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Numerical analysis of experimental studies of atmosphere deposition of contaminants in the vicinity of the Novosibirsk city*

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Abstract. The results of experimental and numerical studies of regional contamination of the snow cover by the atmospheric emissions of impurities coming in the winter period from the territory of Novosibirsk are discussed. The quantitative regularities in removing of impurities are established. The possibility of creating an efficient monitoring system and obtaining on its basis the assessment of the state of the long-term pollution in the vicinity of the city of Novosibirsk and the determination of the characteristic impurities emission from its territory is revealed.

Keywords: atmosphere, impurity, area source, estimation, reconstruction.

1. Introduction

The task of numerical modeling and analysis of the atmospheric pollution from a large number of city sources is extremely complex. The transfer and diffusion of impurities are closely related to the dynamic, thermal and humid conditions of the city, the state of the underlying surface and the terrain relief, the chemical and dispersed composition of impurities, etc. [1–3]. A detailed description of all these factors leads to the need for developing and implementing complex hydrodynamic models, models of transport and transformation of gas and aerosol impurities, that include a significant number of unknown parameters, which is not always consistent with the available technical and economic potentials.

In this situation, we need a more balanced analysis of the results of experimental data and theoretical studies of the impurities propagation in the atmosphere, a certain classification of processes. For example, when modeling the long-term pollution from stationary sources, the current meteorological information can be replaced by the climatic one. A relatively simple mathematical description of impurity transport at large distances from distributed sources of emissions is possible. In specific situations, aggregation of model parameters based on the methods of similarity theory makes it possible to optimize the number of defining complexes of physical values [4–7]. An important stage of the given study is planning the observations based on theoretical concepts about the ongoing processes of impurity

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transport thus leading to an increase in the informative of the experimental data obtained [8–10].

When developing models for the transport and diffusion of impurities in the atmosphere, their stylization and simplification are possible. It is useful to employ the relationship between solutions for a point and a linear source and their asymptotic behavior with distance. The data of field observations and numerical modeling show that under normal conditions, when the distance from the source is a distance of the order of 7–10 km, the impurity concentration in the surface layer of the atmosphere is determined by a relatively small number of factors [4, 5]. To these, in the first place, one can refer the power of a source, the average wind speed and the thickness of a mixing layer. For such distances, the influence of a number of parameters becomes insignificant. These include the height of a source, the rate of settling of aerosol particles, the coefficient of vertical turbulent exchange, etc.

When moving to an area source, the difficulty in describing the spatial distribution and temporal dynamics of impurity emissions are substantially increased. The estimation problem also becomes more complicated since the total impurity release is actually unknown and, moreover, is distributed within a certain region. In this case, for an approximate description of the concentration fields in the vicinity of an area source, the methods of asymptotic expansions are used. These methods make it possible to obtain a number of small-parametric representations of pollution fields in the regional neighborhoods of an area source to the power $1/R$, R is the distance from the effective impurity emission center [11, 12].

2. Objects and methods of research

On the territory of the city of Novosibirsk, there is a large number of sources of gas and aerosol pollution in the atmosphere. Among them, the largest contribution is made by enterprises of the fuel and energy complex, automobile transport, chemical and metallurgical plants. Emissions of these sources have a significant impact not only on the atmosphere of the city, but also on its surroundings. The main polluting impurities are suspended substances, heavy metals, nitrogen oxides, formaldehyde, polyaromatic hydrocarbons (PAHs). The spread of pollutants is closely related to the characteristics of the sources and the current dynamic, thermal and humid regime of the atmosphere, the nature of the underlying surface.

The most convenient and efficient way to obtain data on the entry of pollutants from the atmosphere onto the underlying surface is to study the snow, vegetation and soil cover [13–15]. Of particular interest are these studies when analyzing the long-term pollution processes. The intensity and configuration of the concentration field are determined by the amount of emission, the duration of the accumulation period, the location of sources, the repeatability of wind directions, etc. In order to assess the regional impact on the environment and to determine the integral characteristics of emissions in the vicinity of Novosibirsk in the winter seasons of 2009–2011, the route snow surveys were carried out. Samplings on the routes were mainly confined to the north-east sector, in which a maximum precipitation of aerosol impurities in the winter period is observed. The distances of sampling points from the territory of the city reached 30–40 km. The routes for samplings were chosen with allowance for the directions of prevailing outflows of urban impurities and the system of roads [16]. In this case, the Tomsk–Kemerovo route located to the north-east of the city meets these requirements to a large extent. The winter recurrence of winds in the south-west and the west directions at the altitudes of the boundary layer of the atmosphere is about 60 % [16].

The sampling was carried out at the full depth of the snow cover. The chemical analysis of snow samples for the content of ionic composition, heavy metals in them, PAH was carried out in analytical laboratories of the SB RAS institutes, FBUN SSC "Vector". The spatial dynamics, both in the melted snow sample and in the main inorganic and organic impurities, has a monotonically decreasing character with distance. A stable relationship between the sediment dynamics and organic and inorganic impurities is noted. As a consequence, the regularities found allow us to carry out recalculations of the content of chemical impurities. On the other hand, since the melted sample sediment is determined with the least amount of labor, the dependence on the precipitate is a criterion for the possibility of subsequent carrying out and monitoring more expensive determinations of PAH, ionic, elemental (macro- and micro-) dispersed composition.

The errors in the determination of both organic and inorganic substances were within the limits regulated by GOST [17].

3. A model of estimating regional pollution estimation by an area source

The description of the fields of the impurities concentrations in the atmosphere at considerable distances from the territory of the city, as an area source, allows a considerable simplification. For such distances, the influence of a number of parameters becomes insignificant. Let the axis x be directed to the east, the axis y to the north and S be the area source, which is, for example, the territory of the city. The concentration of a weakly settling impurity over a long-term interval (a month, a season, a year) from a point source is described with the relation [12]:

$$q(x, y) = \frac{m(\xi, \eta) P(\phi + 180^\circ)}{2\pi u H \sqrt{(x-\xi)^2 + (y-\eta)^2}}. \tag{1}$$

Here $(\xi, \eta) \in S$ is a current coordinate of the source, $m(\xi, \eta)$ is the impurity emission from this point, $P(\phi)$ is the wind rose over the considered time interval, u and H are the average wind speed and the height of the mixing layer, respectively, $\phi(\xi, \eta) = \arctan \dfrac{y-\eta}{x-\xi}$. It is assumed that the point (x, y) is at least 7–10 km away from the source. In this case, relation (1) reliably describes the long-term contamination processes of the terrain for such distances. Let the function $m(\xi, \eta)$ be given for the whole territory of the city. Then, taking into account (1), the concentration from an area S source can be represented as

$$Q(x,y) = \frac{1}{2\pi u H} \iint\limits_S \frac{m(\xi,\eta) P(\arctan \frac{y-\eta}{x-\xi} + 180^\circ)}{\sqrt{(x-\xi)^2 + (y-\eta)^2}}\, d\xi\, d\eta. \tag{2}$$

In real conditions, the function $m(\xi, \eta)$, as a rule, is unknown or is given approximately. In this case, the numerical interpretation of the observational data with the help of (2) becomes fairly complicated. The situation can be substantially clarified if expression (2) is transformed using the generalized mean theorem from the integral calculus. According to this theorem, for the two arbitrary continuous functions f and g on a connected compact set, the following equality holds [18]:

$$\iint\limits_S f(\xi,\eta) g(\xi,\eta)\, d\xi\, d\eta = f(\lambda,\mu) \iint\limits_S g(\xi,\eta)\, d\xi\, d\eta, \tag{3}$$

where $(\lambda, \mu) \in S$ and, in addition, it is assumed that $g(\xi, \eta) \geq 0$ on S. In our case, bearing in mind that

$$g(\xi,\eta) = m(\xi,\eta), \quad f(\xi,\eta) = \frac{P(\arctan \frac{y-\eta}{x-\xi} + 180^\circ)}{\sqrt{(x-\xi)^2 + (y-\eta)^2}}, \tag{4}$$

we obtain a fairly simple relation

$$Q(x,y) = \frac{\theta P(\arctan \frac{y-\mu}{x-\lambda} + 180^\circ)}{\sqrt{(x-\lambda)^2 + (y-\mu)^2}}, \tag{5}$$

where $\theta = \dfrac{G}{2\pi u H}$, $G = \iint_S m(\xi,\eta)\, d\xi\, d\eta$ is the total admixture of the admixture from the territory of the city.

Function (4) can be represented in the form

$$Q(x,y) = \frac{\theta P(\arctan(\frac{y}{x} C(R,x,y,\lambda,\mu) + 180^\circ))}{R \cdot B(R,x,y,\lambda,\mu)}, \tag{6}$$

where $R = \sqrt{x^2+y^2}$, $C = \dfrac{y-\mu}{x-\lambda}$, $B = \sqrt{1 + \dfrac{\lambda^2+\mu^2}{R^2} - \dfrac{2(x\lambda+y\mu)}{R^2}}$.

Obviously, for sufficiently large x and y, the functions C and B are close to unity and, with allowance for (5), in this case, in order to estimate the concentration field from an area source, we can use the following approximation

$$Q(x,y) = \frac{\theta P(\arctan \frac{y}{x} + 180°)}{R} \tag{7}$$

To determine the function $Q(x,y)$, it suffices to estimate the unknown parameter θ using, for example, the observational data.

4. Numerical analysis of field observations

4.1. The winter season of 2008/09. The scheme of snow sampling is shown in Figure 1. The quantitative interpretation of the data of expeditionary and chemical-analytical studies of the snow cover was carried out based on the regression relation (6) applied to the north-east sector of the regional impurities removal from the city. The origin was located at the center of Novosibirsk ("Glavpochtamt"). The evaluation of the unknown parameter θ for each of the radial sampling routes under consideration was carried out at the reference observation points 1, 8 and 12, respectively. The results of the numerical interpretation of the experimental winter season of 2008/09 are shown in Figure 2.

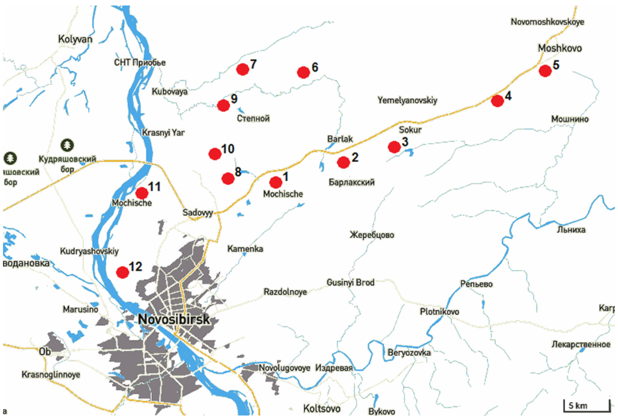

Figure 1. The scheme of snow sampling in the vicinity of the city of Novosibirsk at the end of the winter season of 2009: • locations of the sampling points

4.2. The winter season of 2009/10. The sampling routes in the winter season in question were slightly adjusted as compared to the 2009 season. In order to track more accurately the dynamics of precipitation of impurities from the city, the number of sampling points was increased and the length of the route was increased in the north-north-west direction up to the village Krasny Yar. Also, the number of points in the direction to the north-east was increased. The scheme of selection is shown in Figure 3.

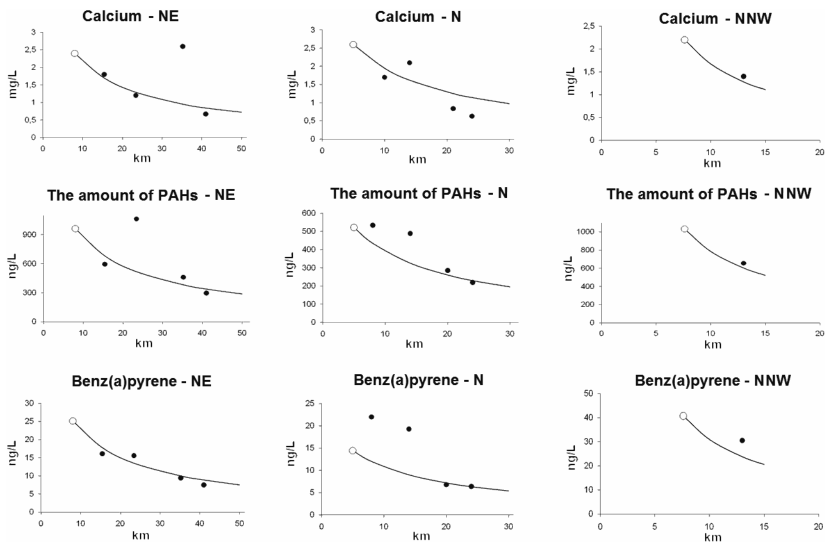

Figure 2. The measured and numerically reconstructed concentrations of water-dissolved calcium, amounts of PAH, benz(a)pyrene in the snow in the north-east, north, and north-north-west directions of the removal from Novosibirsk: ∘ reference points, • reference observational points, and — the impurity concentration restored by model (6)

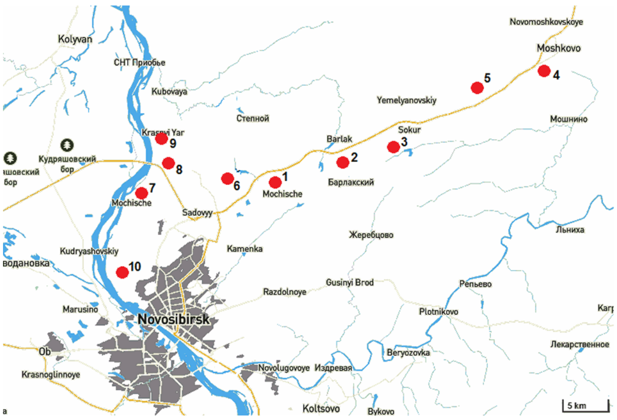

Figure 3. The scheme of snow sampling in the vicinity of Novosibirsk at the end of the winter season of 2010: • locations of the sampling points

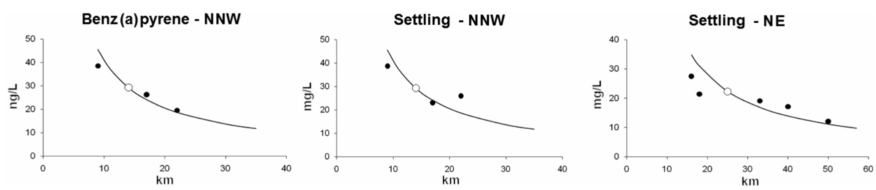

Figure 4. The measured and numerically reconstructed concentrations of benz(a)pyrene, sediment in the snow in the north-east and north-north-west directions of impurity removal from Novosibirsk

Results of numerical interpretation of the experimental studies data of the winter season of 2009/10 are shown in Figure 4.

The analysis of Figures 2 and 4 shows a satisfactory agreement of the calculation of observations at control points (black circles). In spite of a considerable scatter at some points of the comparable concentrations of benz(a)pyrene, PAH, in general, the contribution to the contamination of the snow cover from a combination of sources located on the territory of the city of Novosibirsk prevails. The precipitation of benzo(a)pyrene, which has a significant effect on the health of the city population, is very high. Areal possibility of using dust precipitation as a tracer should be also noted, which in subsequent studies will significantly reduce the amount of relatively expensive chemical analysis, limiting ourselves to determining the concentrations of chemical elements and compounds in question only at a number of reference points.

5. Conclusion

The numerical analysis of the results of expeditionary and chemical-analytical studies based on the model for estimating the deposition of impurities from an area source has made it possible to establish the quantitative patterns of regional removal of impurities from the territory of the city of Novosibirsk. The research carried out has shown that the pollution levels on the prevailing directions of demolition of harmful impurities are highly significant even at distances of several tens of kilometers from the urban area. For example, the content of benz (a) pyrene in the snow was about 20 ng/L per 10 km to the north-east of Novosibirsk (the Mochishche area), and at the points of extraction located near to the Mochishche Holiday House and Kudryashovskiy Bor, 30 and 40 ng/L, respectively, which is quite comparable with the concentrations measured in the snow at the Rozgidromet stations in the city.

It should be specially noted that when studying the residents' health indicators of populated areas located in the zones of intensive demolition of impurities from the urban areas, in addition to the local conditions, this factor of influence must also be taken into account as an additional risk to one's health. The revealed regularities allow one with limited means to perform integral estimates of the removals of the impurities from Novosibirsk for long periods of time, to compare their emissions with each other, and to assess the degree of anthropogenic load on the surrounding areas. These results indicate to the possibility of creating an efficient monitoring system and of obtaining on its basis an assessment of the state of the long-term pollution of the city atmosphere and the determination of the emission of characteristic impurities from its territory.

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