Atmospheric dispersion modelling of dust emissions from the dried bottom of the Aral Sea

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Abstract. The problem of spreading of harmful emissions from the dried part of the Aral Sea is extremely relevant for the Central Asian region, but it is also important for other countries of the near and far abroad in view of the transboundary transport of pollutants in the atmosphere. In order to solve the problem of predicting the distribution of the concentration of air pollutants, researchers are usually use mathematical tools. Modelling the processes of transport and diffusion of pollutants in the atmosphere claims to address various factors, such as weather and climate conditions, soil erosion, physic and mechanical properties of aerosol particles, etc. Thus, this study was aimed to develop a model and computational algorithm for solving the problem. The particular attention was paid to the description of wind erosion since most emissions in the Aral Sea region occur by the removal of salt-dust particles from the soil surface. There were conducted a series of computational experiments using the developed mathematical apparatus. The obtained results presented in the paper are illustrating the influence of various factors on the process of atmospheric dispersion. Comparison of the results of computational experiments with experimental data showed sufficient agreement, which confirms the adequacy of the developed mathematical model of the process of spreading of fine aerosol particles in the atmosphere.

1. Introduction

Monitoring, forecast and analysis of impurities distribution in the atmosphere are some of the most urgent tasks in the environmental protection problems. The solution to these problems is related to many factors that affect the impurities dispersion in the atmosphere. These factors include meteorological conditions, type of source, properties of impurities, etc.

There are many ground sources of pollution of this kind, including natural and artificial ones: waste dumps, industrial sites, drained parts of water bodies (for example, the Aral Sea), salt marshes and desert areas.

The Aral Sea problem is multifaceted and many-sided. It covers a wide range of issues and is currently one of the most pressing issues.

The natural mechanism of the Aral Sea, one of the largest inland basins, is entirely subject to the hydrogeological features of the river network that feeds it. As a result of the water diversion for irrigation, the level of the Aral Sea is rapidly decreasing over time. The defined water area of the sea decreases at a fast pace, as a result, water salinity increases; devastated territories are subject to erosion which leads to ecological state violation of the Central Asian region.
To date, a number of studies have been carried out to determine the effect of the Aral Sea on hydrodynamic and hydrochemical regimes of groundwater and air basins adjacent to the Aral Sea region. Analysis of the results of research in the field of mathematical modelling with the aim of monitoring and predicting the process of harmful substances transfer and diffusion in the atmosphere over the past 5-10 years has shown that one of the significant factors, and the source of fine aerosol particles emission in the atmosphere, is the drained area of seas and oceans. For example, such processes can be observed in Central Asia near the Aral Sea water area, where, under significant change in air mass velocity in the atmosphere, a large volume of salts and aerosol particles are emitted from the earth's surface.

It should be noted that the key parameters of the processes of aerosol particles transfer and diffusion in the atmosphere are the coefficients of turbulent diffusion, the interactions with the underlying surface and the absorption of harmful substances in the atmosphere, which significantly depend on wind speed, temperature stratification etc.

The problems numerical modelling of transport and diffusion of air pollutants in the atmospheric boundary layer are considered by many authors [1-4]. Authors of works [5-8] developed several mathematical models of emissions spread in the atmosphere taking into account the deposition velocity of fine particles. The models were described by multidimensional partial differential equations with appropriate initial and boundary conditions. In order to obtain the numerical solution of the problems, authors used one of the splitting methods according to physical processes involved (transport, diffusion and absorption), as well as a second-order implicit finite-difference scheme in time. Analysis of numerical results showed that the developed computational algorithms provide sufficient accuracy of the problem solution compared with field measurement data and it has a certain advantage over other numerical methods. In the course of computational experiments, there was determined the degree of influence of such parameters as wind speed and direction, absorption coefficient and physic and mechanical properties of particles on the process of atmospheric air pollutants dispersion.

The impact of wind aerodynamic characteristics on the atmospheric dispersion process (long and short distances transport), taking into account such factors as turbulent diffusion, temperature stratification, surface roughness, etc. was also studied in the works of many authors [9-13].

In particular, the wind behavior with height was studied in [14] and empirical formulas were compiled to find turbulent diffusion coefficients; the effect of temperature stratification on wind and on fine aerosol particles transfer and diffusion in the atmosphere was also considered. Numerical calculations have been performed on a computer to study the effect of the lay of land on changes in wind speed in the boundary layer of the atmosphere.

The basic concepts of the thermodynamics of atmosphere are presented in [15], the process of turbulent diffusion in the atmosphere is considered, the behavior of pressure and temperature with height is studied, and the equations of motion of air masses are compiled. Based on them, the wind behavior under various physical conditions is analyzed. The authors give a number of empirical formulas to calculate diffusion coefficients.

In work [16], a general characteristic of the atmospheric boundary layer is given; several dynamic models are studied that describe the process of diffusion transport of aerosol particles in the atmosphere.

The authors in [17] have experimentally investigated the effect of the terrain relief on the turbulent transfer of air mass in the atmosphere and some comments have been made on turbulent diffusion in the atmosphere; analytical solutions of the simplest diffusion equations have been presented. In that paper, the authors described the methodology for calculating emissions from smoke stacks and conducted a detailed analysis of basic chemical reactions that have a harmful effect on the environment and human health.

In [18], empirical formulas were proposed for calculating the turbulent diffusion coefficients; there, the formula for calculating the horizontal turbulent diffusion coefficient is of particular value; one of the ways to introduce a correction into the transfer and diffusion equation describing the process of wet deposition of aerosol particles in the atmosphere is described.
It follows from the foregoing that in mathematical modelling of the process of aerosol particles transfer and diffusion in the atmosphere, it is necessary to take into account the erosion factor of the earth’s surface when monitoring and predicting air basins in Central Asia and the Aral Sea water area.

2. Methods

2.1. Governing Equations

Considering the above, for monitoring and forecasting the aerosols distribution in the environment, determining the volume of aerosols in the area under consideration and the aerosols fell on the underlying surface, a mathematical model is used that takes into account weather and climate conditions, soil erosion, physic and mechanical properties of aerosol particles and other factors [19-22]:

Task a):

\[
\begin{align*}
\frac{\partial \theta}{\partial t} + u \cdot \frac{\partial \theta}{\partial x} + v \cdot \frac{\partial \theta}{\partial y} + \left( w - w_e \right) \frac{\partial \theta}{\partial z} + \sigma \cdot \theta &= \mu \cdot \Delta \theta + \frac{\partial}{\partial z} \left( k \cdot \frac{\partial \theta}{\partial z} \right) + Q \cdot \delta(x, y, z); \\
\theta(x, y, z, 0) &= \theta(x, y, z, 0);
\end{align*}
\]

(1)

\[
\begin{align*}
-\mu \cdot \frac{\partial \theta}{\partial x} \bigg|_{x=0} &= \gamma(\theta - \theta_a); \\
-\mu \cdot \frac{\partial \theta}{\partial x} \bigg|_{x=L_x} &= \gamma(\theta - \theta_a);
\end{align*}
\]

(2)

\[
\begin{align*}
-\mu \cdot \frac{\partial \theta}{\partial y} \bigg|_{y=0} &= \gamma(\theta - \theta_a); \\
-\mu \cdot \frac{\partial \theta}{\partial y} \bigg|_{y=L_y} &= \gamma(\theta - \theta_a);
\end{align*}
\]

(3)

\[
\begin{align*}
-k \cdot \frac{\partial \theta}{\partial z} &= \gamma(\beta \cdot \theta - F_0) \text{ at } z = 0; \\
k \cdot \frac{\partial \theta}{\partial z} &= \gamma(\theta_e - \theta) \text{ at } z = H.
\end{align*}
\]

(4)

(5)

At \( H = 0 \) we have a source raised at the level \( z = H \) \((F_0 = 0)\). At ground sources \( F_0 \neq 0 \) \((Q = 0)\). Consider problem (1) - (6) in domain

\[
D = \{0 < x < a, \ 0 < y < b, \ 0 < z < H\},
\]

when the source is located in the surface layer (Figure 1).

In Figure 1 “crosses” indicate aboveground sources of air pollution. The value of \( F_0 \) is the function of \( x, y, z, t \) and should be determined from experimental data depending on meteorological conditions, properties of the underlying surface, size and density of dust particles.

Statistic processing of data on the effect of various weather and climate conditions on particles entrainment from the earth surface shows that the main factor causing soil erosion is the speed value of incoming flow, and the basic factor is soil moisture content. The effect of remaining parameters, although they play a certain role in the erosion development or prevention, is ambiguous. Therefore, in mathematical modeling of the process of harmful particles propagation and variation in their concentration over time, these parameters must be taken into account, and the physicochemical properties of soil can be considered constant when included in calculation formula.

Wind speed and soil moisture content differently affect the process of harmful particles spread in the atmosphere and the development of soil erosion. While an increase in the speed of the incoming wind flow enhances the erosion process, an increase in soil moisture content suppresses it.
Task b): as stated in [19], the general dependence can be written as:

\[ F_0 = f(u, w). \]

(7)

Here \( F_0 \) is the volume flow rate of particles entrained by the atmospheric front, m\(^3\)/s.

To determine the type of function (7), we proceed to the analysis of the acting forces causing soil destruction and resisting this destruction. Destructive forces are denoted by \( F \). They are always opposed by resistance forces \( R \), which include moisture content and other physical and mechanical properties of soil.

![Figure 1. Location of sources on the ground layer in the drained part of the Aral Sea.](image)

If the force \( F \) exceeds the force \( R \), the process of soil erosion and harmful particles entrainment from the earth’s surface begins. The destruction force \( F \) is mainly determined by the shear stress of the incoming air flow. The greater the volume of solid particles in the flow, the greater the total shear stress destroying soil. To obtain theoretical dependence, consider the equilibrium process. Under dynamic equilibrium, the difference in forces \( F \) and \( R \) must be equal to zero, i.e.

\[ F - R = 0. \]

(8)

Let us draw up an expression for these forces. The relationship between the volume flow rate \( F_0 \) of the entrained particles and the flow rate can be expressed as:

\[ F = \frac{\partial F_0}{\partial u} \chi, \]

(9)

where \( \chi \) is the shear stress, kg/m\(^2\).

Resistance force \( R \), by analogy with \( F \), is taken as

\[ R = c_0 \frac{\mu_e}{l} \frac{\partial F_0}{\partial \zeta}. \]

(10)

where \( \mu_e \) is the viscosity of the mixture (air + soil), kg*f/m\(^2\); \( l \) is the distance between the individual particles, m; \( c_0 \) is the soil constant.

Substituting (9) and (10) into (8) we get
\[
\frac{\partial F_0}{\partial u} \chi - c_0 \frac{\mu_c}{l} \frac{\partial F_0}{\partial \zeta} = 0
\]  
(11)

or

\[
\frac{\partial F_0}{\partial u} - c_0 \frac{\mu_c}{l} \frac{\partial F_0}{\partial \zeta} = 0.
\]  
(12)

After some transformation to determine the number of particles torn off the earth surface as a result of soil erosion, we obtain the following differential equation [19, 20]:

\[
\frac{\partial F_0}{\partial u} - k \rho \zeta \frac{\partial F_0}{\partial \zeta} = 0.
\]  
(13)

So, an equation to determine the volume of particles entrained from the surface is obtained depending on wind speed and soil moisture content. Based on the results of calculated value of \( F_0 \) - the volume flow rate of particles entrained by the atmospheric front - it is possible to solve the problem of the process of harmful substances transfer and diffusion in the atmosphere using the boundary condition (5).

2.2. Solving Method

Since the task a) is described using the complete equation of hydromechanics, it is difficult to obtain an analytical solution. To solve the task a), an effective conservative numerical algorithm was developed based on the substitution of differential operators by finite-difference operators [20]. For the task b) an analytical solution is obtained in the form:

\[
F_0 = c_l \varepsilon^{c_l} h_k \varepsilon^{c_k}.
\]  
(14)

So, on the basis of the obtained solution of the task b), it is possible to calculate the amount of emission of fine particles into the atmosphere depending on the wind speed on the earth’s surface, soil moisture content, roughness coefficient, and other physical and mechanical parameters of soil.

3. Results and Discussion

To predict the concentration of harmful substances in the atmosphere, depending on the above mentioned parameters, computer experiments were conducted based on the developed software. Numerical experiments were conducted at different values of the coefficient of turbulence, earth roughness, horizontal and vertical components of wind speeds, different values of soil moisture content, etc. (figure 2, 3, 4).

When using the model, the transfer was carried out uniformly at all levels, depending on the direction of wind speed. From the theory of the boundary layer, it is known that at unstable stratification, the values of \( k(z) \) increase to the level of 200-400 m and rapidly drops with height, tending to zero at the upper border of the boundary layer (the height of the boundary layer at unstable stratification reaches 1000-2000 m) and at stable stratification \( k(z) \) increases slightly in the surface layer and drops with height (the height of the boundary layer is 400-600 m).

The calculations were carried out for the domain \( D(x, y, z) = 22 * 4000 \text{m} \), \( 0 \leq z \leq 1000 \text{m} \) with a step of grid \( h_x = h_y = 4000 \text{m} \), \( L_z : 100, 200, 300, 400, 500 \text{ m} \), time step \( \Delta t = 3600 \text{ sec} \), at various values of the turbulence coefficient \( k(z) \) and deposition rate \( w_g \).
Figure 2. The growth of soil erosion at different values of the moisture of the earth's surface.

Figure 3. Vertical profiles $\theta(x, y_1, z, t_0)$: at $w_g = 0.2$, $k = k(z)$.

Figure 4. Change in the concentration of nitric oxide at height $H = 500$ m, wind speed $u = 3$ m/s.
Numerical calculations show that transfer and diffusion are realized depending on meteorological conditions, on the properties of particles and substantially depend on the vertical distribution of the turbulence coefficient.

To predict the spread of dust and salt over the drained part of the Aral Sea, we use models a) and b). The characteristic value for weak unstable stratification is used for \( k(z) \), and for the wind speed, the power law of change is used. The domain is represented as

\[
D(0 < x, y > 22 \times h_x, 0 < z < 1500m, h_x = h_y = 1500m, h_z = 100, ... 500m).
\]

Area sources are located in the north-eastern part of the drained part of the Aral Sea southern region. At time \([0,t_5]\), the wind is directed south, at \([t_5,t_{10}]\) – southwest, time step is \( \Delta t = 3600 \) sec \((t_5 = 5 \times \Delta t, t_{10} = 10 \times \Delta t)\).

**4. Conclusion**

In the course of computational experiments, it was found that when the sources are in the northeastern part of the drained zone of the southern Aral Sea or in the middle part of the drained zone with weak unstable stratification, in the case of the northern wind, the aerosol does not reach the city of Nukus city (Uzbekistan), and in case of northeastern wind – it reaches Nukus.

The amount of aerosol deposited on Nukus was \(5 \times 10^{-8} \) (g/m\(^2\)) when the sources were in the northeastern part and \(15 \times 10^{-8} \) (g/m\(^2\)) when the sources were in the middle zone.

The analysis of the conducted computational experiments showed that the volume of fine particles entrainment from the surface of the drained part of the Aral Sea is significantly affected by: the components of wind speed on the surface of earth - with an increase in this parameter, the volume of entrained aerosol particles exponentially grows; the soil moisture content – with an increase in this index the amount of emission of harmful substances into the atmosphere sharply decreases; the coefficient of earth roughness.

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