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THEORETICAL AND MATHEMATICAL PHYSICS

An Impact Assessment of Forest Belts on the SO_2 Transport within the Atmospheric Boundary Layer Using a Hydrodynamic Model

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Abstract—A numerical two-dimensional hydrodynamic model was used to describe the influence of forest belts of different sizes on turbulent transport of SO_2 within the atmospheric surface layer. The results of the model calculations showed that the presence of a forest belt results in an substantial reduction of the horizontal SO_2 flux due to the decrease of the wind speed and the absorption of SO_2 by tree crowns. The extinction coefficient of SO_2 flux increases with an increase in the forest belt size and decrease with the pollution source height.

Keywords: two-dimensional hydrodynamic model, turbulent transport, atmospheric pollution, dry deposition of SO_2, one-and-a-half closure of averaged hydrodynamic equations, forest belts.

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INTRODUCTION

Numerous experimental and theoretical studies have been provided to study the transport of atmospheric contaminants within the atmospheric surface layer [1–4]. This is primarily caused by increased anthropogenic load on the environment and the need for the development and implementation of integrated measures to reduce the negative effects of anthropogenic air pollution on natural ecosystems and improve the quality and conditions of life of the population.

It is well known that vegetation, and primarily forests, actively adsorbs aerosols and gaseous contaminants from the atmosphere and thus reduces the level of atmospheric pollution. Quantitative estimates of such influence are relatively rare for the moment, mainly due to the absence of equipment that is necessary for monitoring of pollutant concentrations, as well as to the lack of representative approaches for the adequate quantitative (modeling) description of airborne contaminant transport from the pollution sources within the atmospheric surface layer above a spatially heterogeneous anthropogenic landscape.

In the present study, the transport of passive airborne contaminants (sulfur dioxide SO_2) from two anthropogenic pollution sources (a motorway and a factory chimney) within the atmospheric surface layer was calculated using a two-dimensional hydrodynamic model, and the effects of forest belts of different size on horizontal fluxes of SO_2 were estimated. Sulfur dioxide is a harmful substance that is a special hazard for humans with respiratory diseases (e.g., asthma). It is released into the atmosphere by fuel- and coal-burning enterprises (e.g., thermal power plants). The emission of SO_2 is also typical for internal-combustion engines of vehicles.

1. A TWO-DIMENSIONAL MODEL OF TURBULENT AIR MOTION WITHIN THE ATMOSPHERIC SURFACE LAYER IN THE PRESENCE OF VEGETATION

A two-dimensional model [16] that is based on one-and-a-half closure of averaged hydrodynamic equations was used to describe the transport of passive airborne contaminant SO_2 within the atmospheric surface layer under neutral thermal stratification. One significant advantage of this model is its capacity to describe the transport processes over a nonuniform land surface, including transport at the boundary between different plant communities that are considered as continuous penetrable media slowing down the airflow.

Let us consider the problem of SO_2 transport in a rectangular domain of $x \in [-L, L]$, $z \in [h_0, H]$. The system of equations for the space- and time-averaged wind speed $\mathbf{V}(x,z,t) = \{U(x,z,t), W(x,z,t)\}$, where U and W are the horizontal and vertical components of the wind speed, respectively, and δP is the averaged deviation of pressure from the hydrostatic pressure, has the form

$$\begin{cases} \dfrac{\partial U}{\partial t} + U\dfrac{\partial U}{\partial x} + W\dfrac{\partial U}{\partial z} = -\dfrac{\partial}{\partial x}\left(\dfrac{\delta P}{\rho_0} + E\right) + \dfrac{\partial}{\partial x}\left(2K\dfrac{\partial U}{\partial x}\right) + \dfrac{\partial}{\partial z}\left(K\dfrac{\partial U}{\partial z}\right) + \dfrac{\partial}{\partial z}\left(K\dfrac{\partial W}{\partial x}\right) + F_U, \\ \dfrac{\partial W}{\partial t} + U\dfrac{\partial W}{\partial x} + W\dfrac{\partial W}{\partial z} = -\dfrac{\partial}{\partial z}\left(\dfrac{\delta P}{\rho_0} + E\right) + \dfrac{\partial}{\partial x}\left(K\dfrac{\partial W}{\partial x}\right) + \dfrac{\partial}{\partial z}\left(2K\dfrac{\partial W}{\partial z}\right) + \dfrac{\partial}{\partial x}\left(K\dfrac{\partial U}{\partial z}\right) + F_W, \\ \dfrac{\partial U}{\partial x} + \dfrac{\partial W}{\partial z} = 0, \end{cases} \tag{1}$$

where ρ_0 is the air density; E is the kinetic energy of turbulent motion; K is the eddy diffusion coefficient; and the values of F_U and F_W describe the changes in the air-flow velocity under its interaction with vegetation:

$$\mathbf{F} = \{F_U, F_W\} = -c_d LAD|\mathbf{V}|\mathbf{V}.$$

Here, LAD is the leaf area density in the unit volume and c_d is the drag coefficient of vegetation elements (in our study, it was taken to be equal to 0.2).

To close Eqs. (1), we express the eddy-diffusion coefficient as follows: $K = C_\mu E^2 \varepsilon^{-1}$, where $C_\mu = 0.09$ is a dimensionless proportionality factor [7] and ε is the dissipation rate of the turbulent kinetic energy, E. The equation set for E and $\phi = \varepsilon E^{-1}$ has the following form [7–9, 16]:

$$\begin{cases} \dfrac{\partial E}{\partial t} + U\dfrac{\partial E}{\partial x} + W\dfrac{\partial E}{\partial z} = \dfrac{\partial}{\partial x}\left(\dfrac{K}{\sigma_E^\phi}\dfrac{\partial E}{\partial x}\right) + \dfrac{\partial}{\partial z}\left(\dfrac{K}{\sigma_E^\phi}\dfrac{\partial E}{\partial z}\right) + P_E - \varepsilon, \\ \dfrac{\partial \phi}{\partial t} + U\dfrac{\partial \phi}{\partial x} + W\dfrac{\partial \phi}{\partial z} = \dfrac{\partial}{\partial x}\left(\dfrac{K}{\sigma_\phi}\dfrac{\partial \phi}{\partial x}\right) + \dfrac{\partial}{\partial z}\left(\dfrac{K}{\sigma_\phi}\dfrac{\partial \phi}{\partial z}\right) + \dfrac{\phi}{E}(C_{\phi 1}P_E - C_{\phi 2}\varepsilon) + \Delta_\phi, \end{cases} \tag{2}$$

where $\sigma_E^\phi = 2$ and $\sigma_\phi = 2$ are the Prandtl numbers for E and ϕ, respectively [10], and P_E is the shear generation of the turbulent kinetic energy. The expression for P_E in the two-dimensional case is as follows:

$$P_E = 2K\left(\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial W}{\partial z}\right)^2\right) + K\left(\frac{\partial U}{\partial z} + \frac{\partial W}{\partial x}\right)^2.$$

The multipliers $C_{\phi 1} = 0.52$ and $C_{\phi 2} = 0.8$ in the right side of the equation for the function ϕ are the model constants [10], and the summand Δ_ϕ characterizes the increase in the dissipation of turbulent kinetic energy due to interaction with vegetation [7]:

$$\Delta_\phi = 12C_\mu^{1/2}(C_{\phi 2} - C_{\phi 1})c_d LAD|\mathbf{V}|\phi.$$

The lateral boundaries $x = \pm L$ of the computational domain are transparent. The so-called drift conditions are usually used at the lateral boundaries [17]: they imply that the normal derivative of the target function to the free boundary is taken to be equal to zero. In our case, these conditions have the form

$$\left.\frac{\partial U}{\partial x}\right|_{x=\pm L} = \left.\frac{\partial W}{\partial x}\right|_{x=\pm L} = \left.\frac{\partial E}{\partial x}\right|_{x=\pm L} = \left.\frac{\partial \phi}{\partial x}\right|_{x=\pm L}\frac{\partial}{\partial x} = \left.\partial P\right|_{x=\pm L} = 0. \tag{3}$$

At the upper boundary $z = H$, we also use the drift conditions for all functions, except for the excessive pressure:

$$\left.\frac{\partial U}{\partial z}\right|_{z=H} = \left.\frac{\partial W}{\partial z}\right|_{z=H} = \left.\frac{\partial E}{\partial z}\right|_{z=H} = \left.\frac{\partial \phi}{\partial z}\right|_{z=H} = 0. \tag{4}$$

Taking into account that the upper boundary of the computational domain is sufficiently far from the roughness elements on the ground surface, it may be supposed that the excessive pressure δP at $z = H$ is equal to zero.

At the lower boundary, we use the following condition for the horizontal component of wind speed [18, 19]:

$$\left.K\frac{\partial U}{\partial z}\right|_{z=h_0} = \left.\frac{\kappa C_\mu^{1/4}E^{1/2}}{\ln((z-d)/z_0)}U\right|_{z=h_0}, \tag{5}$$

where $\kappa = 0.4$ is the empirical von Karman constant; z_0 is the roughness length; and d is the displacement height. For the other functions, we use the following boundary conditions:

$$\begin{gathered} W|_{z=h_0} = 0, \quad \left.\frac{\partial E}{\partial z}\right|_{z=h_0} = 0, \\ \phi|_{z=h_0} = \left.\frac{C_\mu E}{K}\right|_{z=h_0}, \quad \left.\frac{\partial}{\partial z}\delta P\right|_{z=h_0} = 0. \end{gathered} \tag{6}$$

We solve Eqs. (1)–(2) with boundary conditions (3)–(6) as the task to find the steady state solution and use the logarithmic vertical distribution of the wind speed [5, 6], which is valid for the atmospheric surface layer above a homogeneous land surface, as the initial condition for U. We also suppose that W and δP are equal to zero at the reference time, and at $t = 0$, the dependences of E and K on z are described by semiempirical equations that are valid for a uniform land surface [6].

2. THE TRANSPORT OF SO_2 BY AIRFLOW AND UPTAKE BY VEGETATION

Once the steady-state field of the wind velocity $\mathbf{V} = \{U, W\}$ and the distribution of the eddy-diffusion coefficient K were obtained, we solve the initial-boundary value problem for the averaged concentration of the substance, C, that is transported by the airflow. The transport equation for C can be written as

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} + W\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(\frac{K}{Sc}\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{K}{Sc}\frac{\partial C}{\partial z}\right) + F_C,$$

where Sc is the turbulent Schmidt number [20, 21], which is equal to 0.75 in our study, and the function F_C describes the sources and sinks of the transported substance

$$F_C = F_{\text{source}} + F_{\text{sink}}.$$

We use some background value of the SO_2 concentration in the atmosphere $C|_{t=0} = C_0 = 6\ \mu\text{g/m}^3$ as the initial condition for C.

The drift conditions at the free boundaries and the zero C flux at the lower boundary of the domain

$$\left.\frac{\partial C}{\partial x}\right|_{x=\pm L} = 0, \left.\frac{\partial C}{\partial z}\right|_{z=h_0, z=H} = 0$$

are used as the boundary conditions.

Laboratory and field studies show that the rate of SO_2 uptake by plants (dry deposition) is determined by the intensity of turbulent and molecular diffusion within the vegetation canopy air space and the stomatal conductance, which characterizes the rate of passage of atmospheric gases entering through the stomata of leaves [22–24]. In case of wet leaves (e.g., dew or raindrops that are intercepted by the leaves), atmospheric SO_2 can enter into a chemical reaction with water yielding sulfurous acid [H_2SO_3] (wet deposition). H_2SO_3 can also contaminate plants with atmospheric precipitation.

In our study, we consider only dry deposition, the rate of which is determined by the stomatal conductance and, in the simplest case, can be represented as $V_d = \frac{Q}{C}$, where Q is the flux of deposited SO_2 and C is its concentration. The values of the SO_2 dry deposition rate V_d that are available in literature vary depending on the type and species composition of the vegetation in the range from 0.1 to 2 cm/s [22–24].

Thus, vegetation is a sink for SO_2 from the atmosphere and the rate of SO_2 uptake by vegetation can be represented as follows:

$$F_{\text{sink}}(x, z, t) = LAD(z)Q(x, z, t) = V_d LAD(z)C(x, z, t).$$

In our study, we consider a motor way with width l_{source} perpendicular to the Oxz plane and a factory chimney with a height (h_{source}) of 20 m as sources of SO_2.

In the two-dimensional problem of SO_2 transport by the air flow from the motorway, the road cross section is considered as a pollution source and is simulated as a rectangle of width l_{source} and height z_{source} that is located at the lower boundary of the computational domain. The simulation of SO_2 transport from the factory chimney is also characterized by an equivalent emission rate that is located at a height of 20 m over the ground surface.

3. THE RESULTS OF THE MODEL CALCULATION

In the calculations of SO_2 transport from the motor way, it was supposed that the road width is $l_{\text{source}} = 10$ m and the SO_2 emission rate is about 330 μg/s. At the first stage, the calculation of turbulent transport was performed for an open surface area without any vegetation (Fig. 1).

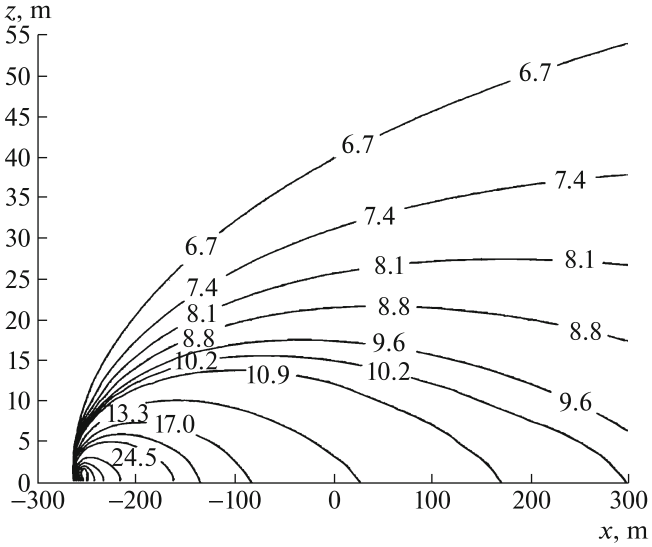

Fig. 1. The distribution of the SO_2 concentration (μg/m^3) near a motor way along the wind direction in the case of open surface area without forest belts around the road. The wind blows from left to right. The wind speed is taken to be equal to 3.5 m/s at a height of 20 m.

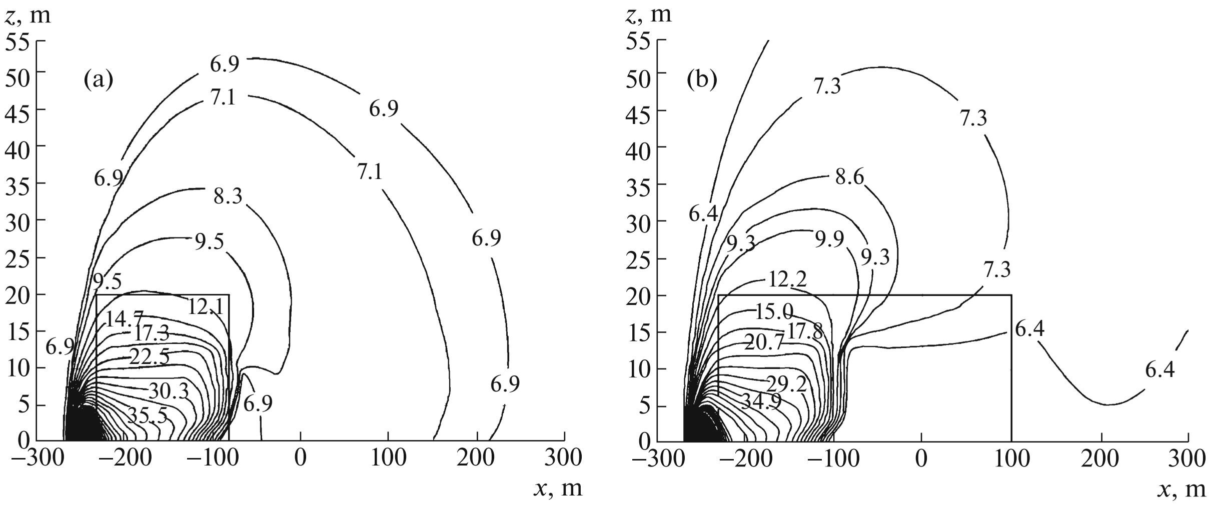

Fig. 2. The distribution of the SO_2 concentration (μg/m^3) near a motor way along the wind direction in the presence of a forest belt of (a) 150 m and (b) 330 m in width. The wind blows from left to right.

On the second stage, a forest belt of different widths was considered as a potential obstacle for the airflow. It was supposed that the forest belt mainly consists of deciduous tree species (birch, aspen, and alder) that are approximately 20 m high. It was also supposed that the boundary of the forest belt is 20 m away from the motorway. The leaf area index of the forest belt is 5. The average rate of SO_2 dry deposition in the tree crowns is $V_d = 1.0$ cm/s, which corresponds to mainly cloudless summer weather conditions with the air temperature ranging between 20 and 25°C and with sufficient soil moisture conditions. The mean wind speed directly over the tree crowns under the assumed friction velocity $u_* = 0.4$ m/s and the selected parameters of the forest belt is about 2 m/s.

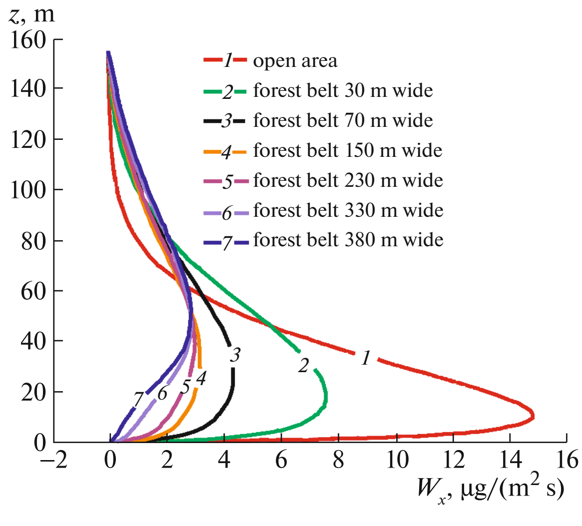

Fig. 3. The horizontal SO_2 flux as a function of the forest belt width at a distance of 510 m from the pollution source (a motorway).

The calculations of the SO_2 concentration distribution within the atmospheric surface layer in the case of availability of forest belts that are 150 and 330 m wide (Fig. 2) showed that the forest belt has a significant impact on the spatial distribution of SO_2 compared to the open surface. This is mainly due to the direct uptake of SO_2 by vegetation (dry deposition) and the changes in the wind speed and direction of the airflow due to its interaction with vegetation elements in the forest belt.

The dependence of the horizontal SO_2 flux density (W_x) on the height at a distance of 510 m from the pollution source for different forest belt widths is shown in Fig. 3. Under a steady-state airflow with the average velocity U, the expression for W_x can be written as follows:

$$W_x = W_x^{\text{av}} + W_x^{\text{turb}} = U(C - C_0) - K_C \frac{\partial C}{\partial x},$$

where $K_C = \frac{K}{Sc}$.

The average values of horizontal flows of SO_2 at a distance of 510 m from the pollution source $\langle W_x \rangle = \frac{1}{h}\int_0^h W_x dz$ are given in Table 1.

The modeling results showed that the presence of a forest belt, even of a minimal width, decreases the horizontal SO_2 flux at a distance of 510 m from the source from 11 to 7 μg/(m^2 s) (by almost 40%). For a forest belt of 150 m and larger, the SO_2 flux reduction near the surface at the same distance exceeds 73% (Fig. 3, Table 1).

Table 1. The integral SO_2 flux as a function of the forest belt width at a distance of 510 m from the pollution source in the case of a motorway considered as a pollution source

Forest belt width, m	Averaged flux, μg/(m^2 s)	Flow decrease, %
0	10.86	–
30	6.85	37
70	4.07	63
150	2.96	73
230	2.65	76
330	2.12	80
380	1.83	83

Table 2. The integral SO_2 flux as a function of the forest belt width at a distance of 510 m from the pollution source in the case of a factory chimney considered as a pollution source

Forest belt width, m	Averaged flux, μg/(m^2 s)	Flow decrease, %
0	41.58	–
30	34.11	18
70	30.27	27
150	27.14	35
230	25.48	39
330	21.88	47
380	20.01	52

To assess the effect of the height of the pollution source on the pollutant flow rate, the factory chimney was considered as a source of SO_2. It was assumed that the pollution source is located at a height of 20 m above the ground surface and that its emission rate is similar to that of the motorway.

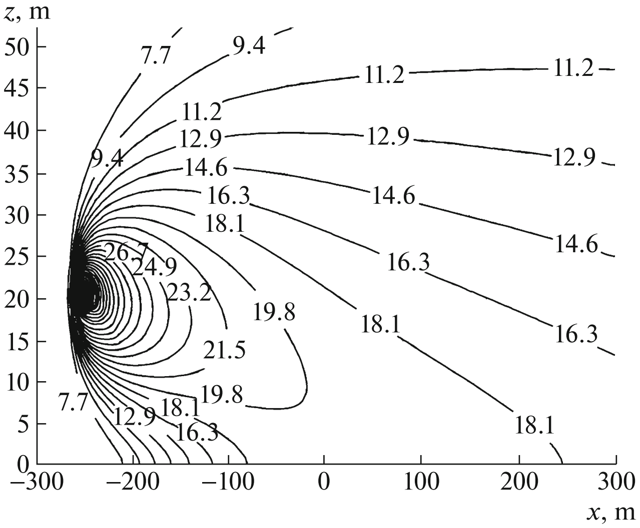

Fig. 4. The distribution of the SO_2 concentration (μg/m^3) near a factory chimney along the wind direction in the absence of obstacles. The wind blows from left to right.

The results of model calculations showed that the location of the SO_2 source over the ground surface significantly increases the polluted area and the transfer velocity of the pollutants. That is linked, first of all, with the higher wind speed near the pollution source and the airflow rounding the forest belt over the upper boundary without significant attenuation (Figs. 4 and 5).

The analysis of horizontal SO_2 fluxes as functions of the forest belt width showed that the SO_2 flux depends significantly less on the forest belt width in the case of the elevated position of the pollution source than in the case of a pollution source that is located directly at the ground surface (Fig. 6, Table 2). In particular, the extinction coefficient of the average SO_2 flux at the ground surface is 52% for a forest belt that is 380 m wide and only 18% for a forest belt that is 30 m wide (Table 2).

CONCLUSIONS

The distribution of SO_2 concentrations around pollution sources, as well as the horizontal fluxes of airborne pollutants in the cases of absence and pres-

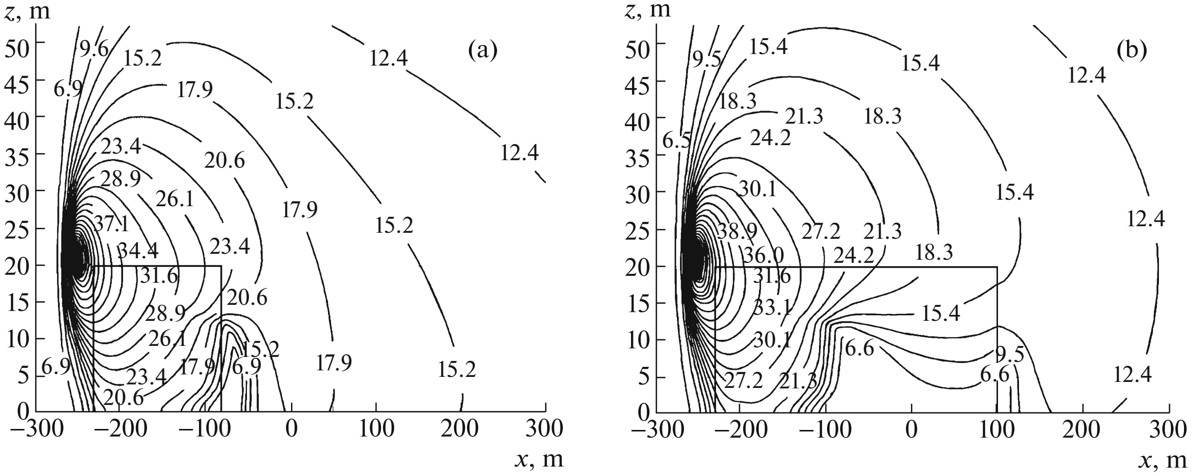

Fig. 5. The distribution of the SO_2 concentration (μg/m^3) near a factory chimney along the wind direction in the presence of a forest belt of (a) 150 m and (b) 330 m in width. The wind blows from left to right.

ence of forest belts, were obtained using the developed two-dimensional hydrodynamic model. It was shown that the forest belt significantly reduces the horizontal SO_2 flux due to forcing the wind to slow down and change its direction, as well as to the direct uptake of SO_2 by the tree crowns.

It was found that the forest belt with the minimum width (30 m) reduces the horizontal SO_2 flux at the ground surface by almost 40% at a distance of 510 m from the pollution source and by only 18% in the case of a pollution source that is located at the height of the tree crowns.

The results showed that the developed mathematical model can be an efficient tool for determining the spatial distribution of pollutant gas within the atmospheric surface layer without use of any measuring equipment. The model is also suitable for the elaboration of measures (including forest belt design) and the construction of facilities that will be able to reduce atmospheric pollutant fluxes from different pollution sources.

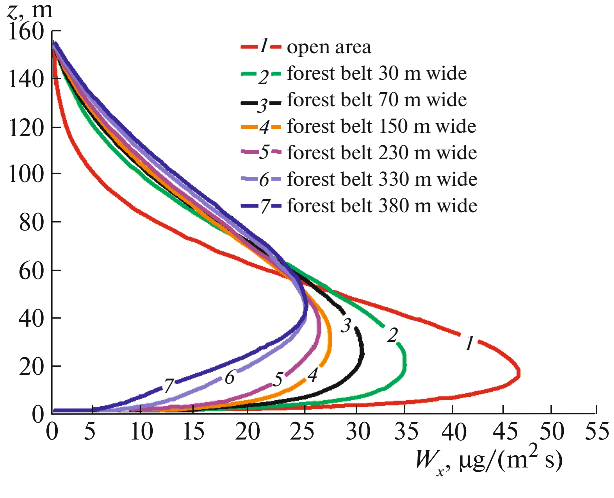

Fig. 6. The horizontal SO_2 flux as a function of the forest belt width at a distance of 510 m from the pollution source (factory chimney).

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