Bull. Nov. Comp. Center, Num. Model. in Atmosph., etc., 10 (2005), 77–83

Regularities of the pollution formation in the axial part of the East-Ural radioactive trace*

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Abstract. Models for the assessment of regional pollution of the territory from a high-altitude aerosol source were constructed on the basis of solutions of the semi-empiric equation of turbulent diffusion. The models were tested using the observational data from the East-Ural radioactive trace, which was formed as a result of explosion of a reservoir with radioactive waste on PA Mayak in Chelyabinsk region in 1957. The possibility of prediction of pollution in the trace axial part using the obtained estimates of parameters is shown.

1. Introduction

The problem of determining the quantitative characteristics of radioactive pollution of a natural environment as a result of nuclear explosions and accidents is rather urgent. Principle, the use of methods of the direct transfer of pollutants gives the opportunity of a correct description of concentration fields, but in some cases this approach presents significant difficulties. First of all, it is the possibility of providing the required input information for the used models. There is an uncertainty as regards the height and power of an explosion, the size of distribution of radioactive particles and the determination of the current meteorological conditions. The use of additional experimental information about the fields of radioactive pollution makes it necessary to develop reconstruction models [1, 2]. The principles of constructing models of this type vary from descriptions of models of pollution processes to observational data [3–5].

2. The description of a radiation accident and experimental studies

As a result of the technical failure on September 29, 1957, an emergency discharge of radioactive substances (20,000,000 Ci) from the waste storage place into the environment occurred at PA Mayak; 18,000,000 Ci fell out not far from the place of explosion. The other 2,000,000 Ci rose to the height of 1–2 km and formed a radioactive cloud, which was born by the wind in the north-east direction. Within 10–11 hours, fallouts from this

*Supported by the Programme of Fundamental Research of Presidium of SB RAS, project 13.5 and ISTC project No. 2311.

cloud formed the East-Ural radioactive trace (EURT) in the northern part of Chelyabinsk region and southern parts of Sverdlovsk and Tyumen regions. Six-eight hours after the formation, the cloud was at a distance of 350 km with ^{90}Sr pollution density of 0.1 Ci/km^2 on the trace axis [6, 7]. During the first days after the accident the survey of the trace was performed at a distance up to 350 km from the pollution source. The pattern of distribution of radioactive substances was defined more exactly during subsequent years by aero-gamma and automobile beta-surveys [6–8].

The discharged mixture contained the maximal amounts of the following isotopes: ^{144}Ce + ^{144}Pr — 66 %, ^{95}Zr + ^{95}Nb — 24.9 %, ^{90}Sr + ^{90}Y — 5.4 %. The radioactive substances made part of the liquid and solid aerosols in well-soluble compounds — nitrates [6, 7, 9].

On September 29, 1957, the weather in the area, where PA Mayak is situated, was characterized by a rapidly moving cyclone. The atmospheric conditions at a height up to 2 km could be described using the data of temperature-wind probing at the nearest aerological station Vysokaya Dubrava [10]. At a height of 10–12 m, the wind speed was 5 m/s, and at the heights exceeding 500 m, the wind speed was higher than 10 m/s. The character of the cyclone movement on September 29 and 30, 1957, caused the right turn of the wind along the movement of the depositing radioactive cloud and resulted in the curvature of the EURT trajectory.

3. Setting inverse problem of aerosol pollutants transfer

Attempts to carry out the direct simulation of the processes of propagation of radioactive pollutants discharged into the atmosphere as a result of an explosion of the reservoir with a radioactive waste encounter a number of rather difficult questions associated with a correct description of initial distribution of aerosol pollutants in the forming cloud and the dispersion composition characteristics [6, 7]. Some improvement is also required in the description of the current meteorological conditions. Such a situation may require setting the inverse problems of pollutants transfer in the boundary atmospheric layer using the data of measuring the locality pollution and a priori data about the source parameters.

Preliminary study of parameters of an explosion of the reservoir with a radioactive waste and meteorological processes that occurred at that time allowed us to reveal and to define more exactly the main factors of the formation of a pollution pattern. Further analysis of observational data along the trace axis demonstrated expediency of distinguishing between the farthest and the nearest pollution zones.

1. According to the data of experimental studies, the efficiency of deposition of an aerosol pollutant depends on the combined effect of the two factors:

the vertical turbulent exchange and the gravitation deposition of particles [11]. In the farthest area, the main portion of the pollutant cloud was already in the lower part of the boundary atmospheric layer. In this case, it is necessary to take into account the changes in the vertical turbulent exchange and the wind speed with height. For the degree approximations of the wind speed and the vertical turbulent exchange, the total (by time) near-ground concentration of a heavy pollutant for a point source with the unit power and the height H is presented in the following form [12]:

$$q_w(x,H) = q(x,H)\,\chi_w(x,H), \tag{1}$$

where

$$q(x,H) = q_{\max}\exp\left[\frac{3}{2}\Big(1-\frac{x_{\max}}{x}\Big)\right]\cdot\Big(\frac{x_{\max}}{x}\Big)^{3/2},$$

$$x_{\max} = \frac{2u_1H^{1+n}}{3k_1(1+n)^2}, \qquad q_{\max} = \frac{0.116(1+n)^2}{u_1H^{1.5(1+n)}}\sqrt{\frac{k_1}{k_0u_1}},$$

$$\chi_w(x,H) = \Big(\frac{1.5x_{\max}}{x}\Big)^{\rho}, \qquad \rho = \frac{w}{k_1(1+n)},$$

w is the sedimentation rate of particles, u_1, k_1, k_0, are the wind speed and turbulent exchange coefficients at certain heights, n is the degree index in the wind speed approximation.

Then the total density of aerosol fallouts will by expressed by the relation

$$p_1(x) = C\int_0^h Q(H)\,q(x,H)\,\chi_w(x,H)\,dH. \tag{2}$$

Here C is the coefficient of the pollutant interaction with the ground surface, h is the height of the pollutant cloud, $Q(H)$ is the amount of pollutant at the height H.

Taking into account the fact that $\exp(-x_{\max}/x) \to 1$ at $x \to \infty$, from (2) it follows that

$$p_1(x) \approx \frac{\theta_1}{x^{1.5+\theta_2}}, \tag{3}$$

where

$$\theta_1 = 1.5^{\rho}C\int_0^h Q(H)\,q_{\max}(H)\,\exp[1.5(1-x_{\max}(H)/x)]\,x_{\max}^{1.5+\rho}(H)\,dH,$$

$$\theta_2 = \rho.$$

2. In the nearest area, the aerosol fallouts of the pollutant are presented by particles of larger fractions falling onto the ground from considerably larger heights. Probably, in this case it is sufficient to consider the wind speed u and the turbulent exchange coefficients k_y, k_z constant for different heights. Then the total (by time) near-ground concentration will be described by the following expression [12]:

$$q_w(x,H) = \frac{2Q(H)k_z}{\sqrt{\pi}\sigma_1 uH^2 k_y} e^{-\sigma^2}\,[1-\sigma_2\sqrt{\sigma_1}\,r(\sigma)], \tag{4}$$

where

$$r(\sigma) = e^{\sigma^2}\,[1-\operatorname{erf}\sigma], \quad \sigma = \frac{1}{\sqrt{\sigma_1}} + \sigma_2\sqrt{\sigma_1}, \quad \sigma_1 = \frac{4k_z x}{uH^2}, \quad \sigma_2 = \frac{wH}{4k_z}.$$

Taking into account the fact that at a significant distance from the source $1-\operatorname{erf}\sigma \approx 0$, $\exp[-uH^2/(4k_z x)] \approx 1$, we obtain the following relation for the density of fallouts:

$$p_2(x) \approx \frac{C}{x}\exp\left[-\frac{w^2}{4k_z u}x\right]\int_0^h f(H,x)\,dH = \frac{\theta_1}{x}e^{-\theta_2 x}, \tag{5}$$

where

$$f(H,x) = \frac{Q(H)}{2\sqrt{\pi}k_y}e^{-2wH}\exp\left[-\frac{uH^2}{4k_z x}\right], \;\; \theta_1 = C\int_0^h f(H,x)\,dH, \;\; \theta_2 = \frac{w^2}{4k_z u}.$$

According to the data of the density observations, the estimates of parameters of regressions (3), (5) can be found by the least-squares method in an explicit form from the solution to systems of nonlinear equations.

4. The reconstruction of the deposition density of radionuclides in the axial part of the trace

The results of experimental investigation of the territory presented in the form of tables in [6], which were prepared on the basis of maps of the 1959 and 1997 radiation situations [8], were used for the numerical analysis of the soil pollution data within the EURT.

1. For the data of the 1959 map, evaluation of parameters of regressions (3), (5) in the farthest and the nearest areas was performed in each case by two reference points on the trace axis located quite optimally relative to each other [13]. It should be noted that the ratio of concentrations at the reference points for the nearest area is 10 times, and that for the farthest area — 500 times. This is indicative of rather large sedimentation rates of aerosol particles carrying radionuclides in the distance ranges in question.

Analysis of the simulation results presented in Figure 1 reveals quite a satisfactory compliance of calculations with observations at control points. This conclusion is also confirmed by the value of the following integral index:

$$k = \frac{1}{n}\sum_{j=1}^{n}\frac{c_j}{p(r_j,\vec{\theta})}, \tag{6}$$

where n is the number of control observational points, c_j are concentrations measored.

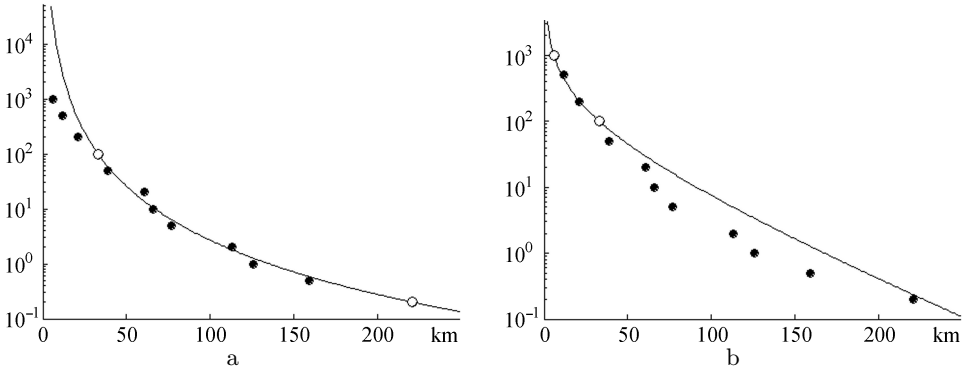

Figure 1. The density of radioactive pollution of soil (Ci/km^2) on the axis of the Eastern-Ural radioactive trace according to the data of the 1959 radiation situation: a) the farthest area of the axial part of the trace, b) the nearest area. The results of experimental studies in reference points and control points of the trace axis are marked as ∘ and •. The deposition density reconstructed by the models (3), (5) is drawn with solid line

In the nearest area, $k = 1.058$. In the farthest area, $k = 0.983$. This means that there is practically no systematic divergence between the used models and the corresponding observational data.

2. Figure 2 presents the results of evaluation of the pollution density in the axial part of the trace in the farthest area using the 1997 observational data.

In this case, the compliance with observational data is also rather high. The integral index $k = 0.979$.

As parameter θ_1 is proportional to the pollutant discharge power, we can perform the extrapolation of the pollution pattern for 1997 with allowance for the results of evaluation of the parameters θ_1, θ_2 using the data of the 1959 map. Figure 2b presents a version of the calculation of the farthest portion of the trace axis with an additional use of only the law of radioactive decay for ^{90}Sr. On the whole, the calculation curve (dash line) passes somewhat lower than the values of the deposition density presented in the 1997 map. In this case, $k = 1.45$.

In the second version of the calculation in Figure 2b, the density of radioactive pollution for 1997 calculated using only one reference point is presented. The parameter θ_2 was considered to be equal to its value obtained using the data of the 1959 map for the farthest part of the trace. In this version of the calculation, the level of compliance of the reconstructed and experimental data considerably increases. The value of the coefficient k in this case was 1.15. A higher accuracy of evaluation is explained by practically full absence of a contribution of other radionuclides to the locality pollution in 1997 as compared to ^{90}Sr.

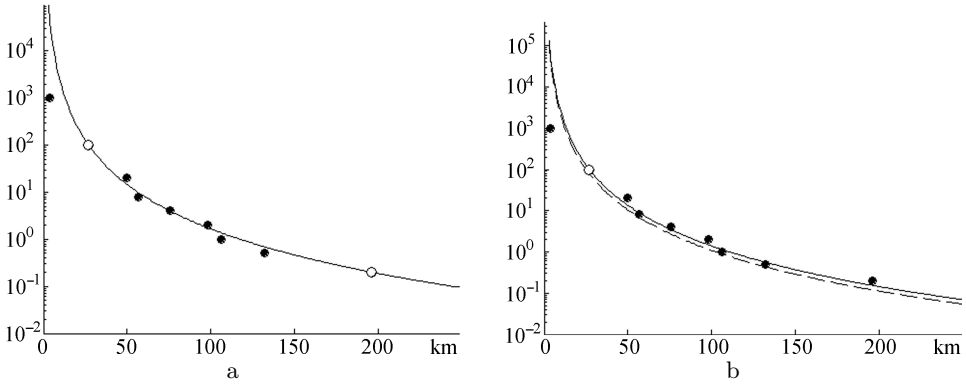

Figure 2. The density of radioactive pollution of soil (Ci/km^2) on the axis of the EURT according to the data of the 1997 radiation situation reconstructed on the the basis of the model (3): a) evaluation by two reference points; b) evaluation using one reference point (solid line) and the predicted pollution (dash line) for 1997 taking into account the law of radioactive decay for ^{90}Sr

5. Conclusion

The performed theoretical study and analysis on the basis of the data of field observations demonstrates the possibility of quite an adequate reconstruction of the pattern of regional pollution of locality from a high-altitude aerosol source within the scope of rather simple regression dependencies arising from the properties of solutions of the semi-empiric equation of turbulent diffusion. The uncertainty in setting the spatial structure of the source and the characteristics of dispersion composition make it necessary to distinguish between the nearest and the farthest areas of aerosol fallouts of radionuclides and the description of the pollutant transfer processes in the boundary atmospheric layer with different degrees of detailing. The efficiency of evaluation of the pollution levels in the axial part of the trace in the proposed ranges of distances from the source was shown. It should be noted that the procedure of aggregation of complexes of unknown parameters allows us to considerably decrease dimensions of solvable inverse problems of falling out of aerosol pollutants.

The relation between the estimates of the parameters θ_1 obtained using the 1959 and 1997 maps for the farthest area is completely described by the radioactive decay law for ^{90}Sr. It should be also noted that the parameters θ_2 characterizing the form of curve (3) practically coincide for these periods of observations. Summing up all the above, we can conclude that the processes of washout and deflation of radionuclides in this part of the trace axis did not produce a significant influence on the change in the density of radioactivity, and relation (3) can be used for the prediction purposes.

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