Regularities of dust contamination in the vicinity of tailing ponds

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A model is suggested for estimation of local dust contamination from areal sources. The model is tested using field observations of mass dust concentration around Lake Selitrennoe (Altai Region) and the data of soil sampling for the content of heavy metals near Salagaevskii Log tailing ponds (Salair, Kemerovo Region).

Introduction

Traditional problems of atmospheric transport and diffusion of aerosol are connected with description of the process of its spread from point or extended sources located in the atmospheric boundary layer.[1–3] The operating mode of sources in such problems is usually preset. The situation changes significantly in the case that the surface itself is the source of aerosol. Then the wind entrainment and transport of aerosol considerably depend on the state of the surface (its humidity, grain size distribution, efficiency of surface sorption, etc.). It is very difficult to solve the problem of wind-induced migration in the general formulation. A certain progress is now achieved in description of the processes of sand transport in dust storms,[4,5] but determination of the amount of lifted dust is still an open question. In practice, this uncertainty is usually resolved empirically through introduction of the wind entrainment coefficient characterizing the admixture concentration ratio in air and on the surface.[6]

Non-reclaimed tailing ponds, where huge amounts of ore mining and processing by-products are accumulated, form powerful sources of dust, heavy metals, and other admixtures.[7,8] Other sources of intense dust uplift are intermittent salt lakes. Experimental investigations show that aeolian drift of dust from the surface of these objects is the dominant mechanism of dust income into the environment that causes an extensive effect on pollution of neighboring lands and the atmosphere. Qualitative study of the processes of both one-time and long pollution is of interest.

As objects of investigation in this work, we took the active Salagaevskii Log tailing pond of the Salair Ore Mining and Processing Enterprise (Salair, Kemerovo Region) and Lake Selitrennoe (Altai Region).

Statement of the inverse problem

Analysis of data available on pollutant concentrations in the atmosphere and soil, as well as on the observation system, spatiotemporal structure of considered sources, and weather and climate conditions shows that it is convenient to interpret the processes involving one-time emissions and long-term operated sources of regional aerosol pollution within the framework of formulations of the inverse problems of pollutant transport.[9,10] The existing routes for field observations and convenient surface orientation of dust sources with respect to the wind directions prevailing in the region under study also point toward the appropriateness of this approach. Figure 1 shows the configuration of sources and the routes of soil and air sampling.

This information allows us to use superposition of concentration fields from a set of linear sources located in the crosswind direction to describe the processes of dust transport from an areal source. Then, the concentration $q_c(r)$ at the distance r from the areal source can be calculated as follows

$$q_c(r) = \int_0^L q_\lambda(r+L-\eta)\,d\eta\,, \qquad (1)$$

where r is oriented along the wind direction; L is the effective width of the areal source in the wind direction; $q_\lambda(x)$ is the concentration generated by a linear source. At this stage of the study, it is more convenient to present $q_\lambda(x)$ in an analytical form,[2,3] that could be as follows:

$$q_\lambda(x) = \frac{M}{K_1(1+n)\,x^\omega}\exp\left(-\frac{r_m}{x}\right), \qquad (2)$$

where

$$r_m = \frac{u_1 H^{1+n}}{(1+n)^2 K_1}\,;\quad \omega = 1 + \frac{W}{K_1(1+n)}\,; \qquad (3)$$

M is the source emission rate; K_1 and u_1 are the turbulent exchange coefficient and the wind velocity at the height of 1 m; n is the exponent in the power-law approximation of the wind speed; H is the height of a

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linear source; W is the rate of gravitational sedimentation of dust particles.

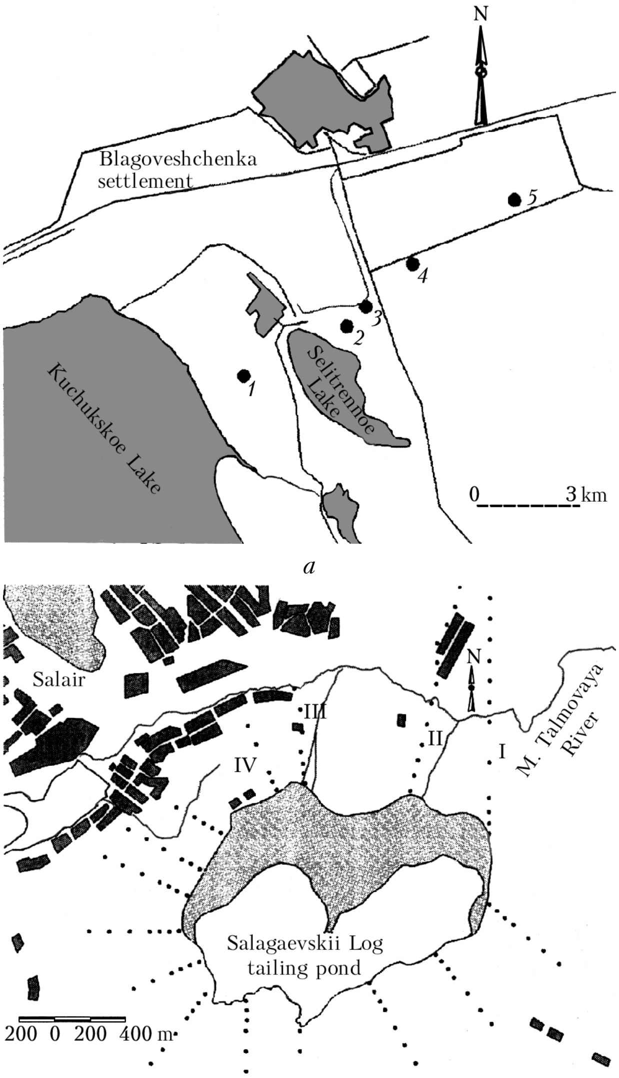

Fig. 1. Scheme of air sampling in the Lake Selitrennoe region (*a*) and soil sampling around Salagaevskii Log tailing pond (*b*): sampling points *1 – 5*.

By substituting Eq. (2) into Eq. (1) and applying the theorem on average from the integral calculus, we obtain

$$q_c(r) = \frac{ML}{K_1(1+n)(r+L-\lambda)^{\omega}} \exp\left(-\frac{r_m}{r+L-\lambda}\right), \quad (4)$$

where $\lambda \in [0, L]$.

Using the parameter aggregation procedure in Eq. (4), we obtain that

$$q_c(r, \boldsymbol{\Theta}) = \frac{\Theta_1}{(r+\Theta_2)^{\Theta_3}} \exp[-\Theta_4/(r+\Theta_2)]. \quad (5)$$

Here

$$\boldsymbol{\Theta} = (\Theta_1, \Theta_2, \Theta_3, \Theta_4), \quad \Theta_1 = \frac{ML}{K_1(1+n)},$$

$$\Theta_2 = L - \lambda, \quad \Theta_3 = \omega, \quad \Theta_4 = r_m.$$

In the general case, the parameter vector $\boldsymbol{\Theta}$ can be estimated by the least-squares method using the sequential analysis and the experiment planning procedures.[11,12] Making certain assumptions, we can simplify Eq. (5). In particular, for the lightweight dust fractions at low uplift height and relatively large r and Θ_2, we obtain

$$q_c(r, \Theta_1, \Theta_2) = \Theta_1/(r + \Theta_2). \quad (6)$$

At large distances from the areal source, the dependence on Θ_2 becomes weak. As a result, we have

$$q_c(r, \Theta) = \Theta/r. \quad (7)$$

Lake Selitrennoe

Lake Selitrennoe is situated about 3 km to the northeast from Lake Kuchukskoe. This lake is used for commercial production of sodium sulfate, and in the dry period it is a powerful source of fine dust. The dusting area can be about 6 to 9 km^2. The lake is elongated from the southeast to the northwest, and this fact allows us to use the regression dependence (5)–(7) to describe the dust concentration field at the prevailing wind direction. The dust was sampled onto filters sequentially at five sites on April 27 of 1997. There were almost no clouds during sampling. The sampling time at each site was 30 min.

The results of observations are given in Table 1. Figure 1*a* depicts the geometry of the sampling points. Analysis of Table 1 and Fig. 1*a* shows that the model (7) can be used for interpretation of the experimental data. To estimate the parameter Θ, it is sufficient to use a single observation point. Figure 2*a* depicts the reconstructed results on the near-surface dust concentration along the sampling route. As a reference point, we took point *2*, which is most informative in this case.

Table 1. Data of field measurements in the region of Lake Selitrennoe

Sampling sites	Local time of observation	Wind speed, m/s	Air temperature, °C	Distance from the lake, km	Mass concentration of dust, mg/m^3
1	08:30	4 – 6	14	1.5	0.01
2	10:15	6 – 8	14	0.5	0.85
3	11:20	6 – 8	15	1.2	0.32
4	12:30	6 – 8	16	3	0.13
5	14:00	8 – 10	17	6	0.08

N o t e . Site 1 is situated windward, other sites are situated leeward of the lake.

Comparison of calculated results with the measurement data at the control points *3–5* demonstrates quite close agreement between them.

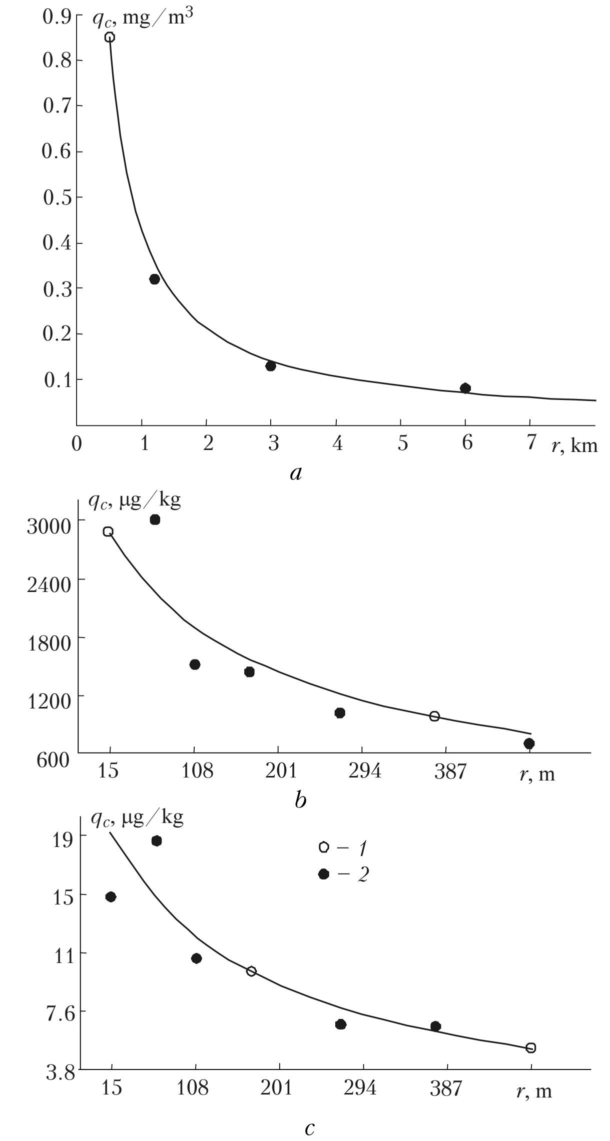

Fig. 2. Mass concentration of dust in air (*a*). Specific content of zinc (*b*) and cadmium (*c*) in soil: concentrations measured at reference (*1*) and control (*2*) points.

Salagaevskii Log tailing pond

The tailing pond is located in two natural ravines to the south from the Salair ore deposit (Salair, Kemerovo Region). The M. Talmovaya River flows on the valley at the foot of the northern slope. The tailing pond is tapered out by the natural slope from the south and bounded by an artificial 25–35 m high dam from the north and flanks. The pond dimensions are roughly 1500 m in the sub-latitudinal direction and 900 m from north to south. The total area of the tailing pond is 1.17 km^2. The volume of waste products accumulated by 2000 was about $20 \cdot 10^6$ m^3 ($35 \cdot 10^6$ t) (Ref. 7).

Soil around the tailing pond was sampled along 15 sub-radial profiles in the field season of 1999. A total of 108 point soil samples were collected from the area of more than 3.5 km^2. The content of heavy metals (Zn, Pb, Cu, Cd, As, Sb) in these samples was determined by the instrumental energy-dispersion X-ray fluorescence analysis (XRFA, was made by Yu.P. Kolmogorov, Institute of Geology SB RAS).

Tentative analysis of the data obtained showed that all heavy metal anomalies are concentrated to the north and northeast from the tailing pond, that is, in accordance with the direction of the prevailing wind.[7]

If we assume, for simplicity, that the dust drift from the constant-size surface is stationary, the level of heavy metal concentrations in soil should be proportional to the concentration in air, the effective height of dust uplift is low (within several meters), and the dust grain size distribution is mostly presented by the fine fraction, then the model (6) is quite applicable in this case. If we restrict our consideration to two observation points along one of the profiles, then for estimating parameters Θ_1 and Θ_2 it is sufficient to solve the following system of equations:

$$\Theta_1/(\Theta_2 + r_i) = y_i, \quad i = 1, 2, \qquad (8)$$

where r_1, r_2 are the distances to the tailing pond boundary ($r_1 < r_2$); y_1, y_2 are the specific metal contents at these points. From this we have

$$\Theta_1 = \frac{y_1 y_2 (r_2 - r_1)}{y_1 - y_2}, \quad \Theta_2 = \frac{r_2 y_2 - r_1 y_1}{y_1 - y_2}. \qquad (9)$$

Figures 2*b* and *c* show the reconstructed data on the Zn and Cd concentrations for the route *3*. Comparison of measurements at the control points with the data calculated by the model (6) demonstrates quite close agreement. Table 2 gives the estimates of the parameters Θ_1 and Θ_2 for the route *3*. The estimates of Θ_1 are proportional to the uplift intensity, and they allow the relative contribution of each element to be determined. The estimates of Θ_2 determine the position of an equivalent linear source about the nearest edge of the tailing pond. The estimates of Θ_2 made for Zn, Pb, Sb, and As, almost coincide and this suggests the conclusion about similar character of these elements transport.

Table 2. Estimates of parameters Θ_1 and Θ_2 for the route *3*

Element	$\Theta_1 \cdot 10^3$	Θ_2
Zn	496	156
Cu	27	361
Pb	156	152
Cd	4	256
Sb	5	197
As	14	204

Conclusion

The investigation carried out revealed rather simple regularities of one-time and long regional pollution from areal sources. The dependences obtained show that, in spite of the complex spatial and temporal structure of the considered sources, dusting processes can be described quantitatively within the framework of stationary modes. Transient nonstationary modes have relatively low weight.

Estimates of the parameters Θ_1 made using additional weather information and the results of heat-balance observations allow dust emission at one-time pollution of the atmospheric surface and boundary layers to be assessed. Estimates of the parameter Θ_2 allow effective description of the drifting processes from an areal source to be done in the approximation of a linear source.

To obtain general dependences, further investigations of dusting processes from areal sources should be conducted using the model of pollution from point sources (by the principle of superposition).

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