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DEVELOPMENT OF A METHOD FOR PREDICTING THE RECURRENCE OF STATES OF ATMOSPHERIC AIR POLLUTION CONCENTRATION IN INDUSTRIAL CITIES

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Розроблено метод прогнозування рекурентності станів забруднення атмосферного повітря промислових міст на основі використання модифікованої віконної міри. Новий науковий результат полягає в тому, що небезпечні стани атмосферних забруднень міст пропонується виявляти і прогнозувати не на основі прогнозу концентрації самих забруднень, а на прогнозі рекурентності стану концентрації забруднень атмосферного повітря. Запропонований метод прогнозу дозволяє оперативно прогнозувати не тільки явні, але і приховані небезпечні стани забруднення повітряного басейну промислових міст. Це забезпечує в цілому підвищення ефективності проведених заходів щодо попередження небезпечних забруднень атмосфери і навколишнього середовища. Результати експериментальної перевірки свідчать про працездатність запропонованого методу. Встановлено, що в тестовому інтервалі спостереження (між 12–36 моментом часу) виявлені різкі характерні зміни прогнозованої міри рекурентності стану. Відзначається, що такі зміни є провісниками прихованих подій, пов'язаних з небезпечними забрудненнями атмосферного повітря промислових міст. Експериментально встановлено, що більш точний прогноз забезпечується для горизонту прогнозу d=1 (6 годин). Показано, що в даному випадку з метою забезпечення надійності прогнозування ламінарних станів в забрудненій атмосфері параметр згладжування повинен вибиратися не менше 0,8. Відзначається, що для прогнозування небезпечних станів забруднень атмосфери по динаміці прогнозу міри рекурентності стану не потрібно інформації про метеорологічні умови в момент прогнозу і в майбутньому. Це є головною відмітною ознакою і перевагою запропонованого методу прогнозу. Даний метод прогнозу виявляється інваріантним до міської конфігурації, типам стаціонарних і мобільних джерел забруднень, а також метеорологічних умов

Ключові слова: забруднення повітря, рекурентність стану, віконна міра, прогноз рекурентності, приховані небезпечні стану

1. Introduction

Atmospheric air is a natural resource whose environmental condition exerts a significant impact on the health of people and quality of the environment. However, as a result of anthropogenic activities, the environmental condition of air demonstrates a tendency towards constant deterioration. At present, 150 cities around the world are reported to have a considerable excess of maximally permissible concentrations (MPC) of polluting substances. Pollution of the atmosphere, unlike other environmental contamination, has no frontiers and is hard to localize. The principal anthropogenic source of atmospheric pollution is large industrial conglomerates, including motor vehicles [1]. Fires are also sources of atmospheric pollution [2]. Moreover, landscape fires [3] and fires at the facilities of the oil and gas industry [4] often lead to environmental disasters. Chemical air pollution on a global scale leads to the greenhouse effect, acid rains [5], and contamination of aquifers [6]. Important directions for reducing harmful air pollution on humans and the environment include preventive interventions aimed at ruling out situations when MPC is exceeded, as well as excluding people staying in such zones. In this regard, it is a particularly pressing issue to predict hazardous states related to urban air pollution.

2. Literature review and problem statement

The atmosphere of modern cities is a complex dynamic system, demonstrating the dissipative structures, nonlinear dynamics of states, as well as elements of self-organization. Application of traditional methods of analysis to such systems fails to detect the hidden dynamics of dangerous concentrations of pollutants in the atmosphere (DHA) because they are based on principles of linearity and are of little use for the case of real systems [7]. At the same time, most known methods and techniques for the analysis of atmospheric air pollution in cities were developed more than 30 years ago. They do not take into consideration the peculiarities and complexity of modern formation of urban air pollution, as well as new options for control, as well as methods of analysis and forecasting. In this context, an active field of research involves the new methods for quantitative nonlinear dynamics of real systems [8].

Analysis in [9] revealed that the levels of atmospheric air pollution at urban areas depend on many different factors. In this case, as noted in [10], even similar meteorological factors differently affect the state of the atmospheric pollution in cities. This is explained by that urban pollution sources have different height and the gas mixtures, which they emit, differ in temperature, composition, and other parameters. This leads to uneven conditions of transformation of contaminants in the air during their propagation. Studying the formation processes of pollution in the atmosphere shows that their level depends on two integrated factors: meteorological and anthropogenic. Meteorological factors include direction of impurities transport, the speed of their transport, thermal state of air masses, cyclonic activity, and atmospheric resistance. Anthropogenic factors are the sources of contaminants, pollutants, pollutant emission intensity, as well as the architectural features of territories.

The process of polluting air at premises due to burning materials was studied in work [11]. Results from the experimental study into the correlations of gas pollution concentration at premises in case of fire are reported in [12]. These works limit the study of processes related to air pollution and the correlation of concentration of gas contamination in a fire to local premises. The recurrence of states of contaminant concentration was not considered in this case. In order to predict ignition and prevent dangerous pollution of gas environment, paper [13] proposed the use of specialized sensors that can be self-adjusted based on the concentration of contaminants. Research into the dynamic properties and the likelihood of early detection of gas environment contamination by such sensors is reported in [14]. In this case, papers [13, 14] are confined to considering the gas environment contamination from fires in closed systems. Contamination of gas environment in open systems was not examined in these works. No features in the process of urban atmospheric pollution, representing an open system for harmful emissions, were investigated. No prediction methods for the states of local gas environment contamination in direct statement were considered. In this case, to predict the levels of concentrations of air pollutants, it is necessary to additionally forecast meteorological conditions and other factors that affect the scattering properties of contaminants. In this case, known methods of forecasting are usually based on multivariate statistical analysis, they are not universal and are suitable only for specific territories and meteorological conditions in cities.

Paper [15] considered the use of the method of frequency-temporal analysis for the temporal localization of hazardous pollution of gas environment. In this case, the results are limited to considering only the local premises. In this regard, the implementation of this method for urban air pollution is difficult. To analyze patterns in DHA in cities as complex dynamic systems, one can apply nonlinear methods, for example, correlation dimensionality, by Lyapunov, and entropy [16]. However, known nonlinear methods are based on rather long samples of observational data and therefore cannot be directly applied to rapidly identify and predict dangerous conditions related to atmospheric pollution. In this case, it is best, in order to analyze and predict the states of the polluted urban atmosphere, to use modern non-linear approaches and methods. Such approaches and methods have a series of important practical advantages. They do not depend on the *a priori* statistical distributions of observational data, they are applicable for short samples masked by natural noises, transients, and artifacts. One of them is the approach based on recurrence (conditional repeatability) of states of complex dynamic systems [17]. This approach, however, as well as appropriate methods, are limited only to consideration of the recurrence of states themselves in complex dynamic systems. Prediction of recurrence of states of complex dynamic systems and thus predicting the properties of such systems is not considered. In this regard, it is important to devise methods for predicting the recurrence of states and, on their basis, for predicting the states of complex dynamic systems in future.

Typically, the recurrence of states of complex dynamic systems is represented in the form of recurrent plots (charts) (RP) [8]. RPs combine a group of methods for visualizing the trajectories of complex dynamic systems in a 2-dimensional phase space. The main advantage of RP is the ability to analyze patterns in processes within complex dynamic systems under the influence of many disturbing factors, including extreme events. In this case, the methods of quantitative analysis usually fit RP to certain numerical measures, based on the density of the recurrence of states. However, there is still no satisfactory theory of quantitative measures of RP and their application. Specifically, there is no theory of forecasting methods for the recurrence of states within complex dynamic systems.

Therefore, the application of the specified approach to the analysis of atmospheric air pollution in cities requires additional research, predetermined not only by the complexity of dynamics in the states of contaminated atmosphere, diversity of urban configurations, meteorological conditions, but also by limitations in the monitoring process. To be specially considered is the development of methods for predicting the recurrence of states of air pollution concentration in urban configurations.

One should note the recent progress in applying the methods from the theory of dynamic systems to analysis of different ecosystems. For example, a study into the concentration of carbon monoxide RP in air environment during a fire in the premises is reported in [18]. An analysis of geophysical systems, based on the theory of dynamical systems, is presented in [19]. Studying the correlation dimensionality of the process of air environment pollution was addressed in [20]. In this case, works [18–20] deal with specific application of the theory of dynamical systems and fractal sets. These applications differ substantially from the applications that are associated with atmospheric pollution of cities. For this reason, they cannot be directly used for the air pollution applications.

In this case, depth of understanding the processes underlying the dynamics of states of air pollution is directly linked to the progress in analysis of complex nonlinear dynamic systems. Recently, the examination and quantification of the topology of complex dynamic systems have commonly employed fractal methods [21], informational and other types of measures [22]. In this case, emphasis is on the use of various measures of recurrence of states (RS) represented by RP [23]. It is noted that the property of RS is typical for most real dynamical systems and processes regardless of their nature.

Thus, RPs in a combination with methods for quantitative analysis of RS make it possible to characterize and identify structural features in the dynamics of states of complex systems, which cannot be identified by using classical methods. This means that analysis of the current and projected state of the atmospheric pollution in modern cities must be based on examining RP and appropriate RS measures.

It is therefore an important part of the unresolved task on predicting dangerous states of urban air pollution is to develop a method for predicting the recurrence od states of air pollution concentrations in industrial cities.

3. The aim and objectives of the study

The aim of this work is to devise a method for predicting the recurrence of states for the concentrations of atmospheric pollution in industrial cities in order to make adequate managerial decisions aimed at preventing and reducing the level of hazardous contamination.

To accomplish the aim, the following tasks have been set:

– to substantiate the choice of a measure for the recurrence of states of the concentration of atmospheric pollutants, and suggest a method to forecast it in real-time;

– to conduct experimental measurement of the concentration of one of the hazardous air pollutants in the form of nitrogen dioxide in the city of Cherkasy (Ukraine), based on which it would be possible to validate efficiency of the proposed method of forecasting in real time.

4. Selection of a measure for the recurrence of states of the concentration of atmospheric pollutants and a method to forecast it in real time

Given the restrictions of known methods for predicting the concentrations of atmospheric pollutants associated with the need for additional forecast of meteorological conditions and other factors for specific territories, it is proposed to use the forecast of RS concentrations of air pollutants using appropriate measures. In this case, it is required that pollution forecast should be performed in real time. The main advantage of forecasting RS of pollution concentration compared to predicting the levels of concentrations themselves is that the RS forecast makes it possible to localize over time the practically important dynamic state of atmosphere pollution, characterized by, for example, the absence of turbulence and dispersion of pollutants in the atmosphere (the laminar features of DHA). These states are associated with dangerous accumulation of contaminants in the atmosphere, which lead to the increased concentration of pollutants in the control zone. By using RS measures, one can also identify transitions from chaotic states of a contamination concentration vector to random states and vice versa. The transition from random states to chaotic states is usually accompanied by increasing concentrations of contaminants in ambient air. In this case, the reverse transition corresponds to the loss of dynamic stability of the vector of current concentrations of contaminants. Paper [24] considers various modified RS measures for the concentrations of air pollutants in urban configurations. To solve the task on prediction, it is proposed to apply one of the modified measures in the form of a window measure of RS with a sliding window of fixed size a along the main diagonal of RP. For the case of an arbitrary fixed moment i during monitoring the specified modified measure of RS is recorded in the form [24]

$$M_2(i,a,\varepsilon)=if\left(i<a,\frac{1}{i+1}\sum_{k=0}^{i}R_{i,k}^{m,\varepsilon},\frac{1}{a}\sum_{k=0}^{a-1}R_{i,i-k}^{m,\varepsilon}\right), \tag{1}$$

where $R_{i,k}^{m,\varepsilon}$ is RP [7] defined for moments $i,j=0, 1, 2,..., N_s-1$; N_s is the maximum number of measurements of contaminant concentrations (sample size); m is the size of the measured vector of contaminant concentrations, defined by the number of controlled pollutants in ambient air; ε is the specified size in the neighborhood of a point for vectors of contaminant concentrations in m-dimensional phase space.

An important advantage of measure (1) is its invariance to the quantity of measured (controlled) air pollutants. This means that measure (1) makes it possible to analyze the density of RS of the concentration vector for an arbitrary number of controlled pollutants in the atmosphere depending on the current measurement time point i, the neighborhood size of ε and a in a moving window. In essence, the measure (1) is the current assessment of the probability of RS of vector of atmospheric contaminant concentrations at window width a and the specified magnitude for neighborhood ε.

In this regard, consider solving the examined problem on forecasting RS of concentration of pollution of the atmosphere in real time of monitoring using the measure (1). Let the original time series be defined by measure $M_2(i, a, \varepsilon)$. Denote via L_i, $i=0, 1, 2,..., N_S-1$ some smoothed (averaged) series, derived from $M_2(i, a, \varepsilon)$. A series L_i is commonly referred to as the level of the original series. It has an important role in the development of various methods for forecasting the values for the examined series $M_2(i, a, \varepsilon)$ for moments $d>i$, where d is the time of forward forecast (the forecast horizon). Let us use one of the common techniques for constructing a series L_i, which is based on the exponential smoothing procedure [25], which is defined from

$$L_i=\alpha M_2(i,a,\varepsilon)+(1-\alpha)L_{i-1}, \tag{2}$$

where $\alpha\epsilon(0, 1)$ is the smoothing parameter. Following [26], expression (2) can be represented as follows

$$L_i=\alpha\sum_{r=1}^{i-1}(1-\alpha)^r M_2(i-r,a,\varepsilon)+(1-\alpha)^i L_0, \tag{3}$$

where L_0 is the quantity required for initial use (3). We assume $L_0=\alpha M_2(0, a, \varepsilon)$. In this case, the simplest method for forecasting RS of air pollution concentrations in industrial cities in controlled areas, following (1) to (3), will be determined from ratio

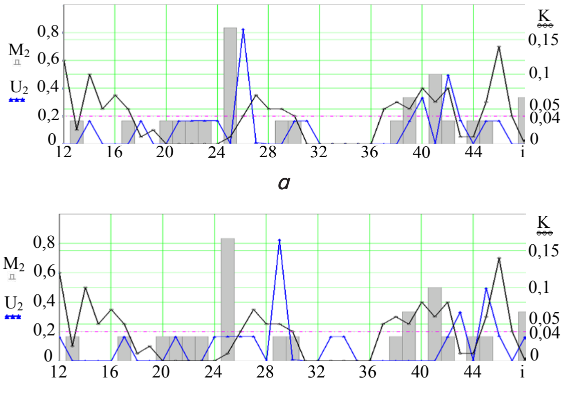
$$U_{2_{i+d}}=L_i, \tag{4}$$

where $U_{2_{i+d}}$ is the RS forecast of pollution concentration at time i and a moment d forward. Important parameters for the forecast of RS based on (1) and (4) are the smoothing parameter $\alpha\epsilon(0, 1)$ [27], the width of window a and the specified size ε of the recurrence region for the examined vector of contamination.

5. Results of experimental verification of the method for predicting the recurrence of states of air pollutants concentration

We verified the developed method for predicting RS of air pollution concentrations based on experimental data on one of the hazardous air pollutants in the city of Cherkassy in the form of nitrogen dioxide (NO_2). The experimental procedure was described in [24]. The tested interval that we selected to validate the proposed prediction method lasted from 01:00 on day 4 (i=12) to 01:00 on day 13 (i=48) during experiment. Over this interval, we evaluated the impact of the forecast horizon (d), a smoothing parameter (α), and a window size (a) for the proposed RS prediction method.

Fig. 1 shows the dynamics of measures M_2, RS forecast of NO_2 concentration, the measured level of NO_2 concentration (mg/m^3), and the maximally permissible concentration of NO_2 (purple line, MPC=0.04 mg/m^3) for two values of the forecast horizon d=1 (6 hours) and d=4 (24 hours). The results in Fig. 1 were obtained at ε=0.01, a=6, and smoothing parameter α=0.99.

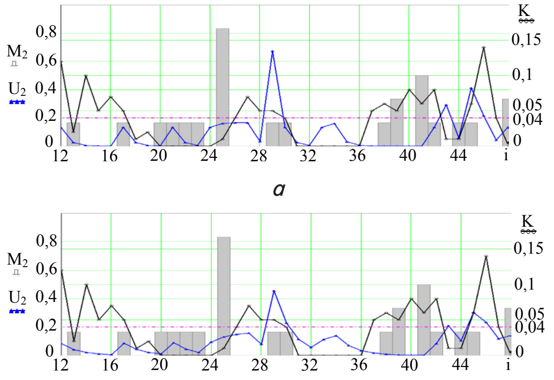


a

b

Fig. 1. Dynamics of measure M_2, RS forecast of NO_2 concentration, the measured (K) NO_2 concentration (mg/m^3), and MPC=0.04 mg/m^3 for two values of the forecast horizon: *a* – *d*=1 (6 hours); *b* – *d* 4 (24 hours)

Fig. 2 shows similar dependences for two different values of the smoothing parameter α=0.8 and α=0.5 at ε=0.01, a=6 for the case of the assigned forecast horizon d=4.

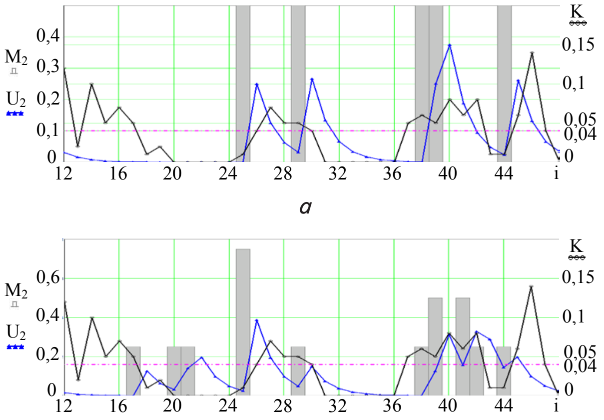


a

b

Fig. 2. Dynamics of measure M_2, RS forecast of NO_2 concentration, the measured (K) $NONO_2$ concentration (mg/m^3) and MPC=0.04 mg/m^3 at the forecast horizon *d*=4 (24 hours) for the different smoothing parameters: *a* – α=0.8; *b* – α=0.5

To illustrate the impact of window size in (1) at the assigned forecast horizon d=1, Fig. 3 shows the dynamics of measure M_2, RS forecast of NO_2 concentration, the measured NO_2 concentration (mg/m^3) and MPC=0.04 mg/m^3 for two values of window size, count a=2 and a=4.



a

b

Fig. 3. Dynamics of measure M_2, RS forecast of NO_2 concentration, the measured (K) NO_2 concentration (mg/m^3) and MPC=0.04 mg/m^3 at the forecast horizon *d*=1 (6 hours) for the values of window size: *a* – a=2; *b* – a=4

The results shown in Fig. 3 were obtained at ε=0.01, α=0.5 for the forecast horizon d=1 (6 hours). They characterize qualitatively and quantitatively the advantages of using a larger width of the window when calculating the measure of recurrence M_2.

6. Discussion of results from devising a method to forecast the recurrence of states of atmospheric pollution concentration

The results of experimental verification of the proposed method for forecasting RS under different forecast horizons d (Fig. 1) indicate its feasibility. It was established that a more accurate forecast is provided for the forecast horizon d=1 (6 hours). The average prediction error value in this case is close to zero, and the average standard deviation is 0.2 units. As the forecast horizon increases d<5, there is a slight growth in the mean error. It was established that in the experiment the method of RS forecasting yields a satisfactory result only for small values of the forecast horizon (d<4).

The effect of smoothing parameter α on the quality of forecast is illustrated by data in Fig. 2 at the limit of the forecast horizon d=4 and a window width for the RS measure, equal to 6 counts (1.5 days). In this case, it was revealed that the decrease in smoothing parameter α decreases the maximum prediction value of RS. Thus, for example, for smoothing parameter α equal to 0.8 the maximum value of RS forecast is 0.7. For the case of a smoothing parameter of 0.5 the maximum value for RS is close to 0.5. Therefore, for the best possible localization of laminar conditions and hazardous contamination of atmospheric air, it is appropriate to select the smoothing parameter α in the examined case to be not less than 0.8. Such a smoothing parameter value accounts for not more than 20 % of past predictions.

The results of studying the influence of the window width for RS measures (Fig. 3), at forecast horizon d=1

(6 hours onwards), demonstrated the usefulness of small window width. The small window width provides a more accurate tracking of dynamics of the RS measure and therefore improves the quality of forecasting RS pollution concentration in order to detect hazardous states. It should be noted, however, that identification of such dangerous states does not require additional data on meteorological conditions of the atmosphere at the time of forecast and in the future. This is important for the practical application of the method for forecasting RS of concentrations of air pollution at industrial cities in different countries.

Our study fully addresses the important and unresolved part of the task on predicting the hazardous pollution of the atmosphere in cities, in terms of using the proposed generic method for predicting the recurrence of states of concentrations of atmospheric contaminants. The proposed method does not require forecasting the meteorological and other conditions associated with a particular territory. Thus, it can be applied at any territory and for any atmospheric pollutants. The results obtained are valid for the field of measurements of nitrogen dioxide concentration at the near-Earth surface layer to a height of about 2 meters. This zone of the atmosphere is considered to be the most dangerous for older urban dwellers, and especially children. This limitation is only due to the height of installing a measuring device and is not linked to the proposed prediction method and the type of pollutant. The results can be reproduced under similar conditions, or close to the examined conditions in the control zone.

Stability of the obtained solutions (invariance or robustness) relative to perturbations in the atmosphere pollution process is ensured by applying, to forecasting, the measure of the recurrence of states of the contaminant concentration. Limitations of this method include a local character of forecast for hazardous pollution conditions, associated with the limited sensitivity of a measuring device. Thus, to cover large areas, one must use multiple points where a measuring device is located. In this regard, the further possible advancement of the proposed method of forecasting is its modification for the case of forecasting a front of dangerous air pollution in cities.

7. Conclusions

1. We have devised a method for predicting the recurrence of states of air pollution in industrial cities based on the modified window measure. The new scientific result implies that the dangerous states of urban air pollution should be identified and predicted not based on the forecast of the concentration of contaminants themselves, but based on results from forecasting the recurrence of states (probabilistic assessment) of ambient air pollution concentrations. Using the modified window measure makes it possible to predict the dangerous states of the atmosphere pollution without regard to the urban structure, the characteristics of sources of pollution, and meteorological conditions. In this case, the modified RS measure of atmospheric pollution concentration makes it possible to quickly identify and predict in the future the existence of laminar conditions in the polluted atmosphere and thereby ensure guaranteed adequate managerial decisions aimed at preventing and reducing the level of dangerous pollution. The method of forecasting based on the RS window measures for pollution concentration makes it possible to predict not only the evident but also hidden dangerous air pollution states of industrial cities. This provides for an overall improvement in the effectiveness of interventions to prevent hazardous contamination of the atmosphere and the environment.

2. We have verified the proposed method for RS forecasting applying experimental data on measuring NO_2 in the atmosphere of the industrial city with a typical urban configuration and the presence of sources of pollution. The results indicate the efficiency of the proposed method. In this case, it was found that over the tested interval of observations between counts 12–36 the current values for NO_2 concentration exceeded MPC by 1.9 to 3.1 times. In addition, the tested interval demonstrated sharp characteristic changes in the predicted RS measure. It is noted that such changes are predictors of hidden events involving hazardous air pollution in industrial cities. It was experimentally determined that a more accurate forecast is provided for the forecast horizon $d=1$ (6 hours). It is noted that a decrease in the smoothing parameter when calculating the modified RS measure decreases the maximum value for RS prediction, from 0.7 to 0.5. It is shown that in the present case, in order to ensure the reliability of the forecast for laminar conditions in the contaminated atmosphere, the smoothing parameter to be selected should be not less than 0.8. Such a smoothing parameter accounts for not more than 20 % of past predictions. It is shown that the small window width provides a more accurate tracking of the predicted dynamics in the RS measures and detection of laminar conditions. It is noted that forecasting the hazardous conditions of the atmosphere pollution based on the dynamics in predicting the RS measure does not require information about the meteorological conditions at the time of forecast and in the future. This is the main distinguishing feature and advantage of the proposed prediction method. A given method for RS forecasting proves to be invariant to urban configuration, the types of stationary and mobile sources of air pollution, as well as meteorological conditions.

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