Study of the processes of long-term pollution of Irkutsk environs with heavy metals

V.F. Raputa, G.P. Koroleva, A.G. Gorshkov, and T.V. Khodzher

Institute of Computational Mathematics and Mathematical Geophysics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk
Institute of Geochemistry, Siberian Branch of the Russian Academy of Sciences, Irkutsk
Limnological Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk

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A model is proposed for reconstruction of pollution from the data of route snow samples in Irkutsk environs. The model is based on solutions of the turbulent diffusion equation. Reconstructed values of beryllium, copper, and lead fallout in snow are compared with the measured data. The dependence of the model parameters on the climatic repetition of wind directions in the atmospheric boundary layer is discussed.

Introduction

Numerical simulation of pollutants dispersal in the atmosphere from a great number of sources in a city falls in the category of very complicated problems. Spreading of pollutants is closely connected with dynamic, thermal, and humidity conditions in the city, properties of the surface, chemical composition of the pollutant, and other factors. Detailed allowance for all these factors leads to the development of complex mathematical models involving a large number of parameters calling for further refinement, and this not always fits the available technical and economic capabilities.[1]

Such a situation requires more weighted analysis of experimental data and theoretical studies of pollutant dispersal in the near-ground and boundary layers of the atmosphere. When modeling long-term pollution of a territory by emissions from stationary sources, the current meteorological information can be replaced by the climatic one.[2] There exists a possibility of relatively simple mathematical description of the processes of pollutant transport at long distances from the distributed sources of pollution.[3–5] Application of methods of similarity theory and dimensional methods allows the number of governing parameters to be decreased. Planning of observations based on the theoretical concepts of pollutant transport may increase the information content of experimental data.

1. Formulation of the inverse problem

To solve the problems of pollutant transport and diffusion in the atmosphere, these problems should be first simplified and stylized to some extent. In this connection, the interdependence between the solutions for point and linear sources is useful. If the horizontal turbulent exchange is assumed proportional to the wind speed, then in the steady state the following equation is valid[6,7]:

$$q(x,\, y,\, z) = S(x,\, z)\, \mathrm{e}^{-y^2/4k_0 x} / (2\sqrt{\pi\, k_0\, x}), \qquad (1)$$

where $q(x, y, z)$ and $S(x, z)$ are the pollutant concentrations produced by the point and linear sources, respectively; k_0 is the coefficient of proportionality between the wind speed and the horizontal turbulent exchange; the x axis coincides with the mean wind direction, the axis y is normal to the z axis and lies in the horizontal plane.

To calculate the function $S(x, z)$, let us use the equation of transport and turbulent diffusion for an infinite linear source[6,7]:

$$u\,\frac{\partial S}{\partial x} - w\,\frac{\partial S}{\partial z} = \frac{\partial}{\partial z}\, k_z\, \frac{\partial S}{\partial z} - \alpha S \qquad (2)$$

with the following boundary conditions:

$$uS\,\big|_{x=0} = Q\delta(z - H), \quad k_z\, \frac{\partial S}{\partial z}\bigg|_{z=0,\ z=h} = 0, \qquad (3)$$

where $u(z)$ is the wind speed in the mixing layer; w is the sedimentation rate of pollutant particles in the atmosphere; k_z is the coefficient of vertical turbulence; α is the coefficient accounting for pollutant transformation and washing-out; Q and H are the power and height of the linear source; h is the height of the mixing layer.

Equations (2) and (3) include a large number of parameters, which should be specified or refined in specific situations, and in this form they are inconvenient for analysis of observations on pollution of the territory. For further simplification, additional *a priori* information on the processes in the near-ground and boundary layers of the atmosphere, pollutant characteristics, spatial scales, and averaging times of concentration fields should be invoked.

According to Refs. 6 and 8, the long-time-averaged concentration field produced by a point source is determined by the equation

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$$\bar{q}(r,\ \varphi,\ z) = \frac{S(r,\ z)\ g(\varphi)}{2\sqrt{\pi k_0\ r}} \int\limits_{-\Delta}^{\Delta} e^{-r \sin^2\psi/4k_0}\ d\psi, \qquad (4)$$

where r and φ are the polar coordinates of the reference point with the origin of coordinates at the source of pollution; $g(\varphi)$ is the probability of the wind direction opposite to φ; Δ is some small angle characterizing plume widening in the direction across to the wind.

For typical $k_0 = 0.5$–1 m, $\Delta < 10$–$15°$ at $r > 1$ km,

$$\bar{q}(r,\ \varphi,\ z) = F\ S(r,\ z)\ g(\varphi)/r. \qquad (5)$$

Here F is the parameter practically independent of r.

Equation (5) can be simplified even more, if we assume $\alpha = 0$ and $w = 0$ in Eq. (2). Then, at a distance about 7 to 10 km from the source of pollution, the function $S(r, z)$ only slightly depends on z (Refs. 3 and 7). In this case, with the allowance for Eq. (5), we have for the density of pollutant fallout on the surface[5]:

$$\bar{q}(r,\ \varphi) = \theta\ g(\varphi)/r, \qquad (6)$$

where

$$\theta = \lambda\ Q/(2\pi\ uh); \qquad (7)$$

λ is the coefficient of pollutant interaction with the surface.

The unknown parameter θ is estimated from the experimental data. At a distance from the source less than 7–10 km, the function $S(r, z)$ should be necessarily taken into account. The coefficient k_z is typically approximated by the parabolic function of the following form[9]:

$$k_z = c\ u_*\ z\ (1 - z/h), \qquad (8)$$

where u_* is the dynamic rate; the parameter c depends on the temperature distribution in the mixing layer.

With the allowance for Eq. (8), the solution of the problem formulated by Eqs. (2) and (3) can be represented as a Fourier series in terms of Legendre polynomials[9]:

$$S(r,\ z) = \frac{Q}{hu}\left[1 + \sum_{n=1}^{\infty} (2n+1)\ P_n\left(2\frac{H}{h} - 1\right)\times\right.$$
$$\left.\times P_n\left(\frac{z}{h} - 1\right)\exp\left(-\ n\ (n+1)\ \frac{cu_* r}{hu}\right)\right]. \qquad (9)$$

At $r > 0$, the series (9) converges very quickly. Because of this property, a small number of terms in the series are enough for efficient description of the field of surface concentration. As a result, we have the following regression dependence:

$$S(r,\ 0,\ \boldsymbol{\theta}) \approx$$
$$\approx \theta_1\left[1 + \sum_{n=1}^{N} (2n+1)\ P_n(-1)\ P_n(\theta_2)\ e^{-n(n+1)\theta_3 r}\right], \qquad (10)$$

where $\boldsymbol{\theta} = (\theta_1, \theta_2, \theta_3)$ is the vector of aggregated parameters,

$$\theta_1 = \frac{Q}{hu},\ \theta_2 = 2\frac{H}{h} - 1,\ \theta_3 = \frac{cu_*}{hu}. \qquad (11)$$

Equation (11) allows correcting the fields of pollutant fallout for shorter distances from the source, although this requires additional experimental data.

2. Analysis of heavy metal fallout

To determine the content of heavy metals in snow, snow was sampled late in winter seasons of 1994–1996. The sampling routes were the following[10]: 1. Irkutsk – Bayandai; 2. Irkutsk – Listvyanka; 3. Irkutsk – Slyudyanka.

Tentative study of the measurements showed the monotonic, on the whole, decrease of Be, Cu, Pb contents on the routes 1 and 2 for all the three winter seasons. For zinc this regularity is much less pronounced. On the route 3, most sampling points are under the direct effect of local sources in Shelekhovo town, and this complicates estimation of the regional component of heavy metal transport on this route and calls for invoking voluminous additional information.

Tables 1 and 2 and Fig. 1 give the estimated levels of Be, Cu, and Pb accumulation in the snow cover along the routes 1 and 2. Estimation was performed with the model (6). The distances at the routes were determined with respect to the center of Irkutsk, which was assumed to be the effective total pollution source.

Analysis of Table 1 demonstrates good agreement between the calculated and measured data at eight control sites. It should be noted that the best agreement is for beryllium.

Table 1. Measured (numerator) and reconstructed (denominator) levels of heavy metal accumulation along the Irkutsk – Bayandai route for winter period of 1995/96

Element	Estimated parameter θ	Level of accumulation, g/km²								
Beryllium	304	19*/19	16.9/11.3	8.9/8.9	6/5.8	5.5/4.3	3.6/3.3	3.9/3.1	2.6/2.7	2.6/2.4
Copper	5798	362*/362	297/215	224/171	67/111	112/82	110/64	62/59	89/52	51/46
Lead	7408	463*/463	289/274	94/218	202/141	81/104	101/81	76/76	43/67	35/58
Distance from the city center, km		16	27	34	52.4	71	91	98	111.3	127

* Used for estimation of the parameter θ.

Table 2. Measured (numerator) and reconstructed (denominator) levels of beryllium accumulation along the Irkutsk – Listvyanka route

Winter season	Estimated parameter θ	Accumulated level, g/km^2					
1993/94	1477	211.1*/211.1	131.6/123.1	60.4/59.1	68.9/42.2	54.8/29.5	45.5/22.7
1994/95	1145	163.5*/163.5	62.5/95.4	38/45.8	55.8/32.7	58.8/22.9	107.9/17.6
1995/96	509	72.7*/72.7	40.8/42.4	20.1/20.4	23.6/14.5	20.7/10.2	30.3/7.8
Distance from the city center, km		7	12	25	35	50	65

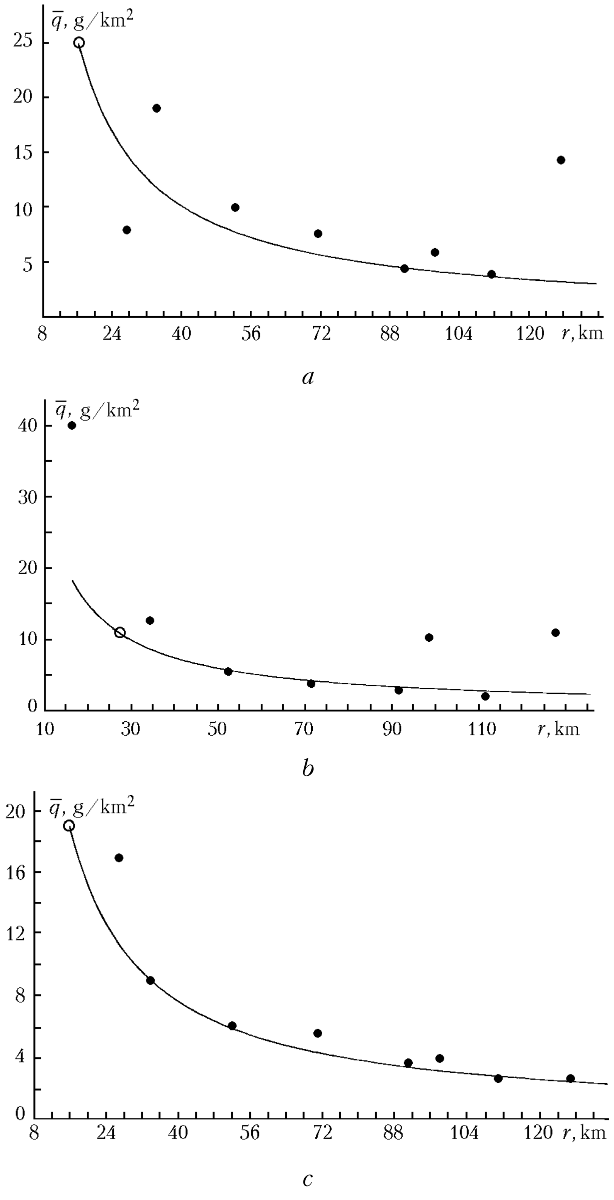

Fig. 1. Levels of beryllium fallout along the route Irkutsk – Bayandai for winter periods of 1993/94 (*a*), 1994/95 (*b*), 1995/96 (*c*): reference and control observation sites (○, ●).

Table 2 represents the dynamics of beryllium accumulation for three winter seasons along the route 2. At the second and third control sites (12 and 25 km), the calculated and measured values almost coincide. Then at the control sites 4–6 the measured values systematically exceed the calculated ones in all the three periods. This fact indicates the presence of additional sources. They include, in the first turn, beryllium emissions from the Shelekhovo Aluminum Production Plant. Winter repetition of the wind in the mixing layer also plays a certain role in the formation of this pattern. It is also worthy to note the decrease of the level of beryllium accumulation from one season to the other. This can be explained by the decrease or termination of the industrial production in those years.

Analysis of the wind fields in winter over Irkutsk shows that the value of the parameter θ obtained for routes 1 and 2 corresponds directly to the climatic repetition of wind directions at the altitudes within the atmospheric boundary layer.[5,11]

Conclusion

The obtained results show that the processes of long-term regional pollution of Irkutsk environs with beryllium, copper, and lead are well described by the regression model (6) based on the solution of a semi-empiric equation of turbulent diffusion. The closest agreement between calculations and observations for beryllium is indicative of the more compact arrangement of beryllium sources than sources of copper and lead. The dynamics of the decreasing emissions of heavy metals for the winter periods of 1993/96 is connected with the decrease of industrial production in those years.

To describe pollution of Irkutsk and its suburbs, the model (6) should be corrected by introducing additional terms in the series (10), and this task will require more voluminous and detailed input information.

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