Розроблено метод оперативного виявлення небезпечної забрудненості атмосфери міст, який ґрунтується на динамічних мірах рекурентності (повторюваності) станів вектора концентрацій забруднень. Новий науковий результат полягає в використанні нетрадиційної модифікації відомих мір рекурентності, що базується на динамічному віконному усередненні поточної рекурентності станів концентрації атмосферних забруднень. Один тип вікна має наростаючу в реальному часі вимірювань ширину. Інший тип використовує рухоме в часі вимірювань вікно фіксованої ширини. Модифіковані міри враховують комплексний характер явних і прихованих дестабілізуючих факторів, що впливають на поточну концентрацію забруднень в пункті контролю. При цьому наголошується, що немає потреби враховувати традиційні метеорологічні чи інші умови при виявленні небезпечних забруднення атмосфери. Розроблений метод дозволяє оперативно виявляти не тільки явні, але і приховані небезпечні забруднення повітряного басейну міст і підвищувати тим самим результативність і своєчасність заходів щодо зниження шкідливого впливу забруднень атмосфери на населення і навколишнє середовище. При експериментальній перевірці методу в якості небезпечного забруднювача розглядався двоокис азоту. Експериментально встановлено, що динаміка концентрації двоокису азоту в атмосфері типової міської конфігурації має фрактальну структуру, що залежить від місць контролю забруднення. При цьому для структур характерно наявність елементів періодичної і екстремальної топології з різкими змінами динаміки. Встановлено, що модифіковані міри характеризують особливості конкретних структур і дозволяє виявляти не тільки явні, але й приховані небезпеки забруднення атмосфери. В даному експерименті динаміка модифікованих мір змінюється від нуля до 0,78 од. Показано, що максимальні значення мір належать інтервалу спостереження, який визначається 12–36 відліками. Встановлено, що в розглянутих пунктах контролю поточні концентрації двоокису азоту перевищували граничні концентрації в 2,75–4,5 разів, а допустимі максимально разові концентрації – в 1,3–2,1 рази. Визначено, що різкі зміни в динаміці модифікованих мір можуть служити індикатором не тільки явної, а й прихованої небезпечної забрудненості атмосфери міст.

Ключові слова: концентрація забруднення повітря, стан атмосфери міста, міра рекурентності, рекурентна діаграма

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DEVELOPMENT OF THE METHOD FOR RAPID DETECTION OF HAZARDOUS ATMOSPHERIC POLLUTION OF CITIES WITH THE HELP OF RECURRENCE MEASURES

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1. Introduction

The general problem of the atmospheric pollution, associated with deterioration of the air quality, today is not less relevant than the arms race and the fight against the global terrorist threat. If the community is capable to cope on its own with the arms race and terrorism, atmospheric pollution poses a threat of total extinction to the humanity. The main danger is that the pollution of the air envelope of the planet is changing the chemical composition of the air. This leads to a significant change in the habitation conditions of humans and living organisms. The problem of air pollution has particular significance for the cities, where a large part of the population of the planet is concentrated. The excess of the maximum admissible concentration of harmful substances in the air by 5 times is observed in 150 cities around the world now. For example, the atmosphere of Ukraine is annually polluted with 6 million tons of harmful substances. Traditionally, the "major" polluters are industrial enterprises. However, an increase of vehicles on the roads leads to the additional increase in harmful emissions into the atmosphere [1]. Over the past few years, the amount of exhaust gases entering the air on the territories of the cities has grown by 50–70 %. Fires also cause the atmospheric pollution [2]. In addition, landscape fires [3] and fires at the facilities of the oil and gas industry [4] typically lead to environmental disasters. Chemical pollution of the atmosphere on a global scale leads to acid rains and greenhouse effect, which greatly restricts the possibilities of using agricultural lands, as well as degrade the water quality [5].

The study of the specific features of the state of atmospheric air of modern cities requires an integrated approach, taking into consideration various aspects. Thus, for example, a comprehensive study of the dynamics of concentrations of pollutants in the atmosphere (DPA) of the cities make it possible to identify some important causal interactions related to the possible emergence of various dangerous (emergency) events. Despite the implemented pollution control techniques, the quality of the atmospheric air in cities is deteriorating with each passing year. Most of the used methods for atmosphere pollution control in urban areas were developed more than 30 years ago, without taking into consideration the characteristics of contemporary processes of the formation of atmospheric pollution in cities, as well as existing metric capacity of control. At the same time, the problem of identifying hazardous pollution of the atmospheric air in modern cities taking into consideration the potential of new technologies remains important and unresolved.

2. Literature review and problem statement

The atmosphere of modern cities is a complex ecosystem that demonstrates dissipation of the structures, nonlinear dynamics and self-organization. In such systems, the traditional methods of analysis may not detect hidden features of DPA, related to the possible occurrence of local emergencies because they are based on linearity principles that are commonly violated under real conditions [6]. The use of such methods under these circumstances will lead to incorrect representation of the actual DPA in urban ecosystems. In this context, the methods of quantitative estimation of non-linear dynamics under conditions of the influence of noises and non-stationarity at short series of observation data become the active area of research [7].

The processes of non-stationary pollution of gas medium, taking into consideration noises are discussed in paper [8]. Experimental studies were performed for the local ecosystem in the form of gas medium in non-pressurized premises, in which ignition of combustible material was performed. The features of pollution of the city atmosphere, which is an open system for harmful emissions, are not considered. In this case, the emphasis is on studying the fluctuation of the parameters of gas medium using the sensors of carbon monoxide, temperature and smoke. Study [9] discusses the application of the method of frequency-temporal analysis for the temporal localization of the pollution of the gas medium. In this case, the obtained results of frequency-temporal analysis relate only to the early ignitions in the premises. The application of this method of frequency-temporal representation for the analysis of atmospheric pollution is difficult. To analyze the features of DPA in cities and identify dangerous conditions, the known nonlinear methods of correlation dimensionality, the Lyapunov method and the entropy method can be applied [10]. However, the specified methods are based on rather long data implementations and cannot be applied directly in the real pace of retrieving data for temporary localization of dangerous events associated with the pollution of the atmospheric air. This means that the known methods have low speed and, in addition, appear quite difficult to implement. For the analysis of urban atmospheric pollution, representing a complex dynamic ecosystem, it is best to use modern non-linear approaches. Such approaches do not depend on the specified statistical distributions of observation data and are applicable for short data samples, masked by natural noises, transient processes and various artifacts. Today, only an analysis based on the recurrence (conditional repeatability) of the states of complex dynamic systems meets the above requirements [11].

It is common to display recurrent behavior of the states of dynamical systems as recurrent plots (RP). Current state of the methods for qualitative and quantitative analysis of RP and their applications is presented in [7]. RP is a group of methods of analysis used for visualization of the trajectories of complex dynamic systems in the phase space of limited dimensionality. The main advantage of RP is that they make it possible to judge about the peculiarities of the processes in complex dynamic systems at the existence and influence of noises, drifting, recurrence and fading of states, extreme events, hidden periodicity, and cyclicity. The methods for quantitative analysis of RP put into line with RP some numerical measures, based on the density of recurrence of points. In this case, it should be noted that so far there is no satisfactory theory of quantitative measures of RP and their application. That is why the application of this approach to analysis of the atmospheric air pollution of cities needs more studies, caused not only the complexity and diversity of the dynamics of states of the polluted atmosphere of urban ecosystems, but also a number of restrictions on their monitoring.

In this regard, the applications to the methods of the theory of dynamic systems to analysis of various ecosystems have been actively developing lately. Thus, for example, paper [12] focuses on the study of RP of carbon monoxide concentration in gas medium in premises at fire. Analysis of geophysical systems from the standpoint of the theory of dynamical systems and fractal sets was studied in [13]. The results of the study of correlation dimensionality of gaseous medium in non-pressurized premises are presented in [14]. These papers were devoted to various particular applications to the methods of the theory of dynamic systems and fractal sets, which differ from the applications, related to analysis of the atmospheric pollution of cities and cannot be directly applied to the solution of the considered problem.

It should be noted that the depth of understanding the processes underlying the dynamics of the states of atmospheric pollutions in modern urban ecosystems is closely connected with the progress in the analysis of complex dynamic systems. At the present time, fractal properties [15], information measures and other types of measures [16] are widely used for studying and quantitative description of the topology of the phase space and dynamical characteristics of different complex systems. Special attention is paid to studying the dynamics of complex systems based on the use of various measures of recurrence of states (RS), displayed by RP [17].

It is noted in these publications that the property of RS is typical of most actual dynamic systems and processes regardless of their nature.

Thus, the RP is one of the modern and effective methods for studying the specific features of the dynamics of complex systems and identification of the patterns according to the data of actual observations. In conjunction with the methods for quantitative analysis of recurrence, RP make it possible to characterize and identify structural features of dynamics of the states of complex systems, which cannot be identified using the classical methods. This means that modern analysis of atmospheric pollution should is based on the study of tRP and PS of the concentration of pollution of the air basin of cities, based on the corresponding measures. However, the measures of RS of dynamic systems, known in the literature, remain complex enough and do not allow studying fully the features of DPA and rapidly identify dangerous events related to the possible occurrence of environmental emergencies in the city. That is why an important and unresolved part of the problem of the analysis of air pollution in modern cities is the development of recurrence measures for rapid identification of the atmospheric air pollution.

3. The aim and objectives of the study

The aim of present research is to develop a method for rapid detection of emergency events related to atmospheric pollution of cities, based on the measures of recurrence of concentrations of atmospheric air pollution.

To achieve the set aim, the following tasks were set:

– to develop the measures of recurrence of states for concentrations of atmospheric air pollution that make it possible to detect rapidly (in real time of observation) hazardous events in the state of the air basin of cities;

– to study experimentally the applicability of the developed recurrence measures for rapid detection of dangerous events associated with the pollution of the air basin of cities, on the example of actual measurements of the concentration of one of the characteristic gas pollutants of urban atmosphere.

4. Development of measures of recurrence of states for concentrations of atmospheric air pollution in cities

By the state of atmospheric air of a city in phase space, we will imply system variables in the form of concentrations of correspondent pollutants, either understood or observed or non-observed but reconstructed by one observed parameter [17]. In the practice of monitoring atmospheric pollution of the cities, there is usually no information about disturbances and the results of measurements of pollution concentrations are the only source information. Normally, measurements are taken at the specified discrete points of time. This information turns out to be enough for the analysis of the dynamics of the state of atmospheric air in the specified region of control on the territory of a city. In the general case, measurement information arriving at discrete moment of time and control, can be represented by a m-dimensional data vector

$$\bar{z}_i = \bar{d}_i + \bar{\Delta}_i, \quad i = 0, 1, 2, ..., N_S - 1, \tag{1}$$

where $\bar{d}_i$ is the vector of true pollution concentration, characterizing the current state of pollution of urban atmosphere in the control region; $\bar{\Delta}_i$ is the vector of current disturbances of pollution concentration; N_s is the maximum number of results of measurement of the vector of pollution concentrations (amount of data sample). The dimensions of m vector of data (1) can be arbitrary, but finite, and are determined either by the number of controllable pollutants of the atmospheric air, or by the dimensions of the restored phase vector for one controllable pollutant.

The application of the RP method [6] to the data (1) is reduced to the calculation of the magnitude

$$R_{i,j}^{m,\varepsilon} = \Theta\left(\varepsilon - \left\|\bar{z}_i - \bar{z}_j\right\|\right)\infty, \quad \bar{z}_i \in \Omega^m, \quad i, j = 1, 2, ..., N_S, \tag{2}$$

where $\Theta(*)$ is the Heaviside function; ε is the dimensions of neighborhood for vector $\bar{z}_i$ of pollution concentration at moment of time i, and $\|*\|$ is the sign of determining the norm of the corresponding vector. This means that the RP method allows mapping trajectories in m-dimensional phase space of pollution (1) on the two-dimensional binary matrix of dimensions $N_s \times N_S$. In this case, the element of the matrix, equal to unity, at some moments of time i and j will correspond to RS of concentrations of atmospheric pollution. In this case, coordinate axes of RP will be determined by the corresponding axes of discreet time of data registration. The study of the dynamics of the states of different complex systems based on representation (2) became possible due to the occurrence of different methods of quantitative analysis of RS [7]. These methods are based on appropriate measures for measuring complexities in RP, displaying special states of the studied dynamical systems. However, most of the known measures do not make it possible to use them for analysis of DPA. In some cases, the known measures appear insufficiently efficient and insensitive to the dynamics of the vector of pollution concentrations for the characterization on their basis of emergence of hazardous events. This greatly limits their possibilities for analysis of DPA with a view to identifying the hazard, caused by atmospheric pollution in the control zone.

The most known and widely used measure is the RS, determined for representation (2), from magnitude

$$R_0(\varepsilon) = \frac{1}{N_S^2} \sum_{i \neq j}^{N_S} R_{i,j}^{m,\varepsilon}. \tag{3}$$

Measure of RS (3) makes it possible to calculate the density of RS of concentrations of atmospheric pollution without taking into consideration the lines of identity in (2). Within the limit $N_s \to \infty$, measure (3) will determine the probability of RS concentrations of air pollution in the control zone of a city. The main limitation of this measure is that it has cumulative properties, and in this context does not make it possible to use it for analysis of the dynamics of atmospheric pollution of cities with a view to quick identifying its dangerous states. That is why instead of measures (3) in the light of representation (2), it is proposed to use the measure that is determined by the functional, depending on the magnitude of neighborhood ε and current moment of time i of measurement, i. e.

$$M_1(\varepsilon, i) = \frac{1}{i+1} \sum_{k=0}^{i} R^{m,\varepsilon}{}_{i,k}, \quad i = 1, 2, ..., N_S. \tag{4}$$

Modification of measure (4), in contrast to measure (3), makes it possible to analyze the density of RS of pollution concentrations for each current moment of time i, given the dimensions of neighborhood ε. That is why measure (4) can be used to analyze RS of the vector of concentrations for a specified number of pollutants in the atmosphere in a controlled urban area in real time. In doing so, it should be noted that the measure (4) with increasing time i of observation of data decreases sensitivity to DPA because of manifestations of its cumulative properties. In addition, measure (4) at the initial stage of data recording has insufficient accuracy. That is why measure (4) has limited capabilities when analyzing DPA and temporary localization of its hazardous states. With a view to eliminating these restrictions, it is proposed to modify measure (4) in the form of the window measure with sliding window of size a along the axis of the time of observation. For arbitrary moment i

of data observation time, the specified window measure is determined from magnitude

$$M_2(i,a,\varepsilon) = if\left(i < a, \frac{1}{i+1}\sum_{k=0}^{i} R^{m,\varepsilon}{}_{i,k}, \frac{1}{a}\sum_{k=0}^{a-1} R^{m,\varepsilon}{}_{i,i-k} \right). \qquad (5)$$

Measure (5) makes it possible to analyze the dynamics of density of RS of the concentration vector for an arbitrary number of pollutants in the atmosphere in a controlled urban area of atmospheric pollution concentrations for the current moment of time i, given the size of the neighborhood ε at the assigned size a of a moving window. Following (5), the measure is the parametric functional of two parameters ε and a, the magnitude of which is selected based on the required quality of analysis of DPA for the purpose of the best detection of its dangerous states. Unlike the measure (4), the proposed measure (5) enables the analysis of the features of dynamics of RS for the vector of concentration of the specified number of pollutants in the atmosphere in the controlled urban area in real time. Measure (5) is averaged in the window of size a at the specified magnitude of neighborhood ε. This means that with the help of the measure (5), it is possible to analyze the dynamics of density of RS vector of concentrations for an arbitrary number of air pollutants in real time, and based on it to identify hazardous events. That is why this measure can be used as a basis for the method of effective detection of hazards, associated with the atmospheric pollution of cities. In this case, the dynamic of density of RS of the vector of pollution concentrations numerically characterizes the degree of repeatability of different states of the vector of concentrations of the studied air pollution for the current moment of time in the specified urban areas.

In this regard, the specified measure makes it possible to localize in time the dynamic states that are important in practice and associated with hazardous events, characterized, for example, by the laminarity of the dynamics of concentrations of atmospheric pollution (absence of turbulence and pollution dissipation). Laminarity of the dynamics means that the concentration of pollution of atmospheric air in a controlled urban area does not change or changes slightly. With the use of this measure, it is also possible to identify the important transitions from the chaotic states of the vector of pollution concentrations in the atmospheric air to random states and vice versa. In this case, the transition from random states to chaotic states is accompanied by increasing concentrations of pollution in the atmospheric air in a controlled urban area. The reverse transition from chaotic states to random states indicates the loss of the dynamic stability of the vector of pollution concentrations in the atmospheric air. In addition, it should be noted that the proposed measures of RS of the vector of concentrations of atmospheric pollution remain reasonable at any dimensionality of vector $\overline{z}_i$. In this case, in a particular case of consideration of one type of pollution, vector $\overline{z}_i$ will degenerate into a scalar.

5. Procedure of experimental research into applicability of the developed recurrence measures for atmospheric pollution concentrations

Verification of applicability of the developed measures of RS of concentrations of urban air pollution was performed by experimental measurements at three route posts for the typical urban configuration with the existence of pollution from stationary and mobile sources. The city configuration, for which the average level of atmospheric pollution index was 6.8 units, was considered as typical. Such atmospheric pollution index is typical of most cities in the world.

Measurement of gas pollution concentrations of the atmosphere was performed using the portable gas analyzer DRÄGER PAC 7000 (Germany). The gas analyzer is constructed based of modern sensors Dräger XXS. It provides a short response time (up to 20 sec) and reliability of measurement results. The device is able to measure concentrations of H_2S, O_2, CO, CO_2, Cl_2, HCN, NH_3, NO_2, NO, PH_3, SO_2 and other gases. Concentrations of gas pollution were measured in accordance with the requirements of GOST 17.2.3.01-86 "Nature conservation. Atmosphere. Rules for monitoring the air quality of residential settlements".

The studies took into consideration the modern strategy of many countries, associated with the tendency of control of a limited set of key air pollutants, which often are indicators for a wider range of pollutants included in the composition of emissions. Such major pollutants include suspended substances (PM10 and PM2.5), nitrogen oxides (NO_x), sulfur oxides SO_2 and ozone (O_3). Following the modern strategy, control of suspended substances is usually associated with mandatory monitoring of concentrations of gaseous pollutants such as NO, NO_2, SO_2, CO. In addition, it is noted that monitoring of concentrations of NO, NO_2 и NMVOC (non-methane volatile organic compounds). Taking into consideration a particular risk to humans and the environment, NO_2 was considered as the major pollutant of the atmosphere of cities during the experimental verification of the proposed measures.

The experiment was conducted over a month (31 days). NO_2 concentrations were measured at three points (A, B and C) of the typical urban configuration. The coordinates of the points of measurement were positions using GPS (A: 49.446361,32.053106; B: 49.407947,32.093376; C: 49.421643, 32.021621). The concentrations of nitrogen dioxide were measured at three points in mg/м^3. Measurements of the concentration of nitrogen dioxide at points A, B and C were performed 4 times a day (01:00, 07:00, 13:00, 19:00). In the experiment, real time of measurement 01.00 of the first day of the experiment corresponded to conditional discrete point of time i=0. At the same time, time 1.00 of the 31st day of the experiment corresponded to conditional moment of time i=120. The basic time interval was selected for experimental verification of the possibility of using the proposed measures of RS of nitrogen dioxide concentrations for the efficient (in the pace of data observation) detection of dangerous events associated with air pollution in the zones of the specified control points. The specified interval was determined from 01:00 of the 4th day (i=12) to 01:00 of the 13th day (i=48) of the experiment.

6. Results of experimental verification of the proposed measures of recurrence of states for rapid detection of hazardous pollution of the atmosphere

The source data for the experimental verification were the results of measurements with the help of device RÄGER PAC 7000 of the values of nitrogen dioxide concentration at control points A, B and C within 31 days, as well as MAC= =0.04 in mg/m^3. Measurements were taken 4 times a day. The specified measurements were not performed for some days. It was due to the organizational activities. The obtained results of measurements in control points are shown in Fig. 1. In order to retain the uniformity of the scale of counts (time scale of measurements), the values of nitrogen dioxide concentrations at control points, which were not taken during certain days, were accepted as zero values (below the background level). Subsequently, it made it possible to exclude them from consideration.

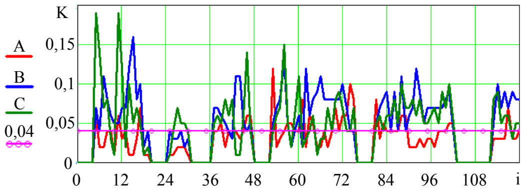

Fig. 1. Values of measured concentration (mg/m^3) of NO_2 in atmospheric air of the typical urban configuration at controls points A, B, C

Analysis of measurements of NO_2 concentration in the atmospheric air of the typical urban configuration at the specified control points (Fig. 1) shows that the possible hidden danger of pollution can occur between 24 and 30 counts. That is why this interval will be considered below as a test level to validate the proposed method.

To illustrate this, Fig. 2 shows recurrent plots (2) in the form of clusters of black and white dots for NO_2 concentrations in the atmospheric air (Fig. 1), measured in the course of the experiment at the assigned size of neighborhood ε=0.01.

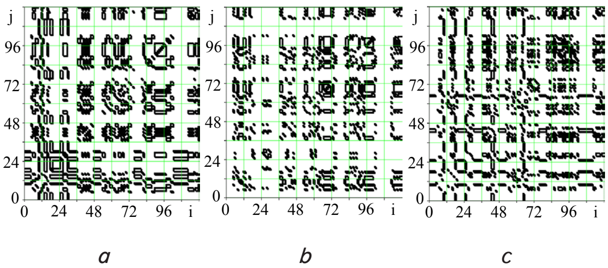

Fig. 2. Recurrent plots (2) for NO_2 concentrations in the atmospheric air of the typical urban configuration at control points: *a* — A; *b* — B; *c* — C

Dynamics of the proposed measure M_1 of RS for nitrogen dioxide concentrations in the atmospheric air at three control points is shown in Fig. 3. In this case, the continuous curves correspond to the size of neighborhood ε=0.01 and dotted – ε=0.001.

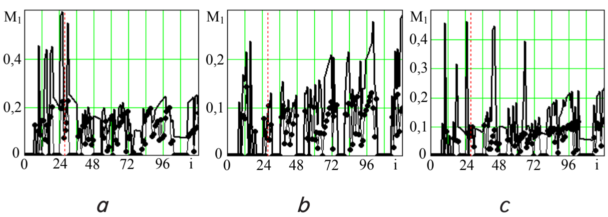

Fig. 3. Dynamics of measure M_1 of RS for NO_2 concentration in the atmospheric air at control places: *a* — A; *b* — B; *c* — C

Similar dependences for measure M_2 of RS for nitrogen dioxide concentration in the atmospheric air at three control points when using a sliding averaging window of the size of 12 counts are shown in Fig. 4.

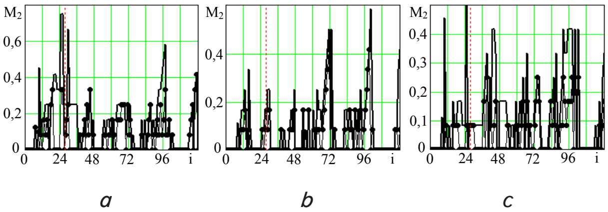

Fig. 4. Dynamics of measure M_2 of RS for NO_2 concentration in the atmospheric air at control places: *a* — A; *b* — B; *c* — C

Fig. 5 shows the histograms of experimentally measured concentrations of nitrogen dioxide in the atmospheric air. Here, K designates concentrations of nitrogen dioxide in mg/m^3, and N – the number of corresponding values of concentration at control points. MAC and maximum single concentration of 0.085 mg/m^3 for measured pollution NO_2 were plotted on the histograms.

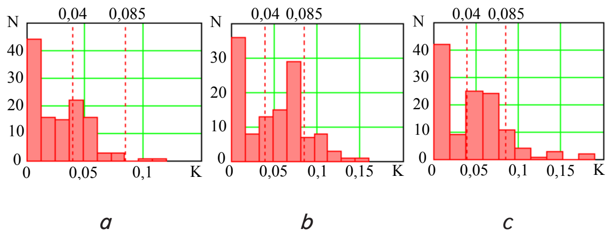

Fig. 5. Histograms of NO_2 concentrations in the atmospheric air for control points: *a* — A; *b* — B; *c* — C

For comparison, Fig. 6 shows the dynamics of the proposed measures M_1 and M_2 of RS for NO_2 concentration at the size of neighborhood ε=0.01, as well as the dynamics of the measured concentration of NO_2 in the atmospheric air K for the assigned control points and MAC for NO_2 in mg/m^3.

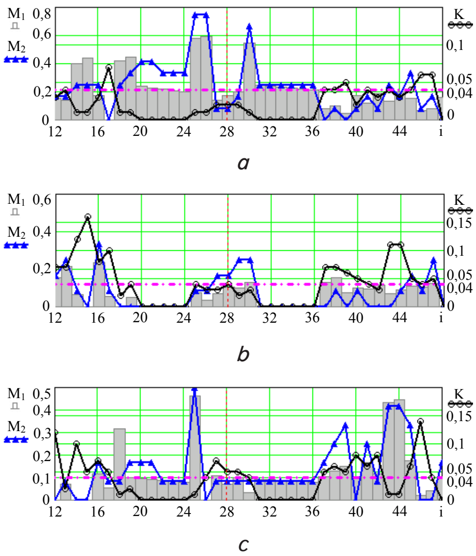

Fig. 6. Comparative dynamics of measures M_1 and M_2 of RS for NO_2 concentration in the atmospheric air, as well as dynamics of the measured NO_2 concentration and magnitude of MAC for assigned control points: *a* — A; *b* — B; *c* — C

The conditional count by number i=28, corresponding to real time 01:00 of the 8th day of the experiment is additionally marked in Fig. 6.

7. Discussion of results of studying the proposed recurrence measures for the concentration of atmospheric pollution in cities

Analysis of RP in Fig. 2 showed that the dynamics of the state of nitrogen dioxide concentration in the atmospheric air of the typical urban configuration in general is not random, but rather chaotic. This means that the actual dynamics of NO_2 concentration in the atmospheric air has a fractal structure. In addition, the fractal structure of dynamics of NO_2 concentration in the course of the experiment turns out to be different for the considered route-posts and is characterized by different topology and texture of RS. It is, first and foremost, characterized by the elements of the periodic and extreme topologies with abrupt changes in the dynamics of NO_2 concentrations in the air. RP simplifies the detection of extreme and rare events associated with atmospheric pollution. Analysis of RP enables identification of small-scale structures, composed of simple points, diagonal, horizontal and vertical lines (Fig. 2, *a*–*c*). Combinations of vertical and horizontal lines form rectangular clusters of recurrent points. Vertical and horizontal lines determined by (2) in Fig. 2 separate the time intervals, in which the nitrogen dioxide concentration in the atmospheric air does not change or changes slightly (atmospheric pollution in the form of NO_2 concentration is "frozen" in these periods). This is a typical behavior under laminar conditions. In such states, adjacent air layers do not mix and, consequently, the dispersion of the pollutant in the atmosphere slows down or is absent, resulting in retained or increased pollution. The specified states are the indicators of possible hidden hazards of atmospheric pollution.

In this case, the existence of irregular black and white RP clusters (Fig. 2) shows irregularity of DPA by nitrogen dioxide, which may be caused by the existence of correlations. Such condition, to great extent, is characteristic of control point A in the interval, determined by 12–36 counts.

Analysis of dynamics of measure M_1 of RS for the nitrogen dioxide concentration in the atmospheric air at the specified control points (Fig. 3) reveals the maximum magnitude of this measure in the interval of 12–36 counts for control points A and C, equal to 0.6 and 0.48, respectively. The similar situation is also observed for measure M_2 (Fig. 4). In this case, the maximum magnitude of the measure of RS is 0.78 and 05 for control points A and C, respectively. In addition, at control point B, the value of measure of RS for the concentration of pollution NO_2 in the specified interval does not exceed 0.3. A rather high value of measure of RS for the concentration of pollution of the atmosphere with NO_2 at control points A and C indicates the existence of a considerable correlation of the pollution concentrations. A small value of the measure of RS for NO_2 concentration at control point B means smaller correlations of pollution concentrations. An analysis of the histograms shown in Fig. 5 revealed that at all control points, current NO_2 concentrations were exceeded the MAC by from 2.75 to 4.5 times. In this case, maximum admissible one-time concentrations were exceeded by 1.3–2.1 times. It was found in the experiment that the distribution of pollution concentration in the studied interval turns out to be non-Gaussian (Fig. 5). In this context, the use of mean values of pollution concentration per month for comparison with the MAC is not quite correct.

Comparative dynamics of the proposed measures M_1, M_2 of RS for the measured NO_2 concentrations in the atmospheric air (Fig. 6) at control points shows that before the 28th count, there was a high value (0.6; 0.78 and 0.48; 0.5) for measures of the RS for control points A and C, respectively, which then sharply decreased. In this case, the specified measures for control point C accepted zero values at the moment of the 26th count. For control point A, there was a value other than zero (close to 0.1) of the specified measures, corresponding to the 28th count. Such dynamics of measures of the RS for the pollution concentration is explained by the sharp transition from laminar state of pollution with NO_2 (high value of RS) to the state associated with the loss of this state and transition to the unstable state (low value of RS). Such a transition of states can pose a certain danger of atmospheric pollution. In this case, it should be noted that in terms of temporal localization of hazardous events by dramatic reduction of the proposed measures of the RS, it is better to use measure M_2, which has great potential for detecting the specified hazards of the atmospheric pollution.

8. Conclusions

1. The method for rapid detection of hazardous pollution of urban atmosphere with the use of the computation of the measures of recurrence (repeatability) of the states for the vector of pollution concentrations was developed. The new research result is a modification of the known recurrence measures aimed at improving their efficiency for the purpose of the possible in real pace of measurement. A distinctive feature of the modified measures is averaging current recurrence of the states of atmospheric pollution concentration in dynamic windows. In this case, the dynamic windows have the width that is increasing in real time of measurements and the fixed width of the sliding window. The proposed measures remain reasonable, both in the case of one-time pollution and of the group of analyzed pollutants. An important feature of these measures is the integrated consideration of explicit and hidden destabilizing factors influencing the current pollution concentrations at the control point. In this case, it does not require the account of traditional meteorological and other conditions during detection of hazardous atmospheric pollution of cities. The developed method makes it possible to identify rapidly not only explicit, but also hidden hazardous pollution of the air basin of cities and thus improve efficiency and timeliness of activities aimed at the prevention of atmospheric pollution in order to protect the population and the environment.

2. It was established experimentally that the dynamics of the nitrogen dioxide concentration in the atmospheric air for the typical urban configuration during the studied month has a fractal structure. In this case, the fractal structure turns out to be different for various control points and is characterized by the existence of the elements of periodic and extreme topologies with abrupt changes in dynamics. The specified features make it possible to identify hidden hazards of the atmospheric pollution. The dynamics of the proposed measures of RS in the observation interval varies from zero to 0.78. It was shown that the maximum value of the measures of RS correspond to the observation

interval, determined by 12–36 counts at control points A and C. It was established that in the studied control points, the current values of NO_2 concentrations exceeded the MAC from 2.75 up to 4.5 times, and maximum admissible one-time concentrations – by 1.3–2.1 times. In this case, the distribution of pollution concentrations in the studied interval turns out to be non-Gaussian. It is noted that the use of mean values of pollution concentration per month for their comparison with the MAC is not quite correct. It was found that a dramatic change in the dynamics of the measures of the RS from their high values to low values and in the reverse order can be used as an indicator of a hidden danger of atmospheric air pollution of cities. It is noted that from the point of view of the temporary localization of the hazard, it is better to use measure M_2, having large localization capabilities.

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