Study of regional dust transfer from city territory

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Based on the average integral theorem, a few-parameter model of long-term regional pollution of a territory by some area source is developed. The model is tested using the data of route observations of snow pollution with the dust near Iskitim (Novosibirsk Region). Estimated pollutant content levels along the observation routes are presented, and their relationship with the occurrence of winter wind direction in the atmospheric boundary layer are discussed.

Introduction

Industrial centers are powerful sources of atmospheric pollutants, many of which are transported by aerosol particles. Pollutants produce a harmful effect on the environment changing its chemical and physical characteristics. Anthropogenically changed biogeochemical provinces are intensely formed near big cities.[1–3]

Regardless of a great number of papers devoted to the study of air pollution in cities and suburbs, quantitative regularities of this process are not yet well studied. If one tries to obtain a detailed pattern of pollution, he or she faces a number of rather complex problems on information provision and mathematical description of the processes of pollutant transfer in the atmosphere.

In connection with these problems, it is worth separating the processes of local and regional transfer. In the cases of local pollution, the following factors are significant: the height of elevation of the pollution source, characteristics of the vertical turbulent exchange, the vertical profile of the wind velocity, surface inhomogeneities, etc.[4,5] Analysis of the experimental data and theoretical results shows that for a light pollutant at the distance of 7 to 10 km from a source these factors almost do not affect the concentration both near the surface and in the whole mixing layer. As a result, it becomes possible to describe the processes of regional pollution using few-parameter models.[6–8]

1. Estimation of regional pollution

Let the axis x be directed to the east, the axis y be directed to the north, and S be an area source (city territory). The concentration of a weakly depositing pollutant for a long time interval (month, season, year) emitted by a point source is described as follows[5,8]:

$$q(x,y)=\frac{m(\xi,\eta)P(\varphi+180°)}{2\pi uH\sqrt{(x-\xi)^2+(y-\eta)^2}}, \qquad (1)$$

where (ξ, η) are the coordinates of the source, $(\xi, \eta) \in S$; $m(\xi, \eta)$ is the pollutant emission from the point with these coordinates; $P(\varphi)$ is the wind rose for the considered period; u and H are the mean wind speed and the height of the mixing layer, respectively; $\varphi(\xi, \eta) = \arctan [(y - \eta)/(x - \xi)]$.

It is assumed that the point (x, y) is separated from the source by 7–10 km. In this case, Eq. (1) rather reliably describes the process of long-term pollution of a territory for such separation.

Denote the function describing the emission of a weakly depositing pollutant in the urban atmosphere as $m(\xi, \eta)$. Then, with the allowance for Eq. (1), the concentration produced by the area source S can be represented as

$$Q(x,y)=\frac{1}{2\pi uH}\iint\limits_S \frac{m(\xi,\eta)P\left(\arctan\frac{y-\eta}{x-\xi}+180°\right)}{\sqrt{(x-\xi)^2+(y-\eta)^2}}\,d\xi d\eta. \qquad (2)$$

It is also assumed here that the point (x, y) is rather far from S.

The function $m(\xi, \eta)$ is usually unknown or known only approximately. In this case, it is rather difficult to interpret observations with the use of Eq. (2). The situation can be improved significantly, if we transform Eq. (2) using the generalized average theorem from integral calculus.[9] According to this theorem, the following equality is valid for two arbitrary continuous functions at a connected compact set:

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

where $(\lambda, \mu) \in S$ and it is additionally assumed that $g(\xi, \eta) \ge 0$ at the set S.

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In our case, assuming that $g(\xi, \eta) = m(\xi, \eta)$,

$$f(\xi,\eta)=\frac{P(\arctan\frac{y-\eta}{x-\xi}+180°)}{\sqrt{(x-\xi)^2+(y-\eta)^2}},$$

we obtain a rather simple equation:

$$Q(x,y)=\frac{\theta P(\arctan\frac{y-\mu}{x-\lambda}+180°)}{\sqrt{(x-\lambda)^2+(y-\mu)^2}}, \quad (4)$$

where $\theta = M/(2\pi uH)$, $M = \iint\limits_S m(\xi,\eta)d\xi d\eta$ is the total pollutant income from the city territory.

Analysis of the dependence (4) shows that to determine the function $Q(x, y)$, it is sufficient to estimate the unknown parameters θ, λ, and μ, using, for instance, the data of observations. The situation can be significantly simplified, if we know the position of a dominant point source at the city territory. In this case $\lambda = x_0$, $\mu = y_0$, where (x_0, y_0) are the coordinates of the effective source.

2. Experimental conditions

The route snow sampling was conducted late in the winters of 2000 and 2001 near Iskitim (Novosibirsk Region). Sampling points were located at the distance up to 15 km from the cement works situated in the northern part of the city.

Iskitim is situated 30 km south of Novosibirsk in the Berd River valley. The level of atmospheric pollution there is much higher than the mean level for Russian cities. This pollution is largely due to Chernorechenskii Cement Works (more than 70%). The dust concentration under the stack plume can exceed the maximum permissible level by more than ten times even at the distance up to 1500 m. The air in the city is also characterized by high concentration of soot and benzapilene. The northern part of the city located in a valley is most strongly polluted.

Winds of the southwestern and western direction have the highest mean winter occurrence in the atmospheric boundary layer (more than 50%) (Ref. 10). In this connection, the sampling routes were oriented to the northeast and east. Observations were mostly conducted at the distance from 6 to 15 km at even and open areas.

3. Numerical simulation

The tentative analysis of the climatic information on the mean winter occurrence of wind directions in the atmospheric boundary layer,[10] the main source of atmospheric pollution in Iskitim, and measurements of pollutants in snow shows that the coordinates of the effective point source should be specified nearby the cement works. In this case, determination of parameters in the regression (4) simplifies considerably and reduces to estimation of θ. To calculate it, it is sufficient to use the data of observations along the considered route at only one reference point. The reference points should be selected not very far from the city, because the resistance of estimated parameters of the dependence (4) to measurement errors decreases with the distance. On the other hand, they should not be located too close, to avoid a significant systematic error.

Figure 1 shows the reconstructed concentrations of dust and polyaromatic hydrocarbons (PAH) in the east-north-east direction (route 1) from the cement works. To estimate the regression parameters, we used the data of route surveys conducted late in winter of 2001. Figure 2 depicts the reconstructed concentrations of cadmium and water-soluble form of calcium in the northeast direction (route 2). The data shown in this figure are dated by the late winter of 2000. To estimate θ in the dependence (4), we used points about 6 km far from the cement works. Other sampling points in this case can be used to control the reconstruction accuracy. It follows from Figs. 1 and 2 that the measured concentrations agree rather closely with the calculated ones.

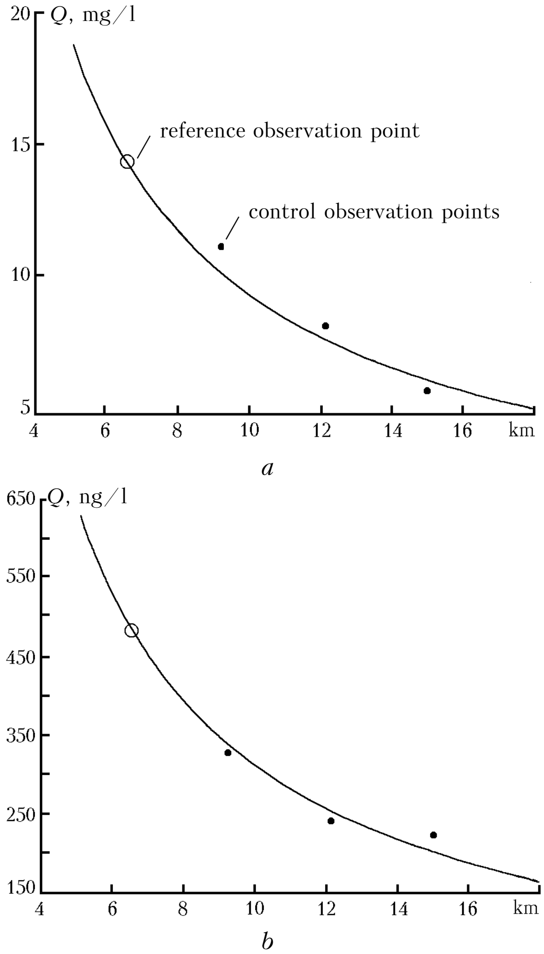

Fig. 1. Reconstructed and measured specific content of dust (*a*) and the sum of PAH (*b*) on route 1. The distance from the source is plotted as abscissa.

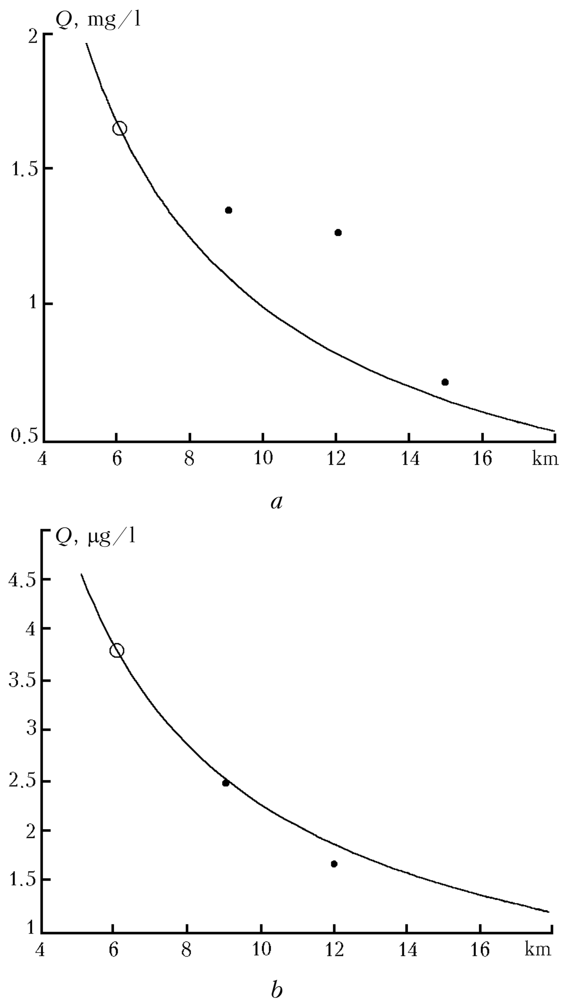

Fig. 2. Specific content of the water-soluble calcium (*a*) and cadmium (*b*) in snow on route 2.

Analysis of data given in Table 1 shows that as the height increases, the wind rose changes considerably from the southern and southeastern to the southwestern and western. This is connected both with the local factors (the city is situated in a valley oriented roughly from south to the north) and with the global reasons such as the dominant western-eastern transport of air masses. With the allowance made for the occurrence of the wind directions in the atmospheric boundary layer, the data from Table 2 allow the pattern of regional pollution of Iskitim environs to be reconstructed and the total amount of dust emissions from city sources estimated. It is interesting to note that, in spite of almost equal frequency of occurrence of the southwestern and western winds at the height of 0.5 km, the level of depositions on route 1 is much higher than that along the route 2. This circumstance points to higher occurrence of winds relative to route 1. It should be expected that along the direction of this route the total amount of atmospheric pollutants achieved the maximum values in the winter seasons of 1999–2001.

Table 1. Winter frequency of occurrence (%) of wind directions at different heights

Wind direction	Height, km			
	Vane	0.1	0.2	0.5
SE	36	8	6	8
S	48	25	17	10
SW	5	32	36	29
W	1	13	18	28

Note. January occurrence is given at the vane level.

Table 2. Estimated parameter θ for routes 1 and 2

Component	θ_1	θ_2	θ_1/θ_2
Dust	93.5	78.7	1.18
PAH	3100	2200	1.4
Cd	16.3	12.6	1.29
Ca^{2+}	12.5	9.9	1.26
NH_4^+	2.6	2.1	1.24
Specific electroconductivity	16.1	12.6	1.27

Conclusion

This study allowed us to obtain quantitative patterns of the regional spread of dust, polyaromatic hydrocarbons, heavy metals, and macrocomponents in Iskitim environs. With the increasing distance from the city, the dominant directions of aerosol transport change from the north and northwest to the northeast and east. This is connected, to a certain degree, with the peculiarities of the region and the dynamics of atmospheric processes.

The obtained regularities of dust deposition in the city environs can be used to determine correlations between the dust concentration in snow and the snow cover albedo, because albedo variations in the snow melting period are proportional to the level of snow cover pollution and closely connected with the variations of image density of pollution aureole in air and space photographs.

The use of the integral average theorem allowed the transition from solution of the infinite-dimension problem of determining the pollutant emission rate from an area source to a finite-dimension problem with few parameters. However, to solve the problem formulated, additional investigations involving development of efficient numerical algorithms and optimization of the observation system are needed.

Acknowledgments

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