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Reconstruction of fields of poly-dispersive impurities falls from high aerosol sources*

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Abstract. This paper deals with mathematical models of reconstructing the fields of poly-dispersive impurities falls from instant sources as applied to traces of nuclear explosions and accidents. In approximation of a semi-kinematics model of aerosol impurities sedimentation in the atmosphere, the relations to evaluate the fields of impurity concentrations were obtained. Based on observational data of radioactive contamination of territories, the proposed evaluation model was tested as applied to a ground nuclear explosion set off on August 29, 1949 on the Semipalatinsk test site. With the help of asymptotic relations, the traces of the underground nuclear explosion "Chegan" were numerically analyzed. The observational data of contamination in the area of the East-Ural radioactive trace were interpreted. Using the obtained estimations of parameters, it is possibile to predict the radioactivity levels for the central part of the trace.

1. Introduction

The problem of defining the quantitative characteristics of radioactive contamination of environment resulting from nuclear explosions and accidents is urgent. Application of methods of direct modeling of contaminating impurities transport makes it possible to correctly describe concentration fields. However, in some cases this approach involves certain difficulties.

In the first place, this is a possibility to provide the models used with a required input information. There is an uncertainty in defining a height and power of an explosion, a distribution of radioactive particles in their sizes, in fixing the current meteorological conditions.

However, attracting supplementary experimental data about radioactive contamination fields brings about the necessity in development of reconstruction models [1, 2]. Concepts of constructing such a type of models are diversified and are a sort of compromise between the descriptions of contamination processes and observational data [3, 4].

By now one can find a variety of publications dealt with experimental studies on radioactive contamination of territories resulted from the nuclear explosions set off. Numerical analysis of this information based on model presentations of impurities propagation process is without doubt of interest

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both for solving many practical tasks and for studying turbulent properties of the atmosphere.

2. Statement of the inverse problem of poly-dispersive impurity transport

In order to describe the impurity propagation process, a semi-kinematics approximation is used, i.e., it is assumed that the turbulent dispersion occurs only in the horizontal directions, but in vertical, particles move with constant Stokes' velocity. A preliminary analysis of experimental data about traces of radioactive impurities falls resulted from nuclear explosions show that the quantitative description of dispersive distribution of particles composition in the original cloud is of considerable importance. It is convenient to set the initial distribution of aerosol impurity in a source with the sedimentation velocities w as the following two-parametric function [5, 6]

$$N(w) = \frac{a^{n+1}}{\Gamma(n+1)}\, w^n\, e^{-aw}, \quad n \geq -1, \quad a = \frac{n}{w_m}, \tag{1}$$

where the parameter w_m characterizes the velocity of an impurity that dominates in the quantity of particles, n is the degree of homogeneity of the impurity particles distribution by the velocities w, $\Gamma(x)$ is the Euler gamma-function.

In this case, the surface concentration of a poly-dispersive impurity is found from the formula

$$\sigma(x,y) = \int\limits_0^\infty \int\limits_0^\infty w\, q(x,y,0,w,t)\, N(w)\, dw\, dt, \tag{2}$$

where $q(x,y,0,w,t)$ is the volumetric concentration described by the equation,

$$\frac{\partial q}{\partial t} + u(z)\frac{\partial q}{\partial x} - w\frac{\partial q}{\partial z} = K_x\frac{\partial^2 q}{\partial x^2} + K_y\frac{\partial^2 q}{\partial y^2}, \tag{3}$$

with initial and boundary conditions,

$$q|_{t=0} = Q\delta(x)\delta(y)\delta(z-H), \tag{4}$$

$$q|_{z>H} = 0; \quad q \to 0 \quad |x|, |y| \to \infty, \quad t \to \infty. \tag{5}$$

Here $u(z)$ is a horizontal wind speed component, K_x, K_y are turbulent exchange factors along the axes x, y,

$$K_x = \alpha U_z^2 \frac{H-z}{w}, \quad K_y = \beta U_z^2 \frac{H-z}{w}, \tag{6}$$

$$U_z = \frac{1}{H-z} \int\limits_z^H u(\xi)\, d\xi.$$

The direct calculation of functional (2) by equations (1), (3)–(6) involves certain difficulties: supplementary simplifications are necessary. In particular, if we restrict ourselves to an asymptotic representation for axial concentrations, then for large z the major part of expression (2) is given in the form [6]:

$$\sigma(x,0) = \frac{QHU_0 N(\frac{HU_0}{x})}{\sqrt{2\pi\beta} x^3}. \tag{7}$$

Assuming the power of the source Q to be a function of the height h, then with allowance for (1), (7) we arrive at the following relations for calculation of the density of poly-dispersive impurity fall along the axis of a trace from a distributed source

$$P(x,\vec{\theta}) = \frac{\theta_1}{x^2} \int\limits_{H_1}^{H_2} Q(h) \Big(\frac{h}{x}\Big)^{\theta_2} \exp\Big(-\theta_3 \frac{h}{x}\Big)\, dh, \tag{8}$$

where

$$\theta_1 = \frac{(\alpha U_0)^{n+1}}{\sqrt{2\pi\beta}\Gamma(n+1)}, \quad \theta_2 = n+1, \quad \theta_3 = aU_0. \tag{9}$$

The vector of unknown parameters $\vec{\theta}$ is evaluated by the method of least squares based on the criterion

$$J(\vec{\theta}) = \sum_{m=1}^{M} \sigma_j^{-2} [r_j - P(x_j, \vec{\theta})]^2 \to \min_{\vec{\theta}\in\Omega}. \tag{10}$$

Here r_j is a measured contamination level at the point x_j.

3. Numerical reconstruction of the axial trace of the nuclear explosion of 29 August 1949

In order to reconstruct the density of radioactive falls along the axis of the trace of the first nuclear test, we made use of the information from [7, 8]. The explosion was carried out at a height of 30 m, its power being nearly 22 kg. The upper edge of the cloud reached a height of 7.5–9 km. Based on available data of the air and ground radioactive prospecting a diagram of changing the power of gamma radiation along the axis of the trace was constructed, from which it is apparent that a maximum of radioactive contamination of

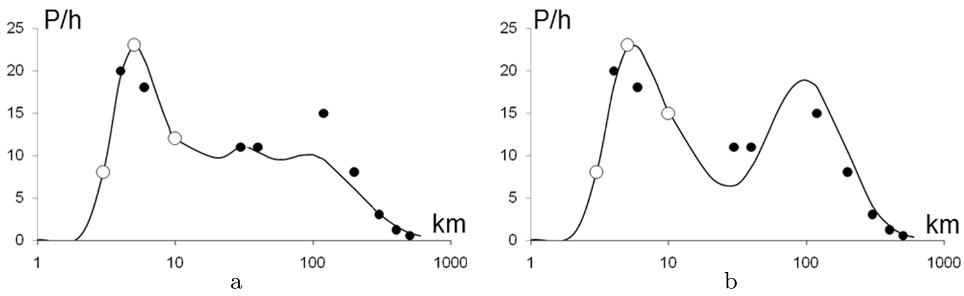

Figure 1. Reconstruction of the axis of trace of explosion of 29.08.1949, where • are control points, ◦ are control observational points and — is a result of numerical modeling. A relative distribution of trace-level activity: (a) $Q(0, 0.4) = 1$, $Q(0.4, 1.5) = 4$, $Q(1.5, 8) = 10$; (b) $Q(0, 0.9) = 1$, $Q(0.9, 4) = 10$, $Q(4, 8) = 15$

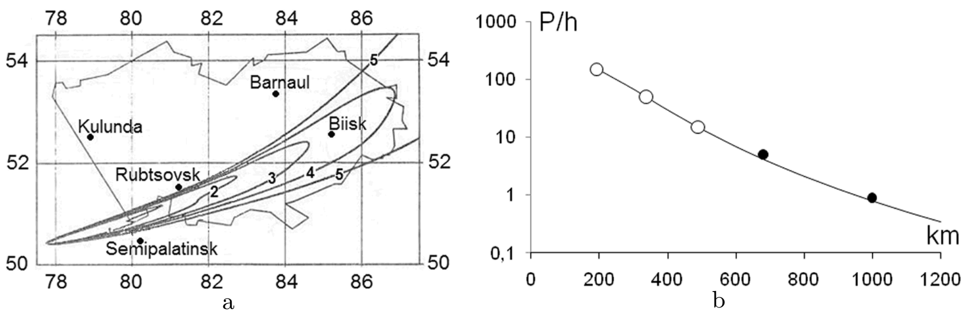

Figure 2. Cs-contamination density field for the instant of explosion on the Altai territory: (a) 1—150 mCi/km^2, 2—50 mCi/km^2, 3—15 mCi/km^2, 4—5 mCi/km^2, 5—1 mCi/km^2 [8]; (b) reconstruction of a remote axial part of the trace

the territory locates at 4–5 km from the site of explosion. Further the power was basically diminishing.

Based on the available observational data and on model (8)–(10), the axial concentration presented in Figure 1a, was reconstructed with a constrained number of control points.

An analysis of the simulation results reveals a satisfactory agreement of the measured and the computed values of activity at control measurement points. A sharp deviation is observed at a point remote from the explosion site at a distance of 120 km (the village of Dolon), which can be associated with excess washing-out by rain of nuclear explosion products from a passing trail of a cloud. It should be noted that another reason of such a deviation can also be not quite an adequate description of activity in height, which is confirmed by the results of numerical modeling (Figure 1b).

With the data from [8], Figure 2 presents the results of numerical reconstruction based on the model of Cs^{137} contamination density on the Altai territory given for the instant of explosion.

4. Numerical analysis of traces from the underground nuclear explosion "Chegan" (No. 1004)

The explosion was carried out for industrial purposes for extracting data about deep craters formation. A mechanical effect of a nuclear explosion of 140 kt strength that was laid at a depth of 178 km has formed a crater of 100 m deep and 520 m in diameter of the ground bulk crest. The explosion cloud having reached a height of 5 km divided into two clouds according to the wind directions at different heights thus forming "northern" and "southern" branches of radioactive falls [9]. A sharp turn of the wind following an increase in height resulted in the radioactive trace formation of a complicated configuration. The explosion cloud bottom being in a layer of 250 m up to 2500 m has formed "a northern branch" of the trace, while its upper part has formed "a southern branch". Figure 3 with model (8)–(10) presents the results of reconstructing the strength of gamma radiation doses along the axes of these traces.

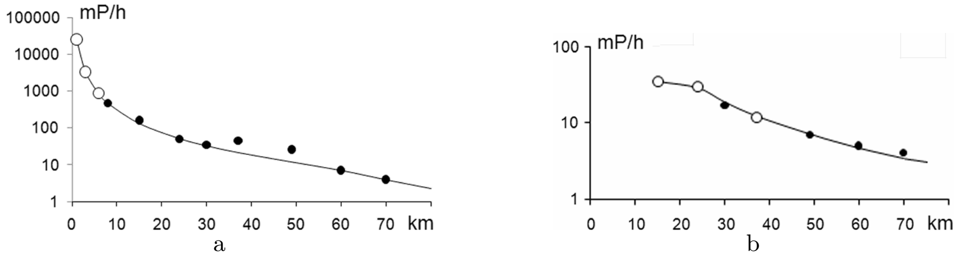

Figure 3. Reconstruction of the axis of the trace of explosion No. 1004 (15.01.1965): (a) Northern branch and (b) Southern branch

A relative distribution of activity in the explosion cloud was given by the following relation

$$Q(z) = 1/z, \quad z \geq 0.1 \text{ km}.$$

Analysis of the simulation results shows a sufficiently high level of agreement with the measurements data. According to the obtained estimations of parameters (9), a dispersive composition of particles fallen varies over wide limits. A near zone of falls was formed of particles fractions with rather high fallout velocities.

It should be noted that for explosion No. 1004, tritium fallouts in the remote trace zone were measured as well [10]. Mechanisms of its fallouts in the remote axial part of the trace are satisfactorily described by the dependence

$$P(x, \theta) = \frac{\theta}{x}. \tag{11}$$

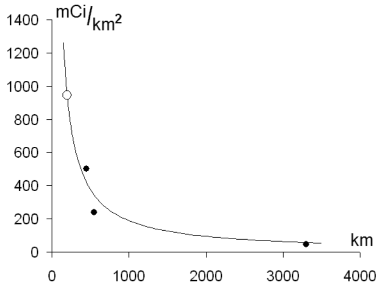

Figure 4. Tritium fallouts in the remote axial part of the trace of explosion No. 1004

Here x is a distance from the source, θ is an unknown parameter, evaluated from the observational data.

Relation (11) expresses the dynamics of measurement of concentration of a weakly settling impurity in the mixing layer at large distances from the source.

5. The East-Ural radioactive trace

On 29 September 1957, a technical trouble on the test site "Mayak" resulted in an accident ejection of 20 MCi radioactive substances from radioactive wastes storage into environment, 18 MCi falling near to the site of explosion. The rest 2 MCi having raised a height of 1–2 km formed a radioactive cloud, which under the action of wind was spreading in the north-east direction. After 10–11 hours falls from this cloud formed the East-Ural radioactive trace (EURT) in the North of the Chelyabinsk region, southern areas of the Sverdlovsk and the Tyumen regions (Figure 5). After 6–8 hours after its formation the cloud has moved to a distance of 350 km with contamination density 0.1 Ci/km^2 of ^{90}Sr on the axis of the trace [11]. Soon after the accident took place, measurements of the trace at a distance of up to 350 km from the contamination source were taken.

In the sequel, the picture of radioactive substances distribution was adjusted by aero-gamma and motor vehicle beta-surveys.

For the numerical analysis of data for the soil cover contamination in the EURT vicinity we made use of the results of fieldwork studies of this territory presented as tables in [12] that were obtained based on the maps of the radioactive situation of 1959 and 1997. For the data of the map of 1959 regression parameters (8) were evaluated according to the three control points on the axis of the trace (Figure 6a), sufficiently optimally located relative to each other [13]. It should be noted that the concentration ratio between the extreme points is 5000, which indicates to significant sedimentation rates of aerosol particles carrying radionuclides in the limit of distances under consideration. In order to evaluate radioactive contamination with the observational data of 1997 and model (8), only one control point of ob-

Figure 5. Map of East-Ural Trace

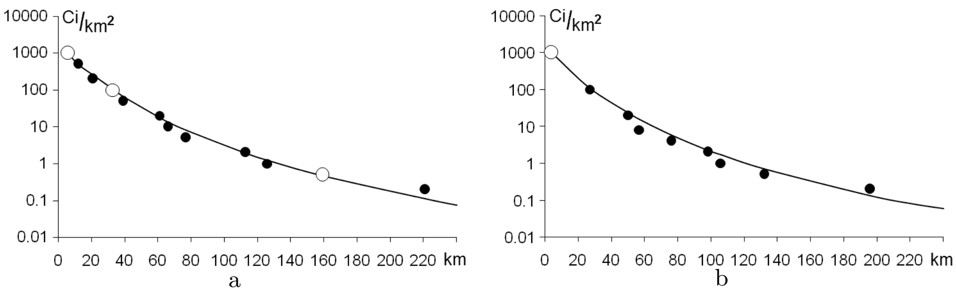

Figure 6. Density of radioactive soil contamination on the axis of East-Ural radioactive trace according to the radioactive situation in 1957 (a) and 1997 (b)

servation, positioned at a distance of 4 km from the site of explosion, was employed (Figure 6b). The parameter θ_1 was evaluated at it on evidence of observations, the other parameters being set from the previous calculation. An analysis of the results of simulation presented in Figure 6, indicates to a satisfactory agreement between calculations and observations at control points.

The use of relations (8), (9) is of interest for the numerical analysis of accident impurities ejections, because in such a situation the information about strength and special configuration of a source, dispersive composition of an impurity are usually absent. Certain difficulties arise in the description of a current field of direction and speed of the wind as well as of turbulent exchange in the surface and boundary layers of the atmosphere.

6. Conclusion

Based on solutions to equations of transport and diffusion of impurities in the atmosphere, a few-parameter model of reconstructing the axial part of a poly-dispersive impurity trace has been developed. This enables us to numerically analyze the observational data along the whole axis of the trace. Testing the model has shown a satisfactory agreement with observational data of traces of the ground and the underground nuclear explosions. It is shown that the effect of the vertical distribution of activity in the cloud of explosion is essential, and in order to take it into account one needs a supplementary a priori information about the character and strength of an explosion.

References

[1] Israel Yu.A., Tsaturov Yu.S., Nasarov I.M. Reconstruction of a realistic picture of radioactive contamination of the locality resulted from accidents and nuclear weapon tests // Meteorology and Hydrology. — 1994. — No. 8. — P. 5–18.

[2] Israel Yu.A., Stukin E.D., Tsaturov Yu.S. On possibility traces of test nuclear explosions and to reconstruct radiation doses of papulation using analysis of long-lived radionuclides // Meteorology and Hydrology. — 1994. — No. 12. — P. 5–14.

[3] Sedunov Yu.S., Borsilov V.A., Klepikova N.V., Chernokozhin E.V., Troyanova N.I. Physico-mathematical modeling of regional transport of radioactive substances to the atmosphere resulted from the accident at the Chernobil hydro-electric station // Meteorology and Hydrology. — 1989. — No. 9. — P. 5–10.

[4] Raputa V.F. Models of reconstruction of the axial part of the East-Ural radioactive trace // Vychislitelnye Tekhnologii. — 2006. — No. 11, Special Issue 2.

[5] Pressman A.Ya. On propagation to the atmosphere of a ready non-homogeneous instant point source // Inzhenerno-Fisichesky Jurnal. — 1959. — Vol. 2, No. 3. — P. 78–87.

[6] Petrov V.N., Pressman A.Ya. Estimation of turbulent diffusion impact in vertical and in wind direction on poly-disperse impurity propagation // DAN SSSR. — 1962. — Vol. 146, No. 1. — P. 86–88.

[7] Andryushin I.A., Chernhyshev A.K., Logachev V.A. et al. Modern interpretation of data of the air and surface radioactivity surveys of the trace of the first nuclear fest in the USSR in 1949 // Vestnik nauchnoy programmy "Semipalatinsky poligon — Altai". — 1995. — No. 2. — P. 102–108.

[8] Lobarev V.M., Zamichlyev B.V., Sudakov V.V. et al. Estimation of radioactive contamination levels on the Altai territory and effective radiation doses of papulation from nuclear explosions carried out on the Semipalatinsk test site

// Yadernye ispitania, okruzhayuschaya sreda i zdorovie naselenia Altaiskogo kraya. — Barnaul, 1993. — Vol. 1, No. 2. — P. 5–125.

[9] Nuclear Weapons Test of the USSR: Modern Radio-Ecology State of Test Sites // V.A. Logachev et al. — Moscow: Ed.AT, 2002.

[10] Israel Yu.A. Radioactive Falls after Nuclear Explosions and Accidents. — St. Petersburg: Progress–Pogoda, 1996.

[11] East-Ural Radioactive Trace / V.N. Chukanov ed. — Ekaterinburg: Ural Branch RAS, 1996.

[12] Volobuev P.V., Chukanov V.N., Shtinov N.A., Alekseenko N.N. Manmade Radiation Accidents in the Ural Region, Estimation and Refinements / V.N. Chukanov ed. // Ural. Radiatsia. Reabilitatsia. — Ekaterinburg: Ural Branch RAS, 2004.

[13] Fedorov V.V. The Theory of an Optimal Experiment. — Moscow: Nauka, 1971.