NUMERICAL MODELLING OF DUST DISTRIBUTION IN THE ATMOSPHERE OF A CITY WITH COMPLEX RELIEF

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ABSTRACT

Microscale processes of dust distribution in the city of Tbilisi with very complex topography are modeled using a 3D regional model of atmospheric processes and numerical integration of the transport-diffusion equation of the impurity. The Terrain-following coordinate system is used to take into account the influence of a very complex relief on the process of atmospheric pollution. Modeling is carried out using horizontal grid steps of 300 m and 400 m along latitude and longitude, respectively. The cases of the stationary background of eastern and western weak winds are considered. In the model, motor transport is considered as a nonstationary source of pollution from which dust is emitted into the atmosphere.

Modelling of dust micro-scale diffusion process showed that the city air pollution depends on spatial distribution of the main sources of city pollution, i.e. on vehicle traffic intensity, as well as on spatial distribution of highways, and micro-orography of city and surrounding territories. It is shown that the dust pollution level in the surface layer of the atmosphere is minimal at 6 a.m. Ground-level concentration rapidly grows with increase of vehicle traffic intensity and by 12 a.m. reaches maximum allowable concentration (MAC = 0.5 mg/m^3) in the vicinity of central city mains. From 12 a.m. to 9 p.m. maximum dust concentration values are within the limits of 0.9-1.2 MAC. In the mentioned time interval formation of the highly dusty zones, and slow growth of their areas and value of ground-level concentrations take place. These zones are located in both central and peripheral parts of the city. Their disposition and area sizes depend on spatial distribution of local wind generated under action of complex terrain, as well as on the processes of turbulent and advective dust transfer. From 9 to 12 p.m. reduction of dust pollution and ground-level concentration takes place. After the midnight city dust pollution process continues quasi-periodically.

As a result of the analysis of the vertical distribution of dust concentration is obtained that a basic dust mass emitted into the atmosphere is located in the 100 m surface layer. The concentration value in the upper part of this layer reaches 0.8 MAC and rapidly decreases with altitude increase.

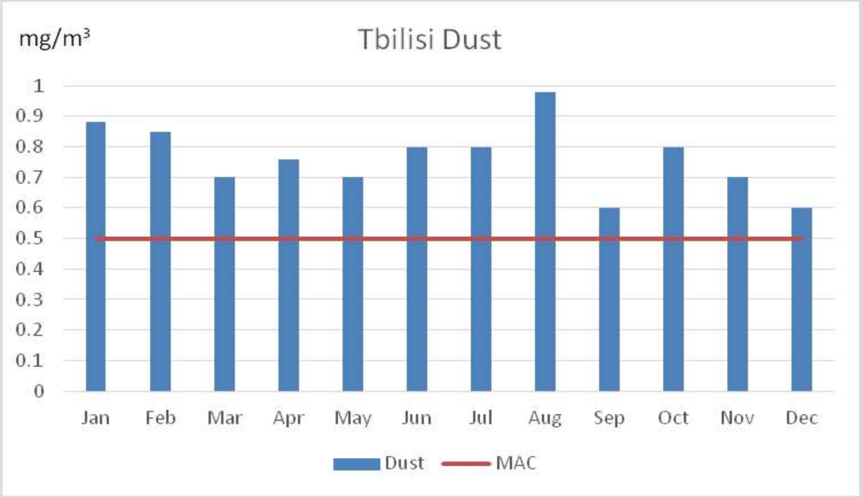
Keywords: *Numerical modeling, pollution source, diffusion, dust distribution, atmospheric wind.*

INTRODUCTION

Human health heavily depends on the level of atmospheric air purity [1], [2]. According to World Health Organization data, 7.6% of population mortality in 2016 has been caused by atmospheric air pollution [3]. Therefore, the study of environmental facilities pollution and its mitigation is a very important problem from both ecological and human health protection standpoints.

Tbilisi is located in the South Caucasus and represents a main junction point of the Great Silk Road that connects Europe and Asia. Many thousands of light and heavy vehicles pass through a city every day, and hundreds of a thousand cars drive about narrow and complex-shape city streets. Microparticles emitted from cars and dust picked up from the underlying surface are the main sources of city pollution. According to data of National Environmental Agency at the Ministry of Environmental Protection and Agriculture of Georgia, dust concentration frequently exceeds maximum allowable concentrations [4] (Fig. 1).

Fig.1. Monthly average dust concentrations in Tbilisi air, in 2015.



Currently, atmospheric air pollution studies using the regular measurements [5], [6], mathematical diagnostic and forecast models [7], [8], [9] are carried out in many cities worldwide.

In the presented article, for the first time for the city of Tbilisi, the kinematics of dust propagation emitted during motion of motor transport – the main polluting source of the atmosphere, will be studied via numerical modelling. The numerical model of atmospheric processes on the Caucasus and polluting ingredients propagation elaborated in the M. Nodia Institute of Geophysics at I. Javakhishvili Tbilisi State University will be used for modelling [10], [11].

STATEMENT OF THE PROBLEM

For modelling of the dust distribution process in the Tbilisi city the area with sizes 30.6×24 km^2 is considered. Tbilisi city is placed in the center of this area. Its relief is very difficult: from the east, west, north and from south-west Tbilisi is c surrounded by mountain ridges, on south-east of city a lowland territory is located. Within the city of Tbilisi there are the several small mountains and gorges. A relief altitude varies from 350 m to 1.5 km from the sea level. In Fig. 2 Tbilisi orography is shown. Actual geographic coordinates are placed on the axes.

For proper description of the spatial-temporary evolution of meteorological and pollution processes over a territory with difficult relief the relief-following coordinate system (x, y, $\zeta=(z-\delta)/h$) is used. Here x and y and z are the orthogonal coordinate axes directed to the east, north and vertically upward, respectively; ζ is no-dimensional vertical axis; δ is altitude of relief; h = H - δ ; $H(t,x,y)$ is height of the tropopause; t is a time.

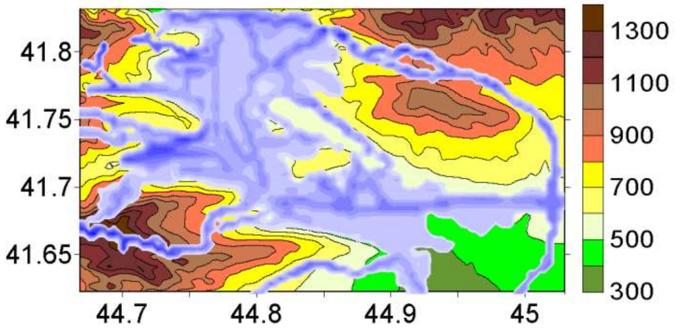


Fig.2. Tbilisi relief (in m) and the pollution sources (blue zone and lines).

Equation for dust atmospheric propagation in the taken coordinate system is written in the following form

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+\mathrm{v}\frac{\partial C}{\partial y}+(\tilde{w}-\frac{w_0}{h})\frac{\partial C}{\partial \zeta}=\mu\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)+\frac{1}{h^2}\frac{\partial}{\partial \zeta}\nu\frac{\partial C}{\partial \zeta}\quad ,\ (1)$$

where, C is dust concentration in atmosphere; u, v, w and $\tilde{w}$ are the components of wind velocity along x, y, z and ζ axes; w_o is rate of dust particle sedimentation determined according to Stokse's formula; μ and ν – kinematic coefficients of horizontal and vertical turbulence.

Initial and boundary conditions used in the model allow to modelling the dust distribution in Tbilisi in case of stationary background eastern light air. The background wind speed grows linearly from 1m/s at z = 2 m to 20 m/s at z = 9 km. Relative atmospheric moisture is 45%.

The wind speed components and kinematic coefficients of turbulences in the surface layer of atmosphere and in free atmosphere on the any moment of the time are defined by means of the Regional Model of Atmospheric Processes in the Caucasus [10], [11].

The initial concentrations of the dust at 2 m height in the populated area are taken as 0.1 mg/m^3, in the unpopulated area – 0. Using analysis of the observation and experimental measurement data there was found that in Tbilisi in the vicinity of central motorways there is almost a linear dependence of dust concentration on car traffic intensity. It was also found that near the central motorways and streets, where intensity of car motion is about 8000 cars per hour, the dust concentration is approximately equal to 0.8-1.3 MAC. Therefore, the initial and boundary concentrations in the vicinity of main city streets are taken in accordance to motor traffic intensity (Fig.2).

Equation (1) is solved numerically using the Crank-Nicolson scheme and splitting method [12]. The grid steps are equal to 300 and 400 m along axes x and y, respectively. The vertical step in the free atmosphere is equal to 1/31in the relief-following system, in the surface layer it varies from 2 to 15 m. Calculations were made for the period 72 h with time step equal to 1 s.

RESULTS OF MODELLING

In Fig. 3 a spatial distributions of dust concentration and wind velocity obtained through calculations at 2, 100 and 600 m heights for t = 0, 3 and 6 hours are shown. It is seen from Fig. 3 that at 2 m height from underlying surface the dust pollution gradually decreases from the midnight and becomes minimal at 6 a.m. At this time, concentration value in the city and surrounding territories varies within the range of 0.001-0.2 MAC. Concentration equal to 0.1 MAC is obtained in the most part of the city, in both urbanistic and recreation zones and in unpopulated areas. At 100 and 600 m height the concentration is less changeable. Its value in the 600 m thick atmospheric layer varies within 0.1-0.3 MAC.

After 6 a.m., along with rapid growth of motor car traffic intensity, the increase of the quantity of dust entering the atmosphere and pollution of the city atmosphere are begins. At 9 a.m. at 2 m height dust concentration is increased alongside the highways and in their vicinity (Fig. 4). Advective, convective and diffusive dust transfer occurs influenced by local wind. Dust transfer direction is different and depends on the direction of local ground wind.

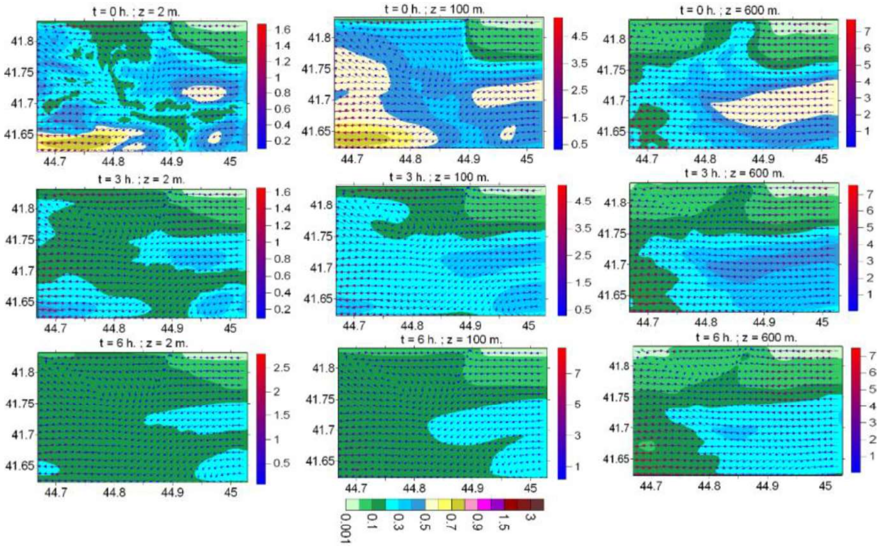


Fig.3. Wind velocity (in m/s) and dust concentration (in MAC) distribution at t = 0, 3 and 6 h at 2, 100 and 600 m heights from earth surface.

From 9 a.m. formation of heavily polluted zones begins. Among these zones are the city center and some territories located in the northern and southern parts of city. In these territories are some motorways or they directly adjoin highways. Concentration values in the vicinity of highways are 0.9-1.2 MAC, and in remoted urban parts they are within the limits of 0.5-0.9 MAC. In recreation and unpopulated areas, where we have

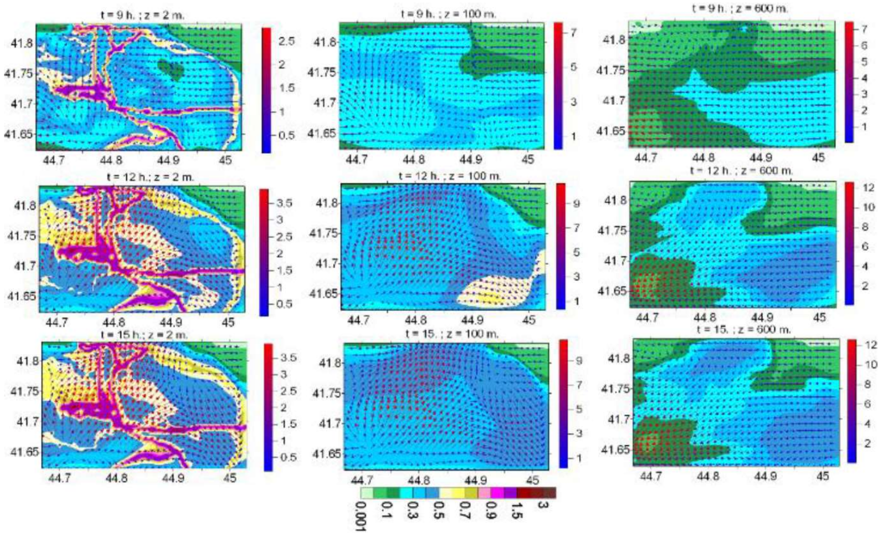


Fig.4. Wind velocity (in m/s) and dust concentration (in MAC) distribution, at t = 9, 12 and 15 h at 2, 100 and 600 m heights from earth surface.

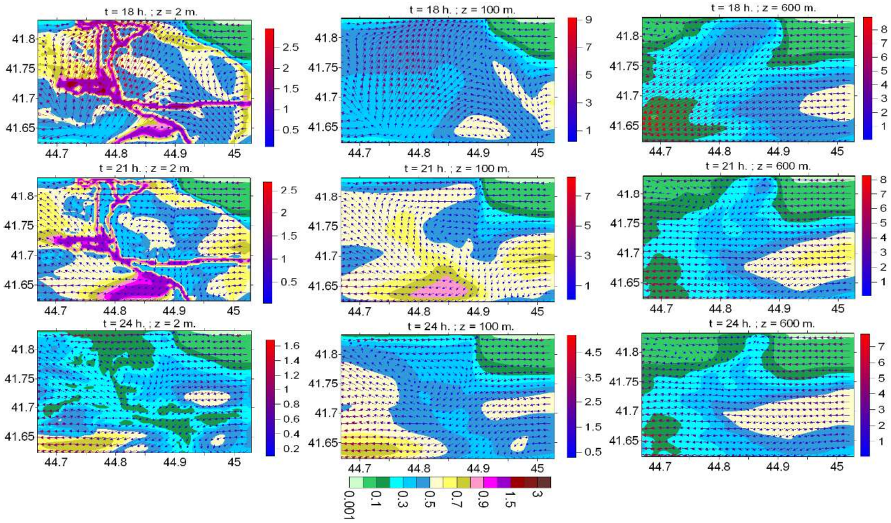


Fig.5. Wind velocity (in m/s) and dust concentration (in MAC) distribution, at t = 18, 21 and 24 h at 2, 100 and 600 m height from earth surface.

no pollution sources, pollution mainly occur according to advective and diffusion transfer mechanisms. As a result, the concentration near to earth surface there is relatively small and varies in the range of 0.3-0.5 MAC. Dust available in the ground layer propagates upward and at noon dust concentration at 100 m height reaches 0.7 MAC, while at 600 m height – 0.5 MAC.

Starting with 3 p.m. and up to 9 p.m. the dust concentration spatial pattern doesn't experience any significant qualitative changes (Fig. 4, 5). Instead, we have quantitative changes: at 2 m height the area of high pollution zones in the central parts of the city is getting smaller, while in southern suburban parts it increases. Concentration increases in the surroundings of Tbilisi by-pass road and Tbilisi Sea, as well. Bands with the same concentration value experience deformation in time. Deformation has a complicated shape and is caused by time and space variation of local wind formed under influence of city terrain.

Maximum pollution level at 100 m height from earth surface is obtained when t =21h and it covers a significant part of modeling area. Its formation depends on mountain-and-valley circulation processes caused by daily temperature variation in the domain with complex relief, resulting from which an intense ascension of warmed air masses and vertical transfer of significant part of the dust take place during the day. By this moment, concentration values obtained via calculation are within the limits of 0.5-0.7 MAC at 100 m height from earth surface.

After 9 p.m. traffic intensity reduces and related dust dispersion in the atmosphere and atmospheric pollution level are getting smaller. When t = 24 h we obtain such spatial distribution of dust concentration, which is close to distribution obtained at t = 0 h. It shows, so the dust accumulated in the city atmosphere is taken out from this territory and city atmosphere self-purification occurs. Further calculations showed that in case of stationary background wind a quasiperiodic change of dust concentration in the city atmosphere takes place.

CONCLUSION

Nonstationary process of dust propagation formed by motor transport in Tbilisi is surveyed. Space and time variation pattern of dust concentration in the city with complex terrain is studied. By analysis of wind velocity and concentration fields there is established that a spatial distribution of heavily polluted areas depends on many factors, namely: on highways disposition, traffic intensity, and on local circulation processes formed as a result of relief and background wind interaction under of the underlying surface thermal action.

It is obtained via calculations that Tbilisi atmosphere at 2 m height from earth surface is minimally polluted at 6 a.m. By this time concentration value doesn't exceed 0.2 MAC. From 6 a.m. to noon a rapid growth of dust surface concentration and formation of high pollution zones in the central and some suburban parts of the city occur. Concentration values in the high pollution zones are within the limits of 0.9-1.2 MAC. From noon to 9 p.m. dust concentration increases relatively slowly. In parallel, concentration spatial distribution change and accumulation zone formation take place. Dust concentration in the accumulation zone is high and roughly equals to 1.5 MAC. Vertical dust transfer becomes especially intense between 3 p.m. and 9 p.m. In this period of time concentration value at 100 m height above dust accumulation zone reaches 0.8-0.9 MAC.

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