Retrieval of the concentration field of aerosol fallen on snow in the vicinity of the Barnaul Heat Power Station-2

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The comparison of experimental and calculation data on concentrations of aerosol, fallen on snow in the vicinity of Heat Power Station-2 (HPS-2) of Barnaul are presented. The scheme is presented of the fallen coal ash distribution at the territories of residential settlements and industrial area of Barnaul, as well as its northeast vicinity (including Ob' river), g/m^2. A simple universal 3D time-dependent model is used for calculating atmospheric aerosol transport and its fallout on the underlying surface. The model is based on the solution of the semiempirical equation of aerosol advection and admixture diffusion, accounting for its interaction with the underlying surface. The pollutant concentration in the atmosphere and quantity of the particles (or mass) fallen on the unit area of the underlying surface during winter are calculated. It is shown that the difference between theoretical and experimental data does not exceed 24%.

Introduction

The character of pollutant distribution in the atmosphere and fallout on the underlying surface is of great interest today.[1,2] Aerosol distribution in the atmosphere occurs through its advective transport by air masses and the diffusion due to turbulent air pulsations. If aerosol consists of large particles, the particles begin to sediment under gravity with a certain constant rate by the Stokes law. Naturally, almost all pollutants finally sediment on the Earth's surface; heavy ones sediment mainly under gravity and easy ones – in the result of the diffusion process.

Along with small scale diffusion, washing out the pollutant plumes, long-term fluctuations of wind speed and direction are of great importance in the theory of pollutant propagation. For this period, air masses, transporting pollutants from some source, change their direction and speed many times. Such many year changes are statistically described by a special chart, the so-called wind rose, where wind speed is proportional to the number of repetitive events related to the movement of air masses in a given direction. Hence, the chart maxima correspond to winds prevailing in the region.[3]

In this work, a simple universal 3D time-dependent model is proposed for calculating atmospheric aerosol transport and its fallout on the underlying surface. The model is based on the solution of the semiempirical equation of pollutant advection and diffusion with accounting for its interaction with the underlying surface. The calculation result is the pollutant concentration in the atmosphere and the number of particles (or mass) fallen on the unit area of underlying surface during the calculation period[1]:

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} + v\frac{\partial s}{\partial y} + (w - w_g)\frac{\partial s}{\partial z} + bs -$$

$$-\frac{\partial}{\partial z}k\frac{\partial s}{\partial z} - \mu_x\frac{\partial^2 s}{\partial x^2} - \mu_y\frac{\partial^2 s}{\partial y^2} = s_0(r,t), \qquad (1)$$

where s is the aerosol concentration; u, v, w are speed components; w_g is the rate of pollutant gravity sedimentation; b is the pollutant absorption coefficient; k is the vertical coefficient of turbulent diffusion; μ_x, μ_y are the horizontal coefficients of turbulent diffusion; $s_0(r,t)$ is the pollutant source. The boundary conditions for pollutants are the following[1]:

$$z = h, \quad k\frac{\partial s}{\partial z} = 0;$$

$$x, y = d; \quad \mu_x\frac{\partial s}{\partial x} = 0, \quad \mu_y\frac{\partial s}{\partial y} = 0.$$

Here h is the pollutant area height and d is its horizontal size. The lower boundary conditions for pollutants have the form[1]

$$z = z_1, \quad k\frac{\partial s}{\partial z} + w_g s = \beta s,$$

where z_1 is the roughness parameter; β is the variable having the speed dimensionality and characterizing the interaction of the pollutant with the underlying surface. The larger β, the more pollutants sediment on the underlying surface. There can be found $\beta = 0.05$–1 m/s for land and $\beta = 1$ m/s for water surface in literature.[1] Rates of gravity sedimentation for different types of aerosols are given in Ref. 4.

Based on the considered model, programs for calculating pollutants distribution in the atmosphere

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and their fallout on the underlying surface have been constructed at IWEP SB RAS.

1. Results of testing programs

The monotonic one-dimensional scheme with directed differences of the second order of approximation is given in Ref. 5 for calculating terms with the 1st derivative in differential equations. By analogy with this scheme, a 3D difference scheme of the 2nd order of approximation was constructed for calculating advective terms in the pollutant transport equation. To test this scheme, the distribution of pollutants was calculated for the case of symmetric wind rose, when wind direction frequencies are the same for each of the eight compass rhumbs. As a result, symmetric distribution of pollutant concentration isolines in the form of regular octagon was obtained. In addition to this scheme, a scheme with central differences of the 2nd order of approximation monotone at small steps was used. The programs were time-consumption optimized. The wind speed components and vertical diffusion coefficient in the considered model can be calculated with the atmospheric boundary layer model.[6] These parameters can also be set as constant within the calculated layer.

The programs were tested for calculating pollutant fallouts on snow by numerical simulation.

There are reference data in the literature on the falling on snow of iron compounds from a large smelter and the volatile ones from a heat power station (HPS), which are the main pollution sources in the region of their location,[3] as well as data on parameters of pollutant sources and wind direction repetitiveness in winter period for the regions under study.

The maximal height of the smelter chimneys is 100–120 m. Particle sizes are larger than 1 μm. South and south-west winds prevail in the region of smelter location. The repetitiveness of the above winds is 75% in the period of snow accumulation; mean wind speed is 5 m/s. A stable snow cover is kept for 120 days. A sampling territory with the area of 50×30 km was chosen with accounting for prevailing wind directions in winter. The prevalence of iron in smelter emissions was ascertained from the analysis. Distinct zones of snow cover pollution, elongated in the direction of prevailing winds up to 35–40 km, were revealed.

The calculation area was 50×25 km in horizontal and to 300 m in vertical. The program calculates pollutant fallout on snow for the entire winter period (120 days). The number of days with a definite wind direction was determined according to the wind rose. Then the wind direction changed automatically according to the wind rose. For the above area, the calculation of aerosol fallout on snow for 4 months consumes less than 1 min, which allows multiple calculations.

While calculating, the values of horizontal diffusion coefficient μ and the parameter of interacting with underlying surface β were determined, at which calculation results best agreed with the experimental ones.[3] To compare the results, the correlation was calculated between calculated and experimental data on pollutant fallouts on snow along the prevailing wind direction, in our case, south-west. The best results correspond to $\mu = 2000$ m^2/s and $\beta = 0.05$ m/s (correlation factor is 0.99).

The chimney heights of the HPS are 150–250 m; particle sizes exceed 1 μm. In the region of the station location, south-west and west (26%) and east (30%) winds prevail; the repetitiveness of other wind directions is 3–9%; mean wind speed is 5 m/s. A sampling territory was chosen with accounting for prevailing wind directions in winter. The snow was sampled along 8 routes radiated from the HPS. The volatile ash dominates in HPS emissions; 100 tons of the ash is emitted every day into the atmosphere. The calculation area was 50×25 km, and to 300 m in vertical; the calculation of aerosol fallout on snow for 4 months consumes less than 1 min, which allows multiple calculations.

According to the calculations, the best results for the Heat Power Station, running on coal, correspond to $\mu = 1000$ m^2/s and $\beta = 0.1$ m/s.

Numerical calculations by our model (Fig. 1) showed a good agreement with the reference experimental data.

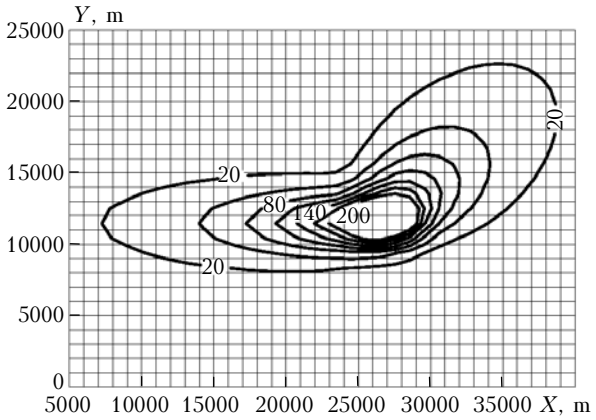

Fig. 1. Isolines of volatile ash fallen on snow during winter (t/km^2).

The diffuse area is northeast and westward expanded in agreement with the prevailing wind directions. The calculated trace areas, corresponding to definite values of slack supplies, differ from experimental ones not more that by 17% (Table 1).

Table 1. Trace areas, corresponding to definite values of slack supplies

Area profile, t/km^2	Area, km^2 (experimental data)	Area, km^2 (calculated data)
> 160	18	15
> 80	61	54
> 40	140	130
> 20	350	300

2. Calculation of the coal ash concentration field (HPS-2, Barnaul)

Using programs, designed at IWEP SB RAS on the base of the considered model, the pollutant (coal ash) fallout on snow during the winter (11.2004–03.2005) from HPS-2, Barnaul, was calculated. The HPS-2 is situated in the northeast part of the city within the urban area. The parameters of pollutant sources have been determined from the inventory data. Kuznetskii and Kemerovo coals are used at the HPS-2, particles of 10–20 μm in size prevail in their disperse composition.[7] As was shown in Ref. 4, the rate of gravity sedimentation w_g for such particles ranges from 0.003 to 0.012 m/s; for our calculations, $w_g = 0.007$ m/s was taken.

The wind rose for the considered period was calculated by the data of Barnaul meteorological station. The south (25%), southwest (24%), and west (12%) winds were prevailing, other directions were characterized by repetitiveness of 1–9% (north direction: 1%, northeast one: 2%, northwest one: 4%, east one: 9%, and southeast wind: 8%). The mean wind velocity for the period was 2.1 m/s. In the period of calculations, the weather dominated in 90% of cases, determined either by the Siberian anticyclone periphery or low-gradient low-pressure field. In such conditions, the vertical component of wind speed did not exceed centimeters or even fractions of centimeter per second.[8] In our calculations, the vertical speed $w = 0.005$ m/s was taken.

Equation (1) was digitized by spatial variables and solved by the method of straight lines. To integrate the system of ordinary differential equations, the Runge–Kutta method of the 2nd order of approximation was used. To calculate the advective terms in the transport equation, a monotonic 3D "directed differences" scheme of the 2nd order of approximation was used. The calculation area was 8×12 km $\times 360$ m. The program computes the pollution fallout on snow for the whole winter period (150 days). The number of days with a definite wind direction was determined by the wind rose; then wind direction changed automatically according to the wind rose. For the above area, the calculation of the aerosol fallout on snow for 5 months consumes no more than 3 min, which allows multiple calculations. While calculating, the values of horizontal diffusion coefficient μ and the parameter of interacting with the underlying surface β were determined, at which calculation results best fit the experimental ones.[3] The calculation result is the mass of pollutant, fallen on the unit area of the underlying surface during the calculations. Empirical model coefficients have been chosen from the comparison of calculated and experimental data. The best results correspond to $\mu = 150$ m^2/s and $\beta = 0.1$ m/s.

The corresponding calculated concentration isolines of the coal ash (g/m^2) from the Barnaul HPS-2, fallen on snow during winter, are shown in Fig. 2.

As is evident, the most part of the coal ash fell just near the station (500–750 g/m^2); 100–400 g/m^2 fell on the territory of the industrial zone, Ob' river, and its bank regions. The HPS-2 emissions mostly influence the residential area in the northeast part of the town at winds of the east quarter, registered in 19% of cases, and in calm (15%); 50–300 g/m^2 of the pollutant fell on the residential territory.

Experimental and calculated aerosol concentrations at different distances from the source are given in Table 2.

Sampling was carried out in the end of winter 2004/05 (March 5–12, 2005). Sampling routes passed on leeward in accordance with the prevailing wind direction. The concentration value at point 1, was obtained when averaging samples taken at seven points, ranged 1 km from the source, at the distance not exceeding 70 km from the principal WNW-directed route. Snow samples at these points were taken throughout the snow depth in the form of cores with 20×20 cm base area; 3–4 samples were taken at each point. The snow cover depth varied from 50 to 70 cm. To increase the reliability of the results, additional sampling was carried out within the 3–5 m radius of a chosen point with further data averaging. Each sample was placed into a chemically inactive container and kept at a temperature between −5 and −20°C till the analysis. Snow was melting at the room temperature in a glass container. To obtain the solid residue, filtration method was used: snow water was filtered through a paper filter with pores of 2 μm in diameter. The filter with the residue was naturally dried. To obtained the aerosol mass concentration, filter mass was measured before and after the filtration with the analytical balance with a weighing accuracy about 10^{-8} g.

Concentrations at points 2, 3, and 4 were obtained in the following way. Snow cores of 20×20 cm in area were taken from the entire snow depth by the "envelope" method. The lowest, ground-adjacent sample layer of 1.5–2 cm in thickness was cut off. The sample was placed on preliminary weighted dry "F" filters in Buchner funnels in laboratory conditions. The snow melting and resulting water filtering proceeded simultaneously, essentially decreasing losses of some aerosol components in dilution. Such losses can be especially significant, if aerosol particles are contained in acidulous water for a long time.[9] After drying, the insoluble residue (not less than 85% of dry mass) was scraped off into glass boxes. The concentration of the fallen matter (g/m^2) was determined from weighing samples and exposed filters.

Point 1 corresponds to the west-north-west wind direction while points 2, 3, and 4 – to the north-north-west one.

Conclusion

The used technique allows the retrieval of the concentration field of aerosol, fallen on snow from a single source, and determination of coefficients of diffusion and pollutant interaction with the underlying surface.

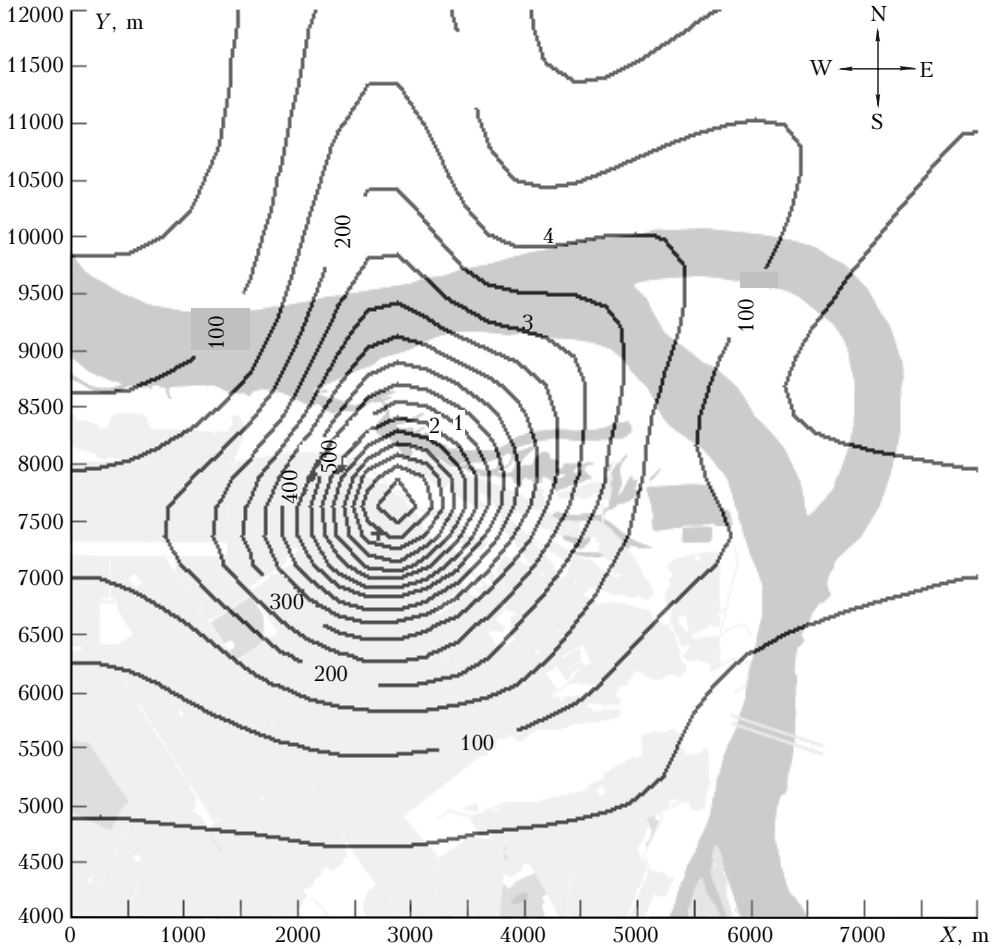

Fig. 2. Scheme of the calculated distribution of the coal ash content (the source coordinates are 2700; 7400).

Table 2

Sampling point No.	Distance from the source, km	Measured aerosol mass per unit area, g/m^2	Calculated aerosol mass per unit area, g/m^2	Relative error, %
1	1(WNW)	500	500	0
2	1(NNW)	653	550	23.4
3	2(NNW)	255	250	1.9
4	3(NNW)	123	125	1.6

The conducted numerical calculations have shown a good agreement with available experimental data (see Table 2). The diffusion area corresponds to prevailing wind directions. The discrepancy between theoretical and experimental data does not exceed 24%. Point 2 is located directly under the Ob' bank of 24 m in height; the conditions for the pollutant deposition here differ from those at other points. Possibly, that is why the accuracy here is the lowest.

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