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ANALYSIS OF THE BERYLLIUM-7 ACTIVITY CONCENTRATION DYNAMICS IN THE ATMOSPHERIC ENVIRONMENT TIME SERIES AFTER THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANTS EMERGENCY

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Abstract. We present the results of an analysis, modelling a temporal dynamics of the beryllium-7 (caesium-137) activation concentration in the atmospheric environment time series in Austria after the Fukushima Daiichi Nuclear Power Plants emergency accident. As method of studying we use the complex of the earlier developed models and microsystem technologies which are based on an advanced non-linear analysis technique and modern chaos theory and dynamical systems and a chaos theory methods (Correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, nonlinear prediction models etc). As the input data we use the data on the long-term time series and activity size distribution of beryllium-7 (caesium-137) in the atmospheric environment time series in Austria after the Fukushima Nuclear Power Plant. We have listed the data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents, Kolmogorov entropy etc and found an availability of the chaos elements in the corresponding Be-7 time series. Regarding the caesium-137, we could not get the analogous adequate conclusion for the corresponding time series.

Keywords: mathematical modelling, new microsystem technologies, radionuclide activation concentration, time series analysis and chaotic elements

АНАЛІЗ ДИНАМІКИ КОНЦЕНТРАЦІЇ РАДІОНУКЛІДА BERYLLIUM-7 В АТМОСФЕРНОМУ СЕРЕДОВИЩУ НА ОСНОВІ АНАЛІЗУ ЧАСОВИХ РЯДОВ ПІСЛЯ АВАРІЙНОЇ СИТУАЦІЇ НА АТОМНІЙ ЕЛЕКТРОСТАНЦІЇ FUKUSHIMA DAIICHI

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Анотація. Наводяться результати аналізу і моделювання часової динаміки концентрації радіонуклідів берилій-7 (цезій-137) в атмосферному середовищі в Австрії на основі відповідного аналізу часових рядів після аварії на атомній електростанції Fukushima Daiichi. В якості методу вивчення використовується комплекс раніше розроблених моделей і мікросистемна технологія, які засновані на використанні методів нелінійного аналізу, теорії хаосу і динамічних систем, таких як метод кореляційного інтеграла і середньої взаємної інформації, алгоритми сурогатних даних і помилкових найближчих сусідів, аналіз на основі показників Ляпунова і ентропії Колмогорова, моделі нелінійного прогнозування і т. д .. В якості вхідних даних використані дані за довгостроковими часовими рядами і розподілу ра змери активності берилію-7 в атмосферному середовищі в Австрії після аварії на атомній електростанції Fukushima Daiichi. Представлені дані про топологічні і динамічні інваріанти, а саме: кореляційну розмірність, розмірності вкладення та Каплана-Йорка, показники Ляпунова, ентропію Колмогорова та ін. і виявлені елементи хаосу в відповідних часових рядах для беррілія-7. Відносно цезію-137, отримати аналогічний адекватний висновок не вдалося.

Ключові слова: математичне моделювання, нові мікросистемні технології, концентрація радіонуклідів, аналіз часових рядів і наявність хаотичних елементів

АНАЛИЗ ДИНАМИКИ КОНЦЕНТРАЦИИ РАДИОНУКЛИДА BERYLLIUM-7 В АТМОСФЕРНОЙ СРЕДЕ НА ОСНОВЕ АНАЛИЗА ВРЕМЕННЫХ РЯДОВ ПОСЛЕ АВАРИЙНОЙ СИТУАЦИИ НА АТОМНОЙ ЭЛЕКТРОСТАНЦИИ FUKUSHIMA DAIICHI

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Аннотация. Приводятся результаты анализа и моделирования временной динамики концентрации радионуклидов бериллий-7 (цезий-137) в атмосферной среде в Австрии на основе соответствующих анализа временных рядов после аварии на атомной электростанции Fukushima Daiichi. В качестве метода изучения используется комплекс ранее разработанных моделей и микросистемная технология, которые основаны на использовании методов нелинейного анализа, теории хаоса и динамических систем, таких как метод корреляционного интеграла и средней взаимной информации, алгоритмы суррогатных данных и ложных ближайших соседей, анализ на основе показателей Ляпунова и энтропии Колмогорова, модели нелинейного прогнозирования и т. д.. В качестве входных данных использованы данные по долгосрочным временным рядам и распределению размера активности бериллия-7 в атмосферной среде в Австрии после аварии на атомной электростанции Fukushima Daiichi. Представлены данные о топологических и динамических инвариантах, а именно: корреляционной размерности и размерности вложения и Каплана-Йорка, показателям Ляпунова, энтропии Колмогорова и др. и обнаружены элементы хаоса в соответствующих временных рядах для беррилия-7. Касательно цезия-137, получить аналогичное адекватное заключение не удалось.

Ключевые слова: математическое моделирование, новые микросистемные технологии, концентрация радионуклидов, анализ временных рядов и наличие хаотических элементов

1. Introduction

Correct quantitative description of environmental radioactivity temporal and spatial dynamics, studying short-and long term radionuclides concentration in the atmosphere and other geospheres remains one of the most actual and important problems as in an applied ecology and environment protection as computational environment physics and informatics [1-12]. As indicated earlier (look, for example, [1-5], generally speaking, a solving such classes of the problems is needed as follows: a long-term investigation of radionuclides behaviour in the environment; elucidation of the mechanism of radionuclides transfer, deposition in the environment, elucidation of the global and local mechanisms of transformation and transportation of radioactive substances due to meteorological and hydrological phenomena and other factors, quantitative studying the radioactive impact on environment (atmosphere, hydrosphere, lithosphere etc), revealing and estimating the sources of radioactive materials and samples and archiving of research methodologies and many others. Especially important and actual is solving these problems in light of the well-known Chenobyl and Fukushima Daiichi Nuclear Power Plants emergency accidents.

In many papers it has been performed an analysis of the short-and long-term temporal (time series) and spatial deposition of the radionuclides in atmosphere and other environments (look, for example, [9-16]). It is well known that the most models, that are currently used to estimate the radionuclides pollution level, are either deterministic or statistical, but their skilfulness are still limited due to both inability for describing non-linearities in pollutant time series and lack of understanding involved physical and/or chemical processes. Very useful alternative to the simplified deterministic and similar methodologies is provided by using the non-linear prediction, non-linear dynamical systems and a chaos theories. These studies show that chaos theory methodology can be applied and the short-range forecast by the non-linear prediction method can be satisfactory. In this paper for the first time we present the results of an analysis, modelling (forecasting is to be presented in the next papers) a temporal dynamics of the of beryllium-7 (caesium-137) in the atmospheric environment time series and activity size distribution of iodine-131 in Austria after the Fukushima Daiichi Nuclear Power Plants emergency accident. As method of studying we use the complex of the earlier developed models and microsystem technologies which are based on an advanced non-linear analysis technique and modern chaos theory and dynamical systems methods have been applied (in versions [7-13]). More concretely, speech is about such methods and algorithms as such as a correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, nonlinear prediction models etc. As the input data we use the data on the long-term time series and activity size distribution of beryllium-7 (caesium-137) in the atmospheric environment time series in Austria after the Fukushima Nuclear Power Plant [6]. We listed the data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents and Kolmogorov entropy etc and found an availability y of the chaos elements in the corresponding time series. Nevertheless this fact is not evidence of the universal availability of the deterministic chaos in any radionuclide concentration time series. In our opinion, the chaotic atmosphere processes are the obligatorily element for chaotic behaviour of the corresponding radionuclide concertation series. All calculations are performed with using "Geomath", "Superatom" and "Quantum Chaos" codes [9-18].

2. Technique of analysis and computing radionuclides pollutants fluctuations time ynamics

As the master elements of the technique of analysing the dynamical time series and computing invariants etc are described in many Refs. (look, for example, [9-11] and Refs. therein), below we are limited only by the key points, basing on our versions of the known algorithms. As usually, one should consider scalar measurements: $s(n)=s(t_0+n\Delta t)=s(n)$, where t_0 is a start time, Δt is time step, and n is number of the measurements. In our case $s(n)$ is the time series of the radionuclide concentration. The important test for a chaos is provided by the known Gottwald-Melbourne criterion. The known Gottwald-Melbourne chaotic test supposes a choice of the real constant c and definition of the following quantities (including a root-mean-square shift):

$$s(n)=\sum_{j=1}^{n} s(j)\cos(jc),$$

$$M(n)=\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N}[s(j+n)-s(j)]^2 . \quad (1)$$

If the dynamics of the system is regular (periodic or quasiperiodic), then with probability 1 the shift M (n) is a limited function of n. However, if the dynamics is chaotic (in a rather non-strict sense), then with probability 1 $M(n)=V(n)+O(1)$ for some $V>0$. One could determine the rate of asymptotic growth of the root-mean-square shift:

$$K=\lim_{n\to\infty}\frac{\log M(n)}{\log n}. \quad (2)$$

The cases of $K = 0$ and $K = 1$ correspond to a regular and chaotic dynamics respectively. As processes resulting in a chaotic behaviour are fundamentally multivariate, one needs to reconstruct phase space using as well as possible information contained in *s(n)*. According the algorithm by Packard et al and Takers-Mane [7,8], the main idea is that direct use of lagged variables $s(n+\tau)$, where τ is some integer to be defined, results in a coordinate system where a structure of orbits in phase space can be captured. Using a collection of time lags to create a vector in d dimensions, $\mathbf{y}(n)=[s(n),s(n+\tau),s(n+2\tau),..,s(n+(d-1)\tau)]$, the required coordinates are provided. The dimension $d=d_E$ is the embedding dimension,. The goal of the embedding dimension determination is to reconstruct a Euclidean space R^d large enough so that the set of points d_A can be unfolded without ambiguity. The embedding dimension, d_E, must be greater, or at least equal, than a dimension of attractor, d_A, i.e. $d_E > d_A$. So, to analyse a measured time histories for the studied radionuclide concentration series, the phase space of the system had been reconstructed by the delay embedding.

Further the corresponding versions of the mutual information approach, correlation integral analysis, false nearest neighbour algorithm, Lyapunov's exponent's analysis, and surrogate data method are used for comprehensive characterization [9-13]. The correlation dimension method provides a fractal-dimensional attractor. Statistical significance of the results was confirmed by testing for a surrogate data. The choice of proper time lag is important for the subsequent reconstruction of phase space. First approach is to compute the linear autocorrelation function $C_L(\delta)$ and to look for that time lag where $C_L(\delta)$ first passes through 0. This gives a good hint of choice for τ at that $s(n+j\tau)$ and $s(n+(j+1)\tau)$ are linearly independent. Alternative approach is given by a nonlinear concept of independence, e.g. an average mutual information.

In order to compute an attractor dimension one should use the known Grassberger- Procaccia correlation integral analysis, which is one of the widely used techniques to investigate the signatures of chaos in a time series. One must compute the correlation integral $C(r)$. If the time series is characterized by an attractor, then the correlation integral $C(r)$ is related to the radius r as follows:

$$d = \lim_{\substack{r\to 0\\ N\to\infty}} \frac{\log C(r)}{\log r}, \quad (3)$$

where d is correlation exponent. If the correlation exponent attains saturation with an increase in the embedding dimension, then the system is generally considered to exhibit chaotic dynamics. The saturation value of the correlation exponent is defined as the correlation dimension (d_2) of the attractor.

The important point of studying the corresponding radionuclide temporal dynamics on the availability of chaotic elements is provided by the Lyapunov's exponents algorithm. It is well-known that the spectrum of the Lyapunov's exponents is one of dynamical invariants for nonlinear system with chaotic behaviour. The Lyapunov's exponents are related to the eigenvalues of the linearized dynamics across the attractor. Negative values show stable behaviour while positive values show local unstable behaviour. The limited predictability of the chaos is quantified by the local and the global Lyapunov's exponents, which can be determined from measurements. The predictability can be estimated by the Kolmogorov entropy, which is proportional to a sum of the positive Lyapunov's exponents. For chaotic systems, being both stable and unstable, the Lyapunov's exponents indicate the complexity of the dynamics. The largest positive value determines some average prediction limit. Since the Lyapunov's exponents are defined as asymptotic average rates, they are independent of the initial conditions, and hence the choice of trajectory, and they do comprise an invariant measure of the attractor. An estimate of this measure is a sum of the positive Lyapunov's exponents. The estimate of the attractor dimension is provided by the conjecture d_L and the Lyapunov's exponents are taken in descending order. To compute Lyapunov's exponents, the known method with linear fitted map, although the maps with higher order polynomials can be used too (look details in Refs. [9-13]).

The principally important point in development of the time series prediction model for complex systems is in the using the traditional concept of a compact geometric attractor in which evolves the measurement data. More advanced versions of the prediction models include using of the neural network and other algorithms. The existing so far in the theory of chaos prediction models are based on the concept of an attractor. The meaning of the concept is in fact a study of the evolution of the attractor in the phase space of the system and, in a sense, modelling ("guessing") time-variable evolution.. From a mathematical point of view, it is a fact that in the phase space of the system an orbit continuously rolled on itself due to the action of dissipative forces and the nonlinear part of the dynamics, so it is possible to stay in the neighborhood of any point of the orbit *y (n)* other points of the orbit $y^r(n)$, $r = 1, 2, ..., N_B$, which come in the neighborhood *y (n)* in a completely different times than *n*. Of course, then one could try to build different types of interpolation functions that take into account all the neighborhoods of the phase space and at the same time explain how the neighborhood evolve from *y (n)* to a whole family of points about *y (n+1)*. Use of the information about the phase space in the simulation of the evolution of some geophysical (environmental, etc.) of the process in time can be regarded as a fundamental element in the simulation of random processes. A principal aspect in obtaining the successful prediction model data is connected with a correct, physically reasonable constructing a parameterized nonlinear function F (x, a), which transform s (n) to s (n + 1) = F (s (n), a), and then using different criteria for determining the parameters a. One of the most spread versions of local prediction algorithm is provided the following form:

$$s(n+\Delta n) = a_0^{(n)} + \sum_{j=1}^{d_A} a_j^{(n)} s(n-(j-1)\tau), \quad (4)$$

where Δ n - the time period for which a forecast .

The coefficients $a_j^{(k)}$, may be determined by a least-squares procedure, involving only points $s(k)$ within a small neighbourhood around the reference point. Thus, the coefficients will vary throughout phase space. Other details can be found, for example, in Refs. [9-13].

3. The results of analysis of beryllium-7 concentrations long-term time series and conclusions

As the input data we use the data on the long-term time series and activity size distribution of beryllium-7 in the atmospheric environment time series and activity size distribution of iodine-131 in Austria after the Fukushima NPP. According to [2], the cosmogenic radionuclide Be-7 is forms through spallation reactions with decreasing production rates with atmospheric depth and about two thirds of the Be-7 production takes place in the stratosphere and one third in the troposphere (mainly in the upper troposphere). Due to stratosphere- to- troposphere exchange the Be-7 is also present in the near-to-ground atmosphere. In Figure 1 there is present the typical time series of Be-7 and Cs-137 over a period of 24 years. As various factors govern the Be-7 activity concentration in the near-to-ground atmosphere they are highly episodic and vary strongly. This is well demonstrated in Figure 2 where the Be-7 results are given per day of the year from the high-altitude station at Sonnblick (3106 m) for a period of 15 years.

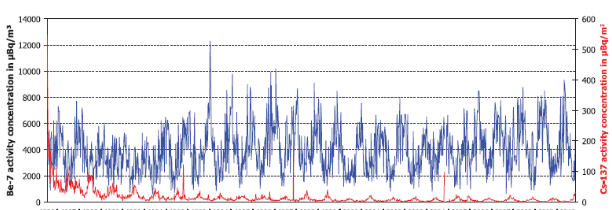

Figure 1. Time series of Be-7 (upper line) and Cs-137 (lower line) in the near-to-ground atmosphere in Klagenfurt (Austria) from August 1986 to December 2010 (Ref. [2]).

In the Table 1 we list the data for the time lag calculated for first 103 values of the Be-7 time series. The autocorrelation function for all time series remains positive. In the Table 2 we present our advanced data on the correlation dimension (d_2), embedding dimension (d_E), Kaplan-Yorke dimension (d_L), two Lyapunov's exponents (λ_1,λ_2), the Kaplan-Yorke dimension (d_L), and average limit of predictability (Pr_{max}, hours) for time series of the NO_2 at sites of the Gdansk (during 2003 year). From the table 2 it can be noted that the Kaplan-Yorke dimensions, which are also the attractor dimensions, are smaller than the dimensions obtained by the algorithm of false nearest neighbours.

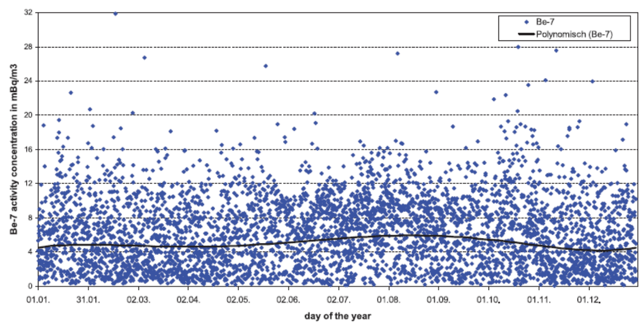

Figure 2. Be-7 results in air per day of the year from a high-altitude station in Austria (Sonnblick, 3106 m) for the period July 1996 to December 2010. (Ref. [2]).

Firstly, one should note that the presence of the two (from six) positive λ_i suggests the system broadens in the line of two axes and converges along four axes that in the six-dimensional space.

Table 1

Time lags (hours) subject to different values of C_L, and first minima of average mutual information, I_{min1}, for the Be-7 time series

$C_L = 0$	$C_L = 0,1$	$C_L = 0,5$	I_{min1}
-	142	22	14

To conclude, we had presented the results of an analysis of temporal dynamics of the beryllium-7 (caesium-137) in the atmospheric environment in Austria after the Fukushima Daiichi Nuclear Power Plants emergency accident. As method of studying we use the complex of the earlier developed algorithms versions and microsystem technology which are based on an advanced non-linear analysis technique and modern chaos theory and dynamical systems methods (in versions [1,9,-13]).

Table 2

The correlation dimension (d_2), embedding dimension (d_E), first two Lyapunov's exponents, E(λ_1,λ_2), Kaplan-Yorke dimension (d_L), and the Kolmogorov entropy (K_{ent}), the Gottwald-Melbourne parameter for the Be-7 time series (see text)

τ	d_2	d_E	λ_1	λ_2	d_L	K_{ent}	K
Be-7							
14	3,7	6	0,0157	0,0053	4,4	0,02	0,61

More concretely, speech is about such methods and algorithms as such as a correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, nonlinear prediction models etc. As the input data we use the data on the long-term time series and activity size distribution of beryllium-7 in the atmospheric environment time series in Austria after the Fukushima NPP [2]. We listed the data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents and Kolmogorov entropy etc and found an availability y of the chaos elements in the corresponding Be-7 time series. Nevertheless this fact is not evidence of the universal availability of the deterministic chaos in any radionuclide concentration time series. In particular, we could not get the analogous conclusion for the corresponding Cs-137 time series.

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Summary

We present the results of an analysis, modelling a temporal dynamics of the beryllium-7 (caesium-137) activation concentration in the atmospheric environment time series in Austria after the Fukushima Daiichi Nuclear Power Plants emergency accident. As method of studying we use the complex of the earlier developed models and microsystem technologies which are based on an advanced non-linear analysis technique and modern chaos theory and dynamical systems and a chaos theory methods (Correlation integral approach, average mutual information, surrogate data, false nearest neighbours algorithms, the Lyapunov's exponents and Kolmogorov entropy analysis, nonlinear prediction models etc). As the input data we use the data on the long-term time series and activity size distribution of beryllium-7 (caesium-137) in the atmospheric environment time series in Austria after the Fukushima Nuclear Power Plant. We have listed the data on the topological and dynamical invariants, namely, the correlation, embedding, Kaplan-Yorke dimensions, the Lyapunov's exponents, Kolmogorov entropy etc and found an availability of the chaos elements in the corresponding Be-7 time series. Regarding the caesium-137, we could not get the analogous adequate conclusion for the corresponding time series.

Keywords: mathematical modelling, new microsystem technologies, radionuclide activation concentration, time series analysis and chaotic elements

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АНАЛІЗ ДИНАМІКИ КОНЦЕНТРАЦІЇ РАДІОНУКЛІДА BERYLLIUM-7 В АТМОСФЕРНОМУ СЕРЕДОВИЩУ НА ОСНОВІ АНАЛІЗУ ЧАСОВИХ РЯДОВ ПІСЛЯ АВАРІЙНОЇ СИТУАЦІЇ НА АТОМНІЙ ЕЛЕКТРОСТАНЦІЇ FUKUSHIMA DAIICHI

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Реферат

Наводяться результати аналізу і моделювання часової динаміки концентрації радіонуклідів берилій-7 (цезій-137) в атмосферному середовищі в Австрії на основі відповідного аналізу часових рядів після аварії на атомній електростанції Fukushima Daiichi. В якості методу вивчення використовується комплекс раніше розроблених моделей і мікросистемна технологія, які засновані на використанні методів нелінійного аналізу, теорії хаосу і динамічних систем, таких як метод кореляційного інтеграла і середньої взаємної інформації, алгоритми сурогатних даних і помилкових найближчих сусідів, аналіз на основі показників Ляпунова і ентропії Колмогорова, моделі нелінійного прогнозування і т. д .. В якості вхідних даних використані дані за довгостроковими часовими рядами і розподілу ра змери активності берилію-7 в атмосферному середовищі в Австрії після аварії на атомній електростанції Fukushima Daiichi. Представлені дані про топологічні і динамічні інваріанти, а саме: кореляційну розмірність, розмірності вкладення та Каплана-Йорка, показники Ляпунова, ентропію Колмогорова та ін. і виявлені елементи хаосу в відповідних часових рядах для беррілія-7. Відносно цезію-137, отримати аналогічний адекватний висновок не вдалося.

Ключові слова: математичне моделювання, нові мікросистемні технології, концентрація радіонуклідів, аналіз часових рядів і наявність хаотичних елементів