UDC 551.509.328 + 517.938

A.V. Glushkov, *d.ph.-m.n.* **, N.G. Serbov**, *c.geogr.n.,* **A.A. Svinarenko,** *d.ph.-m.n.,*
V.V.Buyadzhi, *as.*
Odessa State Environmental University

CHAOS-GEOMETRIC ANALYSIS OF TIME SERIES OF CONCENTRATIONS OF SULPHUR DIOXIDE IN THE ATMOSPHERE OF THE INDUSTRIAL CITY (ON EXAMPLE OF THE GDANSK REGION)

On the basis of the theory of chaos ii is performed an advanced chaos-geometric analysis of time series of concentrations of sulphur dioxide in Gdynia (Gdansk region) and calculated spectrum of the correlation dimension, that confirms the chaos existence. Estimation of the predictability limit in a short-term forecast is given.
Keywords*: time series of concentrations, correlation dimension, chaos-geometric method*

Introduction. Admittedly, air pollution is the most dangerous factor for humans, flora and fauna, and to ensure its purity is the most complex and urgent problem of modern atmospheric ecology [1-4]. One of the key aspects of the problem is that the composition of the atmosphere of the industrial cities is influenced by many factors, which include the characteristics of pollution sources, their location, climate and meteorological parameters, especially the architecture of the city, and the processes of energy transfer, dissipation and relaxation, self-purification and regeneration, etc. The most important aspect of the problem is mathematical one, connected with adequate analysis of time series of the air pollutants concentrations. In recent years, chaos theory methods [4-15] are widely used in the studying anthropogenic impact on the ecological state of the industrial city. They allows to give quite adequate analysis and even a short-term forecast of further time evolution of the pollutants concentrations. It is based on a studying time series of the air pollutants concentrations. This approach has been successfully used in the analysis of fluctuations of meteorological parameters [16-22] etc.

In [4-7], methods of nonlinear forecasting and chaos theory has been successfully applied to the analysis of time series of concentrations of the atmospheric dust, nitrogen dioxide at Odessa, as well as at a few cities in the Gdansk region. In these studies there are used a simplified models of reconstruction of the Liapunov dimensions spectrum and computing the Kalan-York dimension, Kolmogorov entropy. It has been shown that even a simplified method of constructing predictive model gives quite satisfactory forecasting results. The purpose of this paper is in more detailed (in comparison with previous data [6]) investigation of ecological state for atmosphere of the industrial city and computing parameters of the time series for sulphur dioxide in the Gdynia (Gdansk region) and limit of predictability for short-term forecast.

Data and method of analysis. As the initial data we have used the empirical (observed) data for SO_2 in the city of Gdynia during December 2002 and 2003 (see Refs. in [11]). The concentrations of the gases (mg/m^3) was measured every 5 minutes, and then hour-averaged values were computed (all 9480 values) using the data of these measurements. Note that the observations were continuously carried out only at two this stations during 2003 among the ten stations located near Gdansk.

This was the reason for selecting the above posts as chaos theory analysis requires necessary set of data at regular time steps. Table. 1 shows statistical characteristics for the considered input data and Figure 1 shows the time series. Labels on the x-axis in Figure 1 are plotted to fit about the first day of the month. Also, in the figure 1 the dashed line shows the lower limit of the pollution index 2 according to the EU Directive on air quality, which refers

Table 1 - Average ($\bar{f}$), maximum (f_{max}) and minimum (f_{min}) values, mean-square deviation (σ^2), coefficients of asymmetry (γ_1) and excess (γ_2) for time series of the SO_2 (Gdynia, 2003)

$\bar{f}$	f_{max}	f_{min}	σ^2	γ_1	γ_2
9,13	111,99	3,99	6,94	4,79	38,15

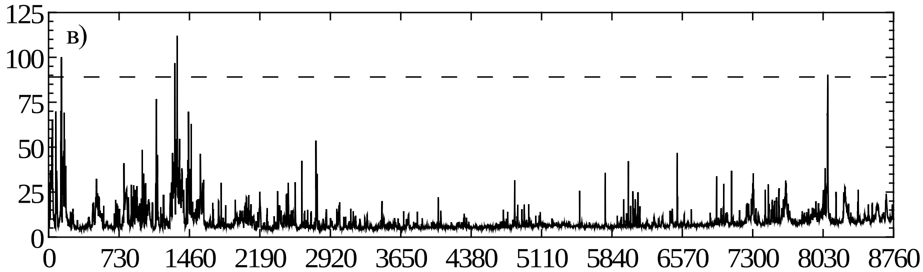

Figure 1 - Time series of SO_2 (in mg/m^3) for atmosphere of the Gdynia (2003); Dashed lines denote the index 2 air pollution. X axis is the ordered number of hour per year

to a low level of contamination. Figure 2 shows the Fourier spectrum for the time series (Figure 1.) Accounting for irregular nature of changes in concentrations, it is not surprising that these spectra look the same as in the random process.

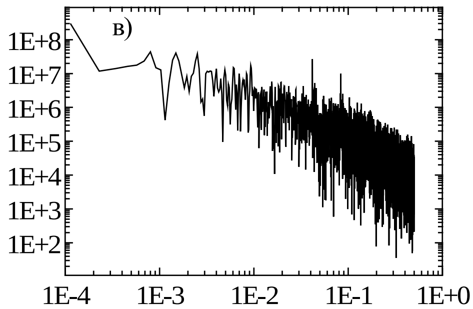

Figure 2 - Fourier spectrum concentration SO_2: X axis – frequency, axis Y - energy

The results of the analysis and conclusions. According to Ref.[1], an important step in the analysis is a recovery of the phase space, which requires determination of the time delay by using the autocorrelation function and mutual information methods. Table 2 summarizes all results for time delay in the range of 1 to 1000. A further step is the numerical experiment on recovering the phase space dimension (d_E), using the method of correlation dimension and algorithm of the false nearest neighboring points.

Table 2 – The time delay (τ) dependence on the different values of the autocorrelation function (C_L) and the first minimum of mutual information (I_{min1}) for time series of NO_2

Gdynia	$C_L = 0$	$C_L = 0{,}1$	$C_L = 0{,}5$	I_{min1}
SO_2	–	232	12	19

Table 3 summarizes all results on the reconstructing attractors and computing the K indicator in the Hottvod-Melben test and global Lyapunov's dimensions. Let us remind that the Hottvod-Melben test indicator takes values from 0 (regularity) to 1 (chaos). It is important to note that the non-zero values of the indicator confirm the chaotic features of a process. In our case, the value of K in all cases are higher than 0.6, that the considered time series are exposed to chaotic dynamics effect. We can also note that the Kaplan-York dimension (one of indicator of the attractor dimension) is in all cases less than the dimension d_A. This fact shows also that it can also serve as an indicator of the correctness of our choice

Table 3 - Time delay (τ), correlation dimension (d_2), the dimension of the embedding space (d_E), the first two Lyapunov dimension (λ_1 i λ_2), Kaplan-York dimension (d_L), the limit of predictability (Pr_{max}, hours) and parameter K for NO_2

	τ	d_2	d_E	λ_1	λ_2	d_L	Pr_{max}	*K*
SO_2	17	3,40	6	0,0150	0,0052	4,60	49	0,73

Let us consider now the results of calculating the spectrum of the Lyapunov dimensions. In Table 3 there are listed the positive λ_i. Availability of two (out of six) positive λ_i suggests on availability of chaotic features. The amount of the positive Lyapunov dimensions determines the Kolmogorov entropy that is inversely proportional to limit of a predictability. In order to use a nonlinear prediction method it is necessary to solve another problem that can be formulated as follows: how many nearest neighboring points (NN) should be taken to provide satisfactory forecasting results. To solve this problem, you can make some preliminary estimates for different number of NN, and then calculate the correlation coefficient between the empirical and predicted data. Typically, the correlation coefficient will increase and reach some maximum [19]. We have used such an approach to give twenty-four hours forecasting for the last 100 points of the time series. Numerical experiments showed that with increasing number of the nearest neighboring points the predicted curve is usually close to the empirical one. The results of computing the correlation coefficient between the empirical and predicted data in 24 hours for some NN are presented in Table 4.

Table 4 - Correlation coefficient (*r*) between empirical and 24-hours forecasting rows in dependence on the number of nearest neighboring points (NN) for last 100 points of a row

NN	80	250	270
r	0,928	0,940	0,941

As mentioned above, the correlation coefficient increases with increasing number of NN and reaches a certain value, after which it changes is essential. As the number of data in the time series is quite large, a correlation coefficient can reach the maximum value for very large number of the nearest neighboring points. However, it does not make sense to take all them to build a forecast model, because the quality of the forecast may not be significantly improved. It is interesting to note that although in this studying there are examined the longer time series, the results obtained do not significantly differ from the results of previous studies for the time series of changes in the concentrations of the nitrogen dioxide in the Gdansk region. It definitely proves the reliability and stability of the corresponding numerical scheme. It is also important to note that he empirical and 12-hours predicted value for concentration of the impurities are in very good agreement with each other. On the other hand, it should be borne in mind that, despite the fact that almost all the peaks on the empirical curve are repeated on the prediction curve, the difference between these data in the case of higher concentrations may be significant, but in this case, the results of this forecasting should be considered as quite satisfactory ones.

References

1. *Bunyakova Yu.Ya. and Glushkov A.V.* Analysis and forecasting effect of anthropogenic factors on air basin of industrial city.-Odessa: Ecology, 2010.-256p.
2. *Chelani A.B.* Predicting chaotic time series of PM10 concentration using artificial neural network // Int. J. Environ. Stud.-2005.-Vol.62.-P. 181-191.
3. *Sivakumar B.* Chaos theory in geophysics: past, present and future // Chaos, Solitons & Fractals.-2004.-Vol.19,№ 2.-P. 441-462.

4. *Glushkov A.V., Bunyakova Yu.Ya., Khokhlov V.N., Prepelitsa G.P., Tsenenko I.A.* Sensing air pollution field structure in the industrial city's atmosphere: stochasticity and effects of chaos // Sensor Electr. and Microsyst. Tech.-2005.-№.1.-P. 80-84.
5. *Glushkov A.V., Khokhlov V.N., Serbov N.G Bunyakova Yu.Ya., Balan A.K., Balanjuk E.P.* Low-dimensional chaos in the time series of the pollution substances concentrations in atmosphere and hydrosphere// Herald of Odessa State Environmental University.-2007.-N4.-C.337-348.
6. *Glushkov A.V., Khokhlov V.N., Loboda N.S., Bunyakova Yu.Ya*. Short-range forecast of atmospheric pollutants using non-linear prediction method// Atmospheric Environment (Elsevier; The Netherlands).-2008.-Vol.42.-P. 7284–7292.
7. *Glushkov A.V., Serga E.N., Bunyakova Yu.Ya*. Chaos in the time series of concentrations of pollutants in the atmosphere (Odessa)// Herald of Odessa State Environmental University.-2009.-N8.-C.233-238.
8. *Lorenz E.N.* Deterministic nonperiodic flow // J. Atmos. Sci.-1963.-Vol.20.-P.130-141.
9. *Abarbanel H.D.I., Brown R., Sidorowich J.J., Tsimring L.Sh.* The analysis of observed chaotic data in physical systems // Rev. Mod. Phys.-1993.- Vol.65.-P.1331-1392.
10. Packard N.H., Crutchfield J.P., Farmer J.D., Shaw R.S. Geometry from a time series // Phys. Rev. Lett. – 1980. – Vol. 45. – P. 712-716.
11. *Pessin Ya.* Characteristic Lyapunov's exponents and smooth ergodic theory// Uspekhi of Math. Nauk.-1977.-Vol.32(1).-P.55-112.
12. *Kaplan J.L., Yorke J.A.* Chaotic behavior of multidimensional difference equations // Lecture Notes in Mathematics No. 730 / H.-O. Peitgen, H.-O. Walter (Eds.). Berlin: Springer, 1979.-P.204-227.
13. *Grassberger P., Procaccia I.* Measuring the strangeness of strange attractors // Physica D.-1983.–Vol.9.–P.189-208.
14. *Sano M., Sawada Y.* Measurement of the Lyapunov spectrum from a chaotic time series // Phys. Rev. Lett.-1985.-Vol.55.-1082-1085.
15. *Schreiber T.* Interdisciplinary application of nonlinear time series methods // Phys. Rep.- 1999.-Vol.308.-P.1-64.
16. *Tsonis A.A., Elsner J.B.* Global temperature as a regulator of climate predictability // Physica D.-1997.-Vol.108.- P.191-196.
17. *Islam M.N., Sivakumar B.* Characterization and prediction of runoff dynamics: a nonlinear dynamical view // Adv. Water Res.-2002.-Vol.25, № 2.-P.179-190
18. *Glushkov A.V., Khokhlov V.N., Prepelitsa G.P., Tsenenko I.A*. Temporal variability of the atmosphere ozone content: Effect of North-Atalantic oscillation// Optics of atmosphere and ocean.-2004.-Vol.14,N7.-p.219.
19. *Glushkov A.V., Loboda N.S., Khokhlov V.N.* Using meteorological data for reconstruction of annual runoff series over an ungauged area: Empirical orthogonal functions approach to Moldova-SW-Ukraine region//Atmosph. Research (Elseiver).-2005.-Vol.77.-P.100-113.
20. *Glushkov A.V., Khokhlov V.N., Tsenenko I.A.* Atmospheric teleconnection patterns and eddy kinetic energy content: wavelet analysis// Nonlinear Processes in Geophysics.-2004.-V.11,N3.-P.285-293.
21. *Glushkov A.V., Loboda N.S., Khokhlov V.N., Lovett L*. Using non-decimated wavelet decomposition to analyse time variations of North Atlantic Oscillation, eddy kinetic energy, and Ukrainian precipitation // Journal of Hydrology (Elsevier; The Netherlands).–2006.–Vol. 322. –N1-4.–P.14-24.
22. *Khokhlov V.N., Glushkov A.V., Loboda N.S.* Relationship between SOI and global temperature anomalies: nonlinear approach// IOP Journ. of CS: Earth and Environmental Science, Spec. Issue: Climate Change - Global Risks, Challenges and Decisions. -2009.-Vol.6.-P. 072034.

Хаос-геометрический анализ временных рядов концентраций диоксида азота в атмосфере промышленного города (на примере Гданьского региона)

Глушков А.В., Сербов Н.Г., Свинаренко А.А.

На основе метода теории хаоса выполнен уточненный анализ временных рядов концентраций диоксида серы в г Гдыня (Гданьский регион) и рассчитан спектр корреляционных размерностей, подтверждающий наличие явления хаоса. Дана оценка предела предсказуемости в методе краткосрочного прогноза.

Ключевые слова: временные ряды концентраций, корреляционная размерность, хаос-геометрический метод

Хаос-геометричний аналіз часових рядів концентрацій діоксиду азоту в атмосфері промислового міста (на прикладі Гданського регіону)

Глушков О.В., Сербов М.Г., Свинаренко А.А.

На основі методів теорії хаосу виконано докладний аналіз часових рядів концентрацій діоксиду сірки у м.Гдиня (Гданський регіон) і розраховано спектр кореляційних розмірностей, що свідчить про наявність рис хаосу. Надано оцінку ліміту передбачуваності у короткостроковому методі прогнозу

Ключові слова*: часові ряди концентрацій, кореляційна розмірність, хаос-геометричний підхід*