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Application of a three-dimensional numerical model for estimation of atmosphere pollution with mountain-valley circulation

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The paper deals with the problem of dispersing some polluting substances on the basis of application of a three-dimensional hydrodynamic model. A brief description of the model is given. The real profiles of wind velocity are used for the calculation of dispersing fields. This enables us to reveal peculiarities of the dispersing fields with various types of mountain-valley circulation.

1. Introduction

In the numerical modelling of polluting substances transport over an inhomogeneous terrestrial surface, including the mountain regions is sufficiently complicated. Nevertheless, the account of the orographic impact is of primary importance. In the research offered to the attention of the reader, the possibility of application of a three-dimensional hydrodynamic model is considered and on its basis the calculation of dispersing substances pollution field for one of the Western Tyan-Shyan-Akhangaran valleys is carried out.

This valley represents an ideal object for realization of model calculations for the following reasons. First, according to its morphometrical and meteorological parameters it is a typical valley not only for the Western Tyan-Shyan, but for other mountain systems of the world as well. Second, it is investigated well enough in the circulation ratio for all the seasons of a year. Third, a great number of large enterprises of non-ferrous metallurgy, chemical, building and fuel generating industries are concentrated there. The valley occupies a leading position among the Central Asian regions as far as the volume of industrial pollutions are concerned.

2. Brief description of the model

The numerical scheme for calculation of an average field of contaminants dissemination on a selected territory has been constructed on the basis of solution of the well-known transport and diffusion equation. Finite difference method has been used [1, 4, 9].

The equation

$$\frac{\partial\varphi}{\partial t}+u\frac{\partial\varphi}{\partial x}+v\frac{\partial\varphi}{\partial y}+(w-w_g)\frac{\partial\varphi}{\partial z}+\sigma\varphi=\frac{\partial}{\partial z}k_z\frac{\partial\varphi}{\partial z}+\mu\Big(\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}\Big)+f. \quad (1)$$

is considered in the domain $D=(0<x<a,\ 0<y<b,\ 0<z<H,\ t>0)$. Boundary conditions are

$$\begin{aligned} &\varphi(x,y,z,t)=\varphi^0(x,y,z), && t=0,\\ &\varphi(x,y,z,t)=0, && \text{on } \Sigma\\ &k_z\frac{\partial\varphi}{\partial z}-\beta\varphi=0, && z=0,\\ &k_z\frac{\partial\varphi}{\partial z}=0, && z=H, \end{aligned} \quad (2)$$

where φ is the amount of dispersed substance; t is time; x, y, z are coordinates; u, v, w are wind velocity components in the directions x, y, z, respectively; w_g is the particle precipitation velocity; k_z is the coefficient of turbulent intermixture; μ is diffusion coefficient; σ is absorption coefficient; β is factor of the interaction with underlying surface; $f=\sum_{i=1}^{n}Q_i\delta(r-r_i)$ is the function of circumscribing parameters of the sources (Q_i is power of the i^{th} source of pollution); Σ is the lateral boundary.

On the basis of the obtained solution $\varphi(x,y,z,t)$ the numerical scheme allows one to calculate the full amount of substance and the average one being in the intermixed form in the area D for the time period $\{0,T\}$:

$$J_D = \int_0^T dt\iiint_D \varphi(x,y,z,t)\,dx\,dy\,dz, \quad (3)$$

$$\bar{J}_D = \frac{1}{T}\int_0^T dt\iiint_D \varphi(x,y,z,t)\,dx\,dy\,dz. \quad (4)$$

We could also calculate the full substance amount and the average one dropped out on the underlying surface for the same period of time $[0,T]$ [9]:

$$J_{D_0} = (w_g+\beta)\int_0^T dt\iint_{D_0}\varphi(x,y,z_0,t)\,dx\,dy, \quad (5)$$

$$\bar{J}_{D_0} = \frac{1}{T}(w_g+\beta)\int_0^T dt\iint_{D_0}\varphi(x,y,z_0,t)\,dx\,dy. \quad (6)$$

With the help of the numerical scheme it is also possible to solve a problem of optimal arrangement of new industrial enterprises. For this purpose, it is necessary to test this model by the multiple selection different variants of sources location. This problem can be uniquely solved with the help of solution of only one variant of conjugate problem. The conjugate problem corresponding to equations (1)–(2) will take the form [9]:

$$\frac{\partial\varphi^*}{\partial t} + u\frac{\partial\varphi^*}{\partial x} + v\frac{\partial\varphi^*}{\partial y} + (w - w_g)\frac{\partial\varphi^*}{\partial z} + \sigma\varphi^* \tag{7}$$

$$= \frac{\partial}{\partial z}k_z\frac{\partial\varphi^*}{\partial z} + \mu\left(\frac{\partial^2\varphi^*}{\partial x^2} + \frac{\partial^2\varphi^*}{\partial y^2}\right) + P_c. \tag{8}$$

$$\begin{aligned} &\varphi^*(x,y,z,t) = \varphi^{*0}(x,y,z), && t = 0,\\ &\varphi^*(x,y,z,t) = 0, && \text{on } \Sigma,\\ &k_z\frac{\partial\varphi^*}{\partial z} - \beta\varphi^* = 0, && z = 0,\\ &k_z\frac{\partial\varphi^*}{\partial z} = 0, && z = H, \end{aligned} \tag{9}$$

where

$$P_c = \begin{cases} 1, & \text{if } r \in D,\\ 0, & \text{if } r \notin D. \end{cases}$$

Equations (8), (9) are solved by analogy to equations (1), (2). The computing algorithm is developed, and the distribution of the function in the domain D is obtained.

It is known that [9]

$$Y_p = \int_0^T dt \int_D P_c\varphi(x,y,z,t)\,dD, \qquad Y_p^* = Q\int_0^T \varphi^*(\vec{r}_0,t)\,dt. \tag{10}$$

The magnitude Y_p^* will be indicated as $Y_p^*(\vec{r})$ because this functional depends parametrically on the location of the industrial object $r_0 D$. By resolving the conjugate equations (8), (9) we find the function $\varphi^*(\vec{r},t)$. Substituting it in (10) we come to

$$Y_p^*(\vec{r}) = Q\int_0^T \varphi^*(\vec{r},t)\,dt. \tag{11}$$

An auxiliary function $Y_p^*(\vec{r})$ is used for determination of $\vec{r}_0$ from the condition

$$Y_p^*(\vec{r}) = \min_{\vec{r}\in D}. \tag{12}$$

Here $\vec{r}_0$ will be the point minimizing $Y_p^*(\vec{r})$. Further it is necessary to construct a field of the function $Y_p^*(x,y,h)$, where h is the height of release. As a result we obtain the field of isolines on the plane (x,y):

$$Y_p^*(x, y, h) = \text{const}\,.$$

According to the field obtained we define the domain D_0, where sanitary norms of pollution hold. Thus, by having solved one variant of the conjugate problem we solve the problem of optimal location of industrial plants keeping the sanitary norms of pollution. This is one of the main peculiarities of duality of functionals of the principal problem and the conjugate one as well. Now the principal problem is solved for a fixed point $r = r_0$. As a result we have the full information about pollution fields on a selected territory.

3. Initial data

In a warm period of a year (from April to October) in the Western Tyan-Shyan valleys, the distinct mountain-valley circulation (MVC) is developed. We used the results of the field investigations carried out in another valley of Tyan-Shyan i.e., the Pskem valley, to set wind velocity profiles [12]. It is necessary to note that in the Akhangaran valley, the stream air structure with the MVC has been studied in earlier works [5, 7, 8, 10].

However it is impossible to set verified profiles of horizontal and vertical components of the wind velocity according to these research data. In addition, the turbulent characteristics of the air stream have not been defined in these papers. Our previous work [6], in which we made a comparison of morphometrical parameters of different stations of both valleys using the method developed at the Bugaev Central Asian Research Institute of Hydrometeorology [3] served the basis for application of the wind profiles of the Pskem valley.

According to paper [12], there are three types of the MVC, depending on a synoptic position (Figure 1).

1. The normal MVC (N type) is observed in slightly ingredient barometric fields from the ground surface up to 3.0–4.0 km. This type is observed in the clear or slightly cloudy weather. The change of the mountain wind for the valley wind at the ground surface happens at 10.00–10.30 a.m., and at 21.00–22.00 p.m. local time the reverse change takes place.
2. The amplification of the valley wind (V type) is observed either with vigorous cold intrusions, penetrating into the valley from southwest, or after them. These are usually fronts of the western or the north-west intrusions connected with cyclones over southern, central, northern Kazakhstan or south of west Siberia. The change of the mountain wind for the valley wind (if it is not fully suppressed) happens, as a

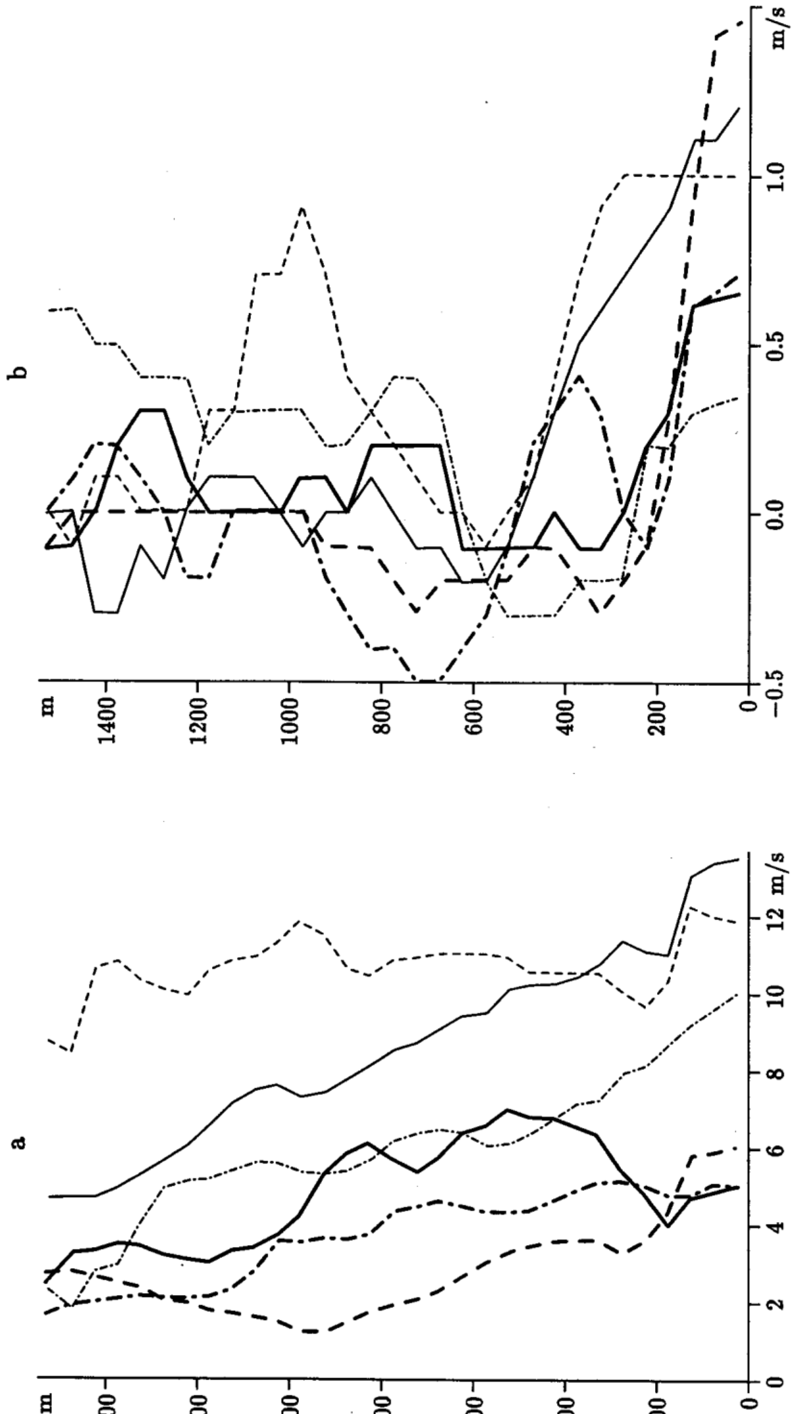

Figure 1. Vertical profiles of horizontal (a) and vertical (b) components of wind velocity for different types of the MVC: —— H-type valley wind; - - - D-type valley wind; ------ G-type valley wind; —— H-type mountain wind; – – D-type mountain wind; –·– G-type mountain wind

rule, at 9.00–9.30 a.m., the reverse change happens at 21.00–24.00 p.m. local time.

3. The amplification of the mountain wind (M type) during the full day is seldom observed. The process is connected with appearance of the northeast winds over the valley up to the height of 5 km (the velocity being 4–7 m/s) on the north-east outlying area of the high altitude anticyclone.

The types V and M are considered to be a violation of the normal MVC. The coefficient of turbulent intermixing was set in correspondence with the type determination, represented in papers [2, 11, 13]. According to these papers k_z grows up to 200–300 m and then it sharply drops tending to zero at the upper bound of the boundary layer (1000–1500 m).

To calculate the impurity diffusion coefficient from a point source, the following formula is used [1]:

$$\mu = |\vec{u}|(k_0 + r\sigma_0^2), \tag{13}$$

where σ_0^2 is dispersion of perturbation of the wind directions average for rather a large time interval; r is distance from the source; k_0 is parameter defined from characteristics of the surface layer; $|\vec{u}|$ is the wind velocity module. The absorption coefficient depends on humidity of air and varies within the limits of $0 < \sigma < 1$.

The interaction factor with underlying surface also varies within the limits of $0 < \beta < 1$.

The sedimentation velocity w_g is calculated under the Stokes formula

$$w_g = \frac{2g\rho_k r_k^2}{9\eta}, \tag{14}$$

where ρ_k is the particle density; r_k is the particle radius; η is the molecular viscosity coefficient.

In carrying out the numerical experiments the domain D was transformed into the grid domain $D_h = (x_i = i\Delta x,\ y_j = j\Delta y,\ z_k = z_{k-1} + \Delta z_k,\ i = \overline{1,21};\ j = \overline{1,16};\ k = 1,2,\ldots,6)$. A grid step in the horizontal direction was uniform ($\Delta x = \Delta y = 3000$ m). In vertical, the height of the calculation domain was 500 m, the grid step being irregular.

4. Results

The numerical experiments were carried out for different values of wind velocity, which corresponds to the most characteristic types of development the MVC in the region under study. According to the calculations, the concentration distribution fields (in fractions of the most admissible concentrations (MAC)) were obtained for 13 types of contaminants emitted into the atmosphere of the valley. These were: nitrogen oxides, sulphide anhydride, charcoal gas, ashes, inorganic dust, dust of cement, Klinker's dust, fluorine hydrogen, sulphuric acid, combinations of arsenic, lead, copper and cynic. As an example, let us consider the distribution of sulphide anhydride (SO_2), which is emitted in large quantities. It is one of the main substances that pollutes the valley.

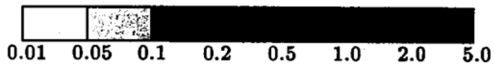

Figure 2. Calibration of SO_2 concentration values in MAC

Analyzing the concentrations distribution fields of SO_2 one can clearly see that the most ecologically dangerous situations are the MVC shifts (Figures 3a, 3b). In these time intervals in the whole Akhangaran valley a vast zone of pollution is formed. Near the pollutions sources (Almalyk, Angren)

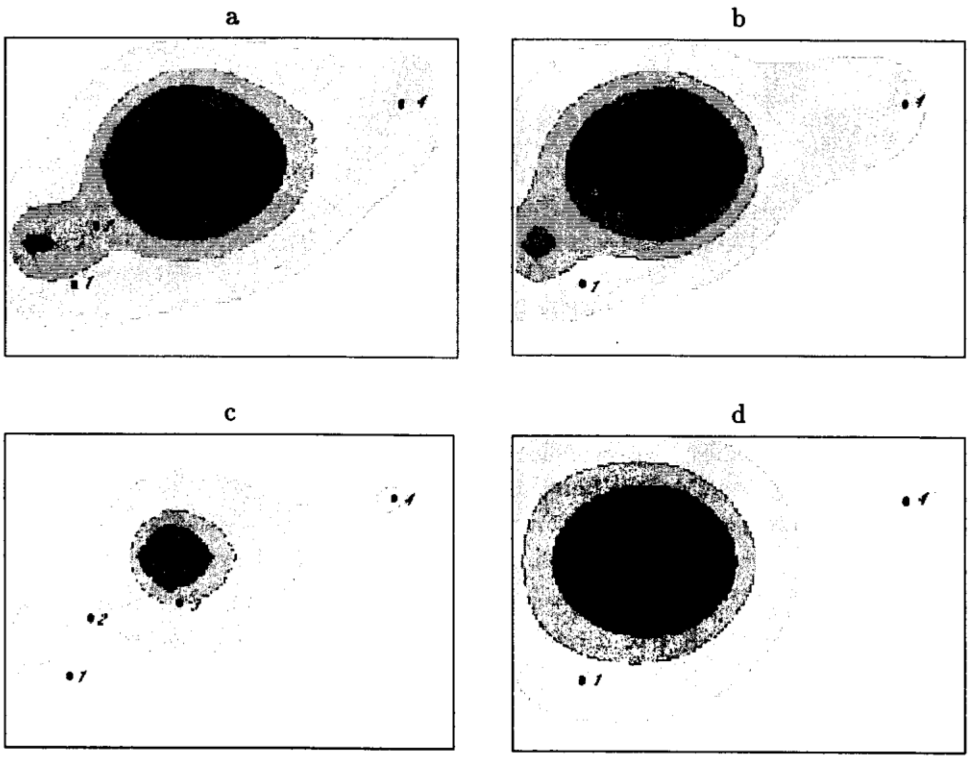

Figure 3. The field of horizontal distribution of SO_2 concentrations at a height of 330 m with: (a) a change of the mountain wind for the valley wind; (b) a change of the valley wind for the mountain wind; (c) the valley wind of H-type; and (d) the valley wind of D-type. Here 1 – Almalyk, 2 – Akangaran, 3 – Nurabad, and 4 – Angren.

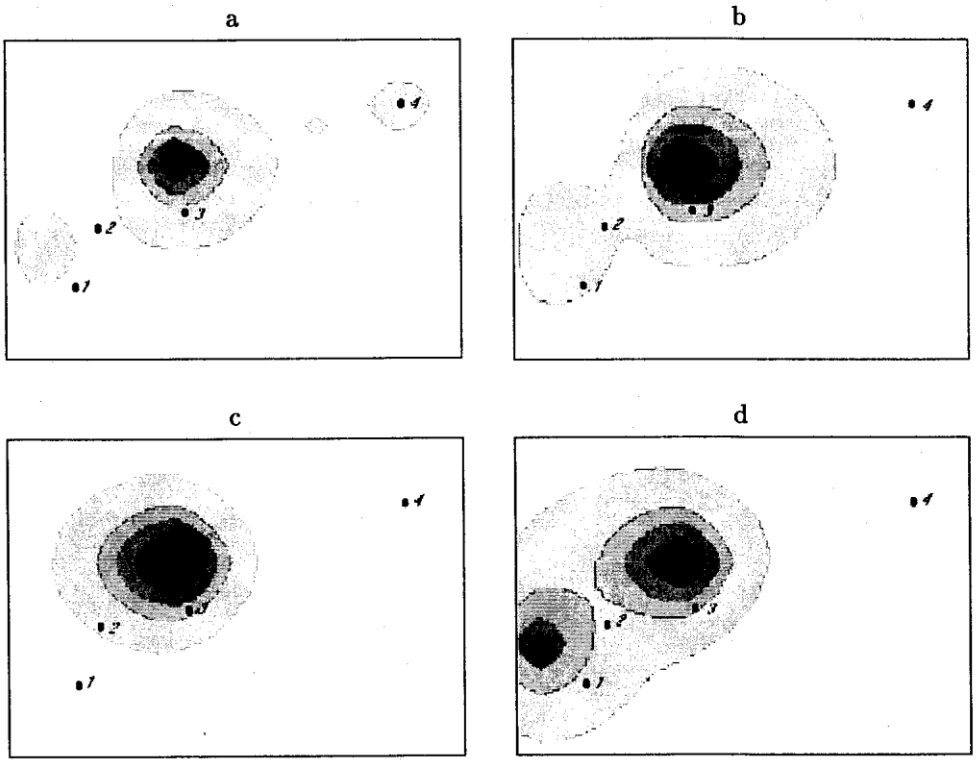

Figure 4. The field of horizontal distribution of SO_2 concentrations at a height of 330 m with: (a) the valley wind of G-type; (b) the mountain wind of H-type; (c) the mountain wind of D-type; and (d) the mountain wind of G-type. Here 1 – Almalyk, 2 – Akangaran, 3 – Nurabad, and 4 – Angren.

the norms higher than 4 MAC are observed. When the valley wind releases SO_2, localized around sources, and contaminant concentration essentially decreases up to 0.5 MAC. When mountain wind sets up, the pollution zone decreases, but the concentration remains sufficiently high (Figures 3c, 3d).

The influence of the intensification of the valley wind as well as the mountain wind is characterized by the following. With the valley wind its intensification brings to a decrease of contaminants concentration (Figure 4a). With the mountain wind intensification, the expansion of pollution boundaries takes place, and the MAC values simultaneously increase in its center (Figure 4b). With the mountain wind, the intensification of the valley wind again causes a decrease of the pollution zone, but it does not decrease the concentration of SO_2 near the source (Figure 4c). With the mountain wind intensification, the stronger vertical and horizontal components of velocity contributes to washing off the contaminants along the Western part of the valley (Figure 4d).

5. Conclusion

To sum up the results of the present paper, we can draw some conclusions. First, the calculations of contaminant distribution fields have shown that the MVC does not contribute to their full washing out from the valley. Due to the weakness of vertical streams the contaminants are not carried away into the upper layers of the atmosphere and are re-distributed within the valley as well as accumulated in its neighborhood. With the valley wind the atmospheric release is brought to the upper parts of the valley. Here they are deposited at mountain peaks, causing the pollution of other media (soil, water). The mountain wind brings the air in the direction of the plain thus forming a peculiar cone of precipitation.

The most dangerous situations occur at wind changes and the greatest washing out of contaminants takes place under synoptical conditions, corresponding to V type of the valley wind. Second, analyzing the obtained concentrations of contaminants it was noticed that to the large amount of contaminants being in the air basin of the valley correspond rather small MAC values. For example, for 40.5 tons of SO_2 release the corresponding values of MAC make up only 4. Thus, we can make a conclusion that MAC values should be re-considered because they are irrelevant to the real situation. In the problem of the MAC determination we should use a complex approach taking into account medical, physical and biochemical factors.

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