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NEW APPROACH AND MICROSYSTEM TECHNOLOGY OF ADVANCED NON-LINEAR ANALYSIS AND MODELLING CHAOTIC ENVIRONMENTAL RADIOACTIVITY DYNAMICS

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Abstract. We firstly present an advanced mathematical formalism and new microsystem technology to analysis, modeling and prediction of the environmental radioactivity dynamics at whole, and chaotic time series of the radionuclide dynamics in particular. It inlcuded a qualitative analysis of dynamical problem of the typical environmental radioactivity dynamics, reconstruction of the phase space with using methods of correlation dimension algorithm and false nearest neighbor points, determination of the dynamic invariants of a chaotic system, including the global Lyapunov exponents, the Kaplan-York dimension d_L , Kolmogorov entropy etc. The forecasting block contains new (in a theory of environmental radioactivity dynamics and environmental protection) methods and algorithms of nonlinear prediction such as methods of predicted trajectories and neural networks modelling. As an illustration, the first data of analysis of the time series for the radon pore activity are presented and indicated on availability of the low- (and indeed middle) dimensional chaos.

Keywords: radionuclides concentration dynamics, new mathematical models, new microsystem technologies, time series analysis and prediction modelling

НОВИЙ ПІДХІД І МІКРОСИСТЕМНА ТЕХНОЛОГІЯ ВДОСКОНАЛЕНОГО НЕЛІНІЙНОГО АНАЛІЗУ І МОДЕЛЮВАННЯ ХАОТИЧНОЇ ДИНАМІКИ КОНЦЕНТРАЦІЙ РАДІОНУКЛИДІВ У НАВКОЛИШНЬОМУ СЕРЕДОВИЩУ

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Анотація. Вперше ми представляємо удосконалений математичний формалізм та нову мікросистемну технологію для аналізу, моделювання та прогнозування динаміки радіоактивності навколишнього середовища в цілому та хаотичних часових рядів, зокрема динаміки радіонуклідів. Наведені якісний та кількісний підхід до проблеми аналізу часової динаміки радіоактивності у навколишньому середовищу, реконструкції фазового простору з використанням методів алгоритму кореляційної розмірності, помилкових сусідніх точок, ефективний підхід до визначення динамічних інваріантів хаотичної системи, в тому числі глобальних показників Ляпунова, розмірності Каплана-Йорка, ентропії Колмогорова тощо. Прогнозний блок містить нові (в теорії динаміки радіоактивності навколишнього середовища та охорону навколишнього середовища) методи та алгоритми нелінійного прогнозування, у т.ч. методи прогнозування траєкторій та моделювання нейронних мереж. Як ілюстрація, представлені перші дані аналізу часових рядів для порової активності радону і вказано на наявність елементів детерміністичного хаосу.

Ключові слова: динаміка концентрацій радіонуклідів, нові математичні моделі, нові мікросистемні технології, аналіз та прогнозування часових рядів

НОВЫЙ ПОДХОД И МИКРОСИСТЕМНАЯ ТЕХНОЛОГИЯ УСОВЕРШЕНСТВОВАННОГО НЕЛИНЕЙНОГО АНАЛИЗА И МОДЕЛИРОВАНИЯ ХАОТИЧЕСКОЙ ДИНАМИКИ КОНЦЕНТРАЦИЙ РАДИОНУКЛИДОВ В ОКРУЖАЮЩЕЙ СРЕДЕ

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Аннотация. Мы впервые представляем усовершенствованный математический формализм и новую микросистемную технологию для анализа, моделирования и прогнозирования динамики радиоактивности окружающей среды в целом и хаотических временных рядов, в частности, динамики радионуклидов. Приведены новый качественный и количественный подход к проблеме анализа временной динамики радиоактивности в окружающей среде, реконструкции фазового пространства с использованием методов алгоритма корреляционной размерности, ложных соседних точек, эффективный подход к определению динамических инвариантов хаотической системы, в том числе глобальных показателей Ляпунова, размерности Каплана-Йорка, энтропии Колмогорова и др. Прогнозный блок содержит новые (в теории динамики радиоактивности окружающей среды и охраны окружающей среды) методы и алгоритмы нелинейного прогнозирования, в т.ч. методы прогнозирования траекторий и моделирование нейронных сетей. В качестве иллюстрации, представлены первые данные анализа временных рядов для поровой активности радона и указано на наличие элементов детерминистического хаоса.

Ключевые слова: динамика концентраций радионуклидов, новые математические модели, новые микросистемные технологии, анализ и прогнозирование временных рядов

1. Introduction

The correct quantitative description of environmental radioactivity dynamics is one of the most actual and important problem of the applied radioecology and radioactive environment protection with (look for example, [1-5]). The key problems of the atmospheric, hydrological and soil radionuclide dynamics includes the research radionuclide transport in the atmospheric, hydrological, soil etc environment respectively, the terrestrial radionuclide dynamics - research radionuclide transfer and migration in the terrestrial environment, marine radionuclide dynamics - research radionuclide transfer in the marine environment and radiological hydrology - research radionuclide transfer from land to fresh water environments due to hydrological phenomena. The main purposes of modeling, measurements and forecasting approach include to evaluate and predict environmental radionuclide transfer and radiation through using computer simulations and other methods, to develop improved technologies to monitor and measure radiation, to develop mechatronics systems and remote control technologies that will enable sampling and other operations in areas where humans cannot approach, to make analysis and archiving of research outputs and research samples produced by IER and other institutes around the world. Problem of studying the dynamics of chaotic dynamical systems arises in many areas of science and technology [16-20]. We are talking about a class of problems of identifying and estimating the parameters of interaction between the sources of complex (chaotic) oscillations of the time series of experimentally observed values. Problem of an analysis and forecasting the impact of anthropogenic pressure on the state of atmosphere in an industrial city and development of the consistent, adequate schemes for modeling the properties of the concentration fields of air pollutions has been in details considered, for example, in Ref.[15].

Let us remind [1-6] that most of the models currently used to assess a state (as well as, the forecast) of an environment pollution are presently by the deterministic models or simplified ones, based on a simple statistical regressions.

The success of these models, however, is limited by their inability to describe the nonlinear characteristics of the pollutant concentration behaviour and lack of understanding of the involved physical and chemical processes. Certainly, these models can't principally used in treating the chaotic nature systems (see [7-21]). Although the use of methods of a chaos theory establishes certain fundamental limitation on the long-term predictions, however, as has been shown in a series of the papers (see, for example, [7-22]), these methods can be successfully applied to a short- or medium-term forecasting. In Ref.[5,15,16] there are presented the successful examples of the quantitatively correct description of the temporary changes in the concentration of nitrogen dioxide (NO2) and sulfur dioxide (SO2) in several industrial cities (Odessa, Triste, Aleppo and cities of the Gdansk region) with discovery of the low-dimensional chaos.

The main purpose of this paper is formally to present an advanced mathematical formalism and new microsystem technology to analysis, modeling and prediction of the environmental radioactivity dynamics at whole, and chaotic time series of the radionuclide dynamics in particular. It inlcuded a qualitative analysis of dynamical problem of the typical environmental radioactivity dynamics, reconstruction of the phase space with using methods of correlation dimension algorithm and false nearest neighbor points, determination of the dynamic invariants of a chaotic system, including the global Lyapunov exponents, the Kaplan-York dimension d_L, Kolmogorov entropy etc. The forecasting block contains new (in a theory of environmental radioactivity dynamics and environmental protection) methods and algorithms of nonlinear prediction such as methods of predicted trajectories and neural networks modelling. As an illustration, the first data of analysis of the time series for the radon pore activity are presented and indicated on availability of the low- (and indeed middle) dimensional chaos. All calculations are performed with using “Geomath”, “Superatom” and “Quantum Chaos” computational codes [15-84].

2. Advanced technique to analysis radionuclide dynamics in environment systems

As usually, we start from the first key task on testing a chaos in the time series of environmental radioactivity dynamics. Firstly, as usually, one should consider scalar measurements of the system dynamical parameter, say, radionuclide concentration:

$$(n)=s(t_0+ n\Delta t) =s(n). \qquad (1)$$

Here t_0 is a start time, Δt is the time step, and n is number of the measurements. The first step of the whole methodology begins with the use of a known test for the presence of chaos in the system noise, which was proposed Gottwald and Melbourne [7]. Its main idea boils down to the choice of some constant c, rather, several values of c, which further define the value (with accounting for Eq.(1)): :

$$p(n) = \sum_{j=1}^{n} F(j)\cos(jc), \qquad (2)$$

and then mean-squared shift:

$$M(n) = \lim_{N\to\infty} \frac{1}{N}\sum_{j=1}^{N}[p(j+n) - p(j)]^2, \qquad (3)$$

and at last a asymptotic growth rate $M(n)$:

$$K = \lim_{n\to\infty} \frac{\log M(n)}{\log n}. \qquad (4)$$

According to Ref. [7], in the case of regular dynamics M (n) is a limited function of n with a unit probability; respectively, in the case of chaotic dynamics M(n)=V(n)+O(1) for some V>0. If the parameter K = 0, a dynamics of the studied system is considered as a regular, in the case of K = 1 one should talk about chaotic dynamics. The fundamental idea of our approach to studying the dynamical radionuclide characteristics in atmospheric and others environment is ideologically reduced to chaos-cybernetic analysis, playback (and reconstruction) phase space of the system and, accordingly, the phase trajectory prediction about the temporal evolution of the dynamical parameters. Further in order to implement the ideology simulation of compact geometric attractor and apply a chaos-cybernetic specified phase trajectories algorithm to restore the phase space of the system one should use the concept of average mutual information, and secondly, the concept of using properties of the relevant linear autocorrelation function. In terms of mathematical modeling the problem reduces to the consideration of unambiguous mapping form:

$$\boldsymbol{F}_{i+1} = \mathbf{G}(F_i), \qquad (5)$$

where $F \in \mathbf{R}^D$ is a vector of environmental state, D is a dimension of the system, i is a discrete time, $\mathbf{G}$ is a D-dimensional mapping.

In order to reconstruction a phase space of the radionuclide environment system one should use ideas by to Packard et al [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,

$$\mathbf{y}(n)=[s(n), s(n + \tau),s(n + 2\tau),..,s(n +(d-1)\tau)], \qquad (6)$$

the required coordinates are provided. In a nonlinear system, $s(n + j\tau)$ are some unknown nonlinear combination of the actual physical variables. The dimension d is the embedding dimension, d_E (see details, for example, in Refs. [7-9,15-18]). The choice of proper time lag is important for the subsequent reconstruction of phase space. There are known two effective algorithms to solve this problem, namely, method of autocorrelation function $C_L(\delta)$ and an average mutual information approach.

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. $d_E > d_A$. The correlation integral analysis is one of the widely used techniques to investigate the signatures of chaos in a time series. The analysis uses the correlation integral, $C(r)$, to distinguish between chaotic and stochastic systems.

According to [13], one should calculate 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

$$d = \lim_{\substack{r \to 0 \\ N \to \infty}} \frac{\log C(r)}{\log r} , \quad (7)$$

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 correlation exponent is defined as the correlation dimension (d_2) of the attractor (see details in refs. [4,23,24]). As alternative method to computing embedding dimension, one could use an algorithm of the false nearest neighbor points by Kennel et al [9] (look [10-15] too).

The main idea is as follows. In dimension d each vector $\mathbf{y}(k)$ has a nearest neighbour $\mathbf{y}^{NN}(k)$ with nearness in the sense of some distance function. The Euclidean distance in dimension d between $\mathbf{y}(k)$ and $\mathbf{y}^{NN}(k)$ is called as $R_d(k)$:

$$R_d^2(k) = [s(k) - s^{NN}(k)]^2 + [s(k+\tau) - s^{NN}(k+\tau)]^2 + \ldots + [s(k+\tau(d-1)) - s^{NN}(k+\tau(d-1))]^2. \quad (8)$$

$R_d(k)$ is presumably small when one has a lot a data, and for a dataset with N measurements, this distance is of order $1/N^{1/d}$. In dimension $d + 1$ this nearest-neighbour distance is changed due to the $(d + 1)$st coordinates $s(k + d\tau)$ and $s^{NN}(k + d\tau)$ to

$$R_{d+1}^2(k) = R_d^2(k) + [s(k+d\tau) - s^{NN}(k+d\tau)]^2 . \quad (9)$$

Further one could define some threshold size RT to decide when neighbours are false. Then if

$$\frac{|s(k+d\tau) - s^{NN}(k+d\tau)|}{R_d(k)} > R_T , \quad (10)$$

the nearest neighbours at time point k are declared false. Kennel et al. [9] showed that for values in the range $10 \le R_T \le 50$ the number of false neighbours identified by this criterion is constant. In practice, the percentage of false nearest neighbours is determined for each dimension d. A value at which the percentage is almost equal to zero can be considered as the embedding dimension.

One of the most important results of a modern chaos theory is that studying the chaotic time series based on the standard linear analysis methods (including standard Fourier analysis) is fundamentally not possible. For this reason, it is not possible to indicate a trajectory of the most probable evolution of dynamic system on the basis of linear analysis methods even when a phase space is reconstructed. For nonlinear systems with a chaotic chaotic dynamics a great interest represents using of invariants which that do not change during evolution of a system. Besides, it is important fulfilling the additional condition of constancy of invariants even under little changes of the initial conditions.

As one of the fractal dimensions (correlation) has been described above, further we consider the Lyapunov exponents. In fact, analysis on the basis of the Lyapunov exponents was carried out to determine a stability of linear and nonlinear systems. In fact a spectrum of the Lyapunov exponents is one of dynamical invariants for non-linear system with chaotic behaviour. As usually, the predictability can be estimated by the Kolmogorov entropy, which is proportional to a sum of positive Lyapunov exponents. The limited predictability of the chaos is quantified by the local and global

Lyapunov exponents, which can be determined from measurements. The Lyapunov 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. For chaotic systems, being both stable and unstable, Lyapunov exponents indicate the complexity of the dynamics. The largest positive value determines some average prediction limit. Since the Lyapunov 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 exponents. The Kolmogorov entropy measures the average rate at which information about the state is lost with time. The estimate of the dimension of the attractor is provided by the Kaplan and Yorke conjecture (see details in Refs. [7-15]):

$$d_L = j + \frac{\sum_{\alpha=1}^{j} \lambda_\alpha}{|\lambda_{j+1}|} , \tag{11}$$

where j is such that $\sum_{\alpha=1}^{j} \lambda_\alpha > 0$ and $\sum_{\alpha=1}^{j+1} \lambda_\alpha < 0$, and the Lyapunov exponents are taken in descending order.

To compute the Lyapunov exponents, one should use a method with linear fitted map, although maps with higher order polynomials can be used too (e.g.[4,13]. Another new approach has been recently developed by Glushkov et al and in using the neural networks technique [17-20]. Summing up above said and results of Refs. [1-3], the whole technique of analysis, processing and forecasting any time series of the radioactive pollutants in different geospheres will be looked as follows (see figure 1).

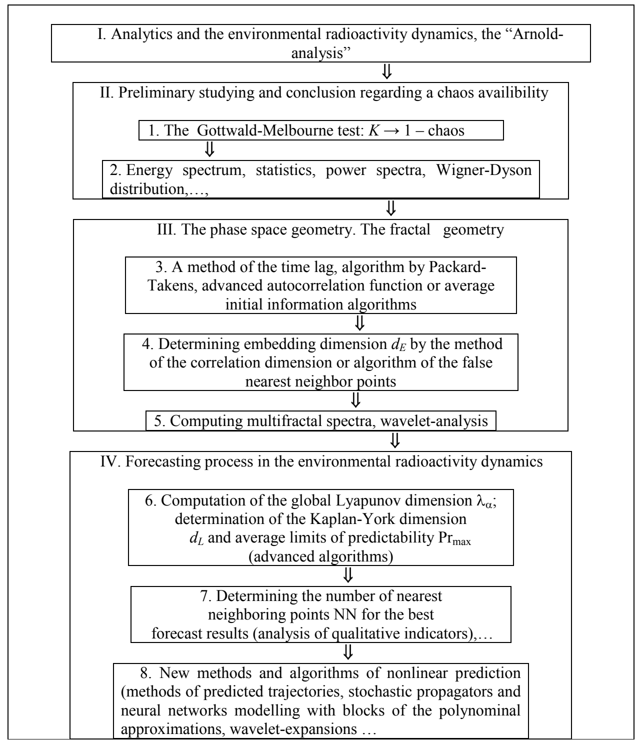

Figure 1. General compact scheme for computation of the characteristics of the environmental radioactivity dynamics time series and a non-linear analysis, modelling and prediction.

The last block indeed includes the methods and algorithms of nonlinear prediction such as methods of predicted trajectories, stochastic propagators and neural networks modelling, renorm-analysis with blocks of the polynomial approximations, wavelet-expansions [4.23,24]. All calculations can be performed with using "Geomath" and "Quantum Chaos" computational codes [4,21-38].

3. Illustrative results and conclusions

As an illustration of the presented approach we have preliminarily studied the temporal dynamics of of the radon pore activity. The data of measurements on the monitoring stations of the Petropavlovsk-Kamchatsky geodynamical poligone [2,3]. It has been earlier shown that the radon density flow can be treated as perspective characteristics in studying geodynamical porcesses in epy Earth's crust. We have carried out a preliminary computing the time series for the radon pore activity (data from [29,30]; Figure 2) using the above presented approach. In Table 1 we list the data of the preliminary computation of the key invariants: time lag (τ) correlation dimension (d_2), embedding dimension (d_E), Kaplan-Yorke dimension (d_L), two Lyapunov exponents, the Kolmogorov entropy for the time series of the radon pore activity (preliminary data). The preliminary data indicate on availability of the low- (and indeed middle) dimensional chaos in the time series of the radon pore activity.

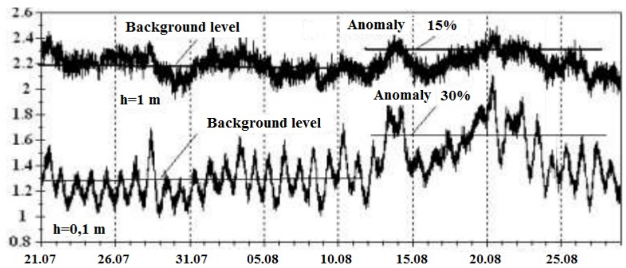

Figure 2 . The temporal dynamics of the radon pore activity at a depth of the sensor arrangement (1.0 m and 0.1 m).

Table 1.

Time lag (τ) correlation dimension (d_2), embedding dimension (d_E), Kaplan-Yorke dimension (d_L), two Lyapunov exponents, the Kolmogorov entropy for the time series of the radon pore activity (preliminary data)

τ	d_2	d_E	λ	λ	d_L	K_{entr}
9	5,6	6	0,018	0,001	4,31	0.019

This is in agreement with the fractal picture data [2,3]. To reconstruct the corresponding chaotic attractor, the time delay and embedding dimension were computed on the basis of the methods of autocorrelation function and average mutual information, correlation dimension, false nearest neighbours. 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.

It is important to underline that the Kaplan-Yorke dimensions, which are also the attractor dimensions, are smaller than the dimensions obtained by the algorithm of false nearest neighbours. Computing K_{entr} and correspondingly an average limit of predictability can show the limit to which the corresponding amplitude of the average intensity can be provided. In any case, one should keep in mind that usually a limited set of data may probably lead to an underestimation of the actual dimension of the system.

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NEW APPROACH AND MICROSYSTEM TECHNOLOGY OF ADVANCED NON-LINEAR ANALYSIS AND MODELLING CHAOTIC ENVIRONMENTAL RADIOACTIVITY DYNAMICS

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Summary

The aim of the work is to develop and present a new approach and correspondingly a new microsystem technology for advanced non-linear analysis, modelling and forecasting the environmental radioactivity dynamics and apply it to studying a temporal dynamics of the atmospheric radionuclides such as radon and others. The new approach includes a qualitative analysis of dynamical problem of the typical environmental radioactivity dynamics, reconstruction of the phase space with using methods of correlation dimension algorithm and false nearest neighbor points. To reconstruct the corresponding chaotic attractor, the time delay and embedding dimension were computed on the basis of the methods of autocorrelation function and average mutual information. The correlation integral algorithm has been used to compute the fractal dimension. The approach includes an effective computing of the dynamic and topological invariants of a chaotic system, including the global Lyapunov's exponents, the Kaplan-York dimension, Kolmogorov entropy and others.

The forecasting block contains new (in a theory of environmental radioactivity dynamics and environmental protection) methods and algorithms of nonlinear prediction such as methods of predicted trajectories and neural networks modelling.

As an illustration, the first data of analysis of the time series for the radon pore activity are presented and indicated on availability of the low- (and indeed middle) dimensional chaos. The data of measurements on the monitoring stations of the Petropavlovsk-Kamchatsky geodynamical poligone have been analysed. The presence of the two (from six) positive the global Lyapunov's exponents suggests the system broadens in the line of two axes and converges along four axes that in the six-dimensional space. It is important to underline that the Kaplan-Yorke dimensions, which are also the attractor dimensions, are smaller than the dimensions obtained by the algorithm of false nearest neighbours. It has been confirmed that the radon density flow can be treated as perspective characteristics in studying geodynamical porcesses in the Earth's crust.

Keywords: radionuclides concentration dynamics, new mathematical models, new microsystem technologies, time series analysis and prediction modelling

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НОВИЙ ПІДХІД І МІКРОСИСТЕМНА ТЕХНОЛОГІЯ ВДОСКОНАЛЕНОГО НЕЛІНІЙНОГО АНАЛІЗУ І МОДЕЛЮВАННЯ ХАОТИЧНОЇ ДИНАМІКИ КОНЦЕНТРАЦІЙ РАДІОНУКЛИДІВ У НАВКОЛИШНЬОМУ СЕРЕДОВИЩУ

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Реферат

Мета роботи полягає у розробці та презентації нового підходу та, відповідно, нової мікросистемної технології для поглибленого, вдосконаленого кількісного дослідження часової та просторової динаміки концентрацій радіоактивних забруднюючих навколишнє середовище (атмосферу, гідросферу тощо) речовин та застосування її до вивчення характеристик часових рядів концентрацій забруднюючих атмосферу радіонуклідів типу радону та інших.

Новий підхід включає якісний та кількісний аналіз проблеми часової динаміки радіоактивності довкілля, реконструкцію фазового простору з використанням методів алгоритму кореляційного інтегралу та методу помилкових сусідніх точок. Для реконструкції відповідного хаотичного атрактору, обчислення затримки часу та розмірності вкладення виконане на основі методів автокореляційної функції та середньої взаємної інформації. Алгоритм кореляційного інтеграла використаний для обчислення кореляційної розмірності. Підхід природньо включає ефективне обчислення динамічних та топологічних інваріантів хаотичної системи, в тому числі глобальних показників Ляпунова, розмірності Каплана-Йорка, ентропії Колмогорова та інших.

Прогнозний блок містить нові (вперше в теорії динаміки радіоактивності навколишнього середовища та охорону довкілля) методи та алгоритми нелінійного прогнозування, такі як методи передбачених траєкторій та моделювання на основі нейронних мереж.

Як ілюстрація, представлені результати аналізу даних по поровій активності радону і вперше вказано на можливу наявність елементів хаосу. Проаналізовано дані вимірювань на станціях спостережень на геодинамічному полігоні Петропавловськ-Камчатського. Наявність двох (з шести) позитивних глобальних показників Ляпунова передбачає, що система розширюється в лінії двох осей і сходиться уздовж чотирьох осей у 6-мірному просторі. Важливо підкреслити, що розмірність Каплана-Йорка, яка є також розмірністю атрактору, менша, ніж розмірність, отримана на основі алгоритму фальшивих найближчих сусідів. Підтверджено, що потік густини радону можна розглядати як перспективну характеристику при вивченні геодинамічних поршень у земній корі.

Ключові слова: динаміка концентрацій радіонуклідів, нові математичні моделі, нові мікросистемні технології, аналіз та прогнозування часових рядів