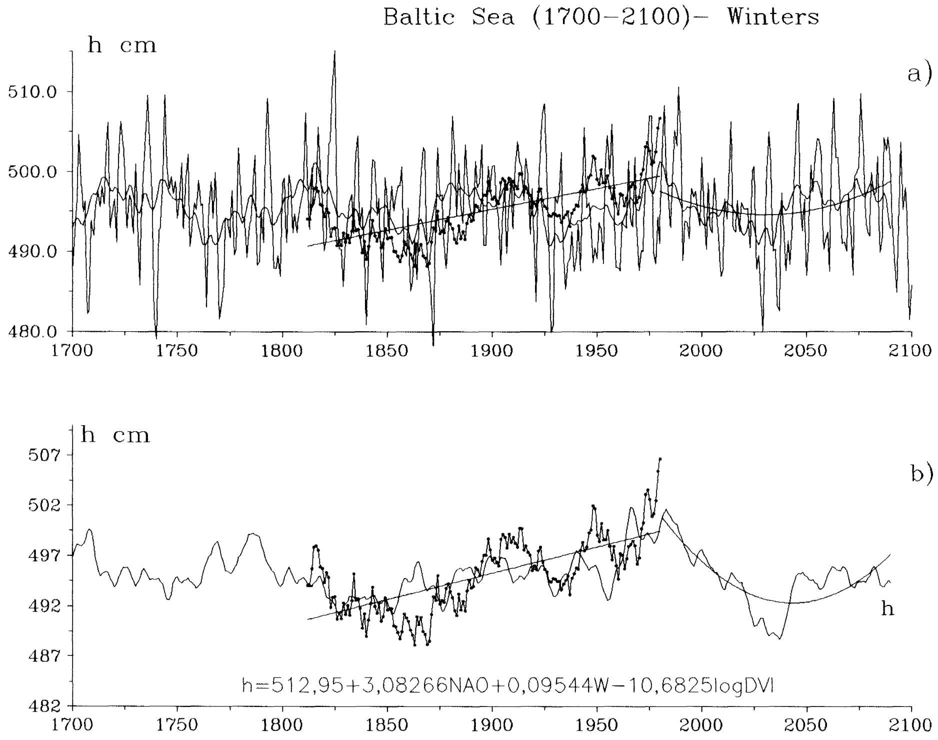

Fig. 4. Forecasts of the Baltic Sea level during winters in the 21st century (in Świnoujście) according (a) to the interference of the cycles, $h = f(t)$; and (b) according to the multiple regression, $h = f(\text{NAO}, \log DVI, W)$.

THE DOMINATING ROLE OF VOLCANIC DUST IN THE SHAPING OF THE EARTH'S CLIMATE (17TH–21ST CENTURIES)

A dominating influence is exerted on the global changes of climate by the volcanic dust ejected into the stratosphere, like after the eruption of the Tambora volcano (Indonesia, 1815) — up to the height of 60–70 km. The sulphur compounds (sulphate aerosols), which absorb and disperse the short-wave solar radiation, bring about the heating up of the stratosphere. At the same time the lower layers of the troposphere are cooler due to the decrease of total radiation at the level of the Earth's surface.

The main cooling at the beginning of the 19th century coincided with the secular minimum of the solar activity — it took place during the weakest 13-year cycle (1811–1823) and the maximum of volcanic activity. At the beginning of the 19th century volcanic eruptions occurred entailing the highest values of the dust veil index: Tambora (1815, DVI = 3000) and Cosiguina (1835, DVI = 4000).

The balance of the solar energy in the annual cycle is not closed — the net value is not equal zero, because the influx of solar radiation is shaped

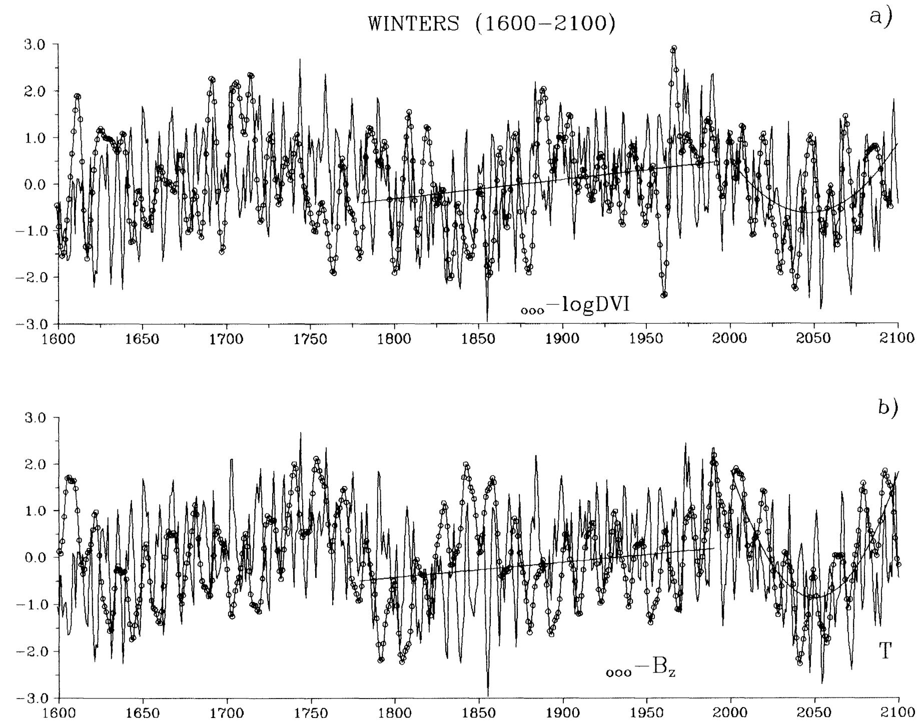

Fig. 5. Analogous fluctuations of air temperature during winters in Warsaw (T) in the years 1700 – 2100 and a) the indicator of purification of the atmosphere of the volcanic dust (-log*DVI*) and b) the indicator of concentration of the planetary mass with respect to the ecliptics ($-B_z$, B_z — mass dispersion).

by the long-term changes of the solar constant and the dust concentrations in the atmosphere.

Close to the maximums of the cycles, the excesses of the solar energy are used up for the heating of the increasingly deeper layers of the land and the oceans. The reach of the fluctuations of temperature down into the Earth is bigger, when the period of oscillation of the influx of solar radiation to the Earth's surface is longer.

Even very slow, small increments of solar energy in the consecutive years lead to global warming, while the decrements — to cooling (glaciation of the Earth).

Hence, the influence of the volcanic dust on the Earth's climate is "legible", when we refer to a longer unit of time (of several or a dozen years), for instance — to the consecutive 11-year averages.

The dominating role of the volcanic dust in the atmosphere in the shaping of the Earth's climate in the $17^{th} – 21^{st}$ centuries is demonstrated by the almost identical diagrams of the temporal changes in the air temperature according to the interference of the cycles, $T = f(t)$, and the indicator of purification of the atmosphere from the volcanic dust (-log*DVI*). The forecasted cooling in the 21st century corresponds to the minimum of the curve of -log*DVI*, characterising the purification of the atmosphere from the volcanic dust (Fig. 5a).

It is interesting to note the "parallel" course of the diagrams of changes (Fig. 5b) in the air temperature in winter in Warsaw and the coefficient ($-B_z$) of the concentration of the planetary mass with respect to the ecliptic plane (B_z — moment of inertia of the planets — dispersion of the mass). The forecasted cooling in the 21st century corresponds to the secular minimum of concentration of the planetary mass with respect to the ecliptics.

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