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Numerical Modeling of Dust Propagation in the Atmosphere of a City with Complex Terrain. The Case of Background Eastern Light Air

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Abstract

Micro-scale 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. Cases of the stationary background eastern light air are considered. In the model, motor transport is considered as a nonstationary source of pollution from which dust is emitted into the atmosphere. Modeling of dust micro-scale diffusion process showed that the city air pollution depends on the spatial distribution of the main sources of city pollution, *i.e.* on vehicle traffic intensity, as well as on the spatial distribution of highways, and micro-orography of city and relief of the 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 the increase of vehicle traffic intensity and at 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 high pollution zones, the slow growth of their areas and the 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 the spatial distribution of local wind-generated under the action of complex terrain, as well as on the processes of turbulent and advective dust transfer. From 9 p.m. to 24 p.m. reduction of dust pollution and ground-level concentration takes place. After midnight the city dust pollution process continues quasi-periodically.

Keywords

Numerical Modeling, Pollution Source, Diffusion, Dust Distribution, Wind

1. Introduction

Human health substantially depends on the level of atmospheric air purity [1] [2] [3]. According to World Health Organization data, 7.6% of worldwide mortality is caused by atmospheric air pollution [4]. Therefore, the study and mitigation of pollution of environmental locations is a very important ecological and human health protection task. Though Tbilisi is not ranked among 500 cities worldwide, that is most polluted by micro-particles [5]; however, according to information of the National Environmental Agency of Georgia concentration of dust and micro particles frequently exceed the maximum allowable concentrations [6].

Tbilisi represents the main junction point of the Great Silk Road connecting Europe and Asia, as well as Russia and Asia Minor countries. Many thousands of light and heavy vehicles pass through a city every day. Hundreds of thousands of cars drive about narrow and complex-shape city streets. There are no atmosphere-polluting large industrial enterprises in the city, which is why micro-particles emitted from cars are the major pollution source.

Dust propagation kinematics in the atmospheric air of Tbilisi city having complex terrain will be studied for the first time in the presented article using numerical modeling. The numerical model of atmospheric process development and polluting ingredients propagation in the Caucasus developed in the M. Nodia Institute of Geophysics at I. Javakhishvili Tbilisi State University is used for simulation [7] [8].

2. Research Objective and Methodology

The area of size 30.6 × 24 km^2 is considered for dust propagation. C. Tbilisi is placed in the center of this area. The terrain of Tbilisi city and surrounding territory are very complex. That is why for the proper description of atmospheric processes it is convenient to use the relief succeeding coordinate system $\zeta = (z-\delta)/h$. The axes x, y, z and ζ are directed along latitude, longitude, vertically up and normally to the earth surface, respectively. $\delta = \delta_0(x, y)$ is a terrain height from a sea-level; $h = H - \delta$; $H(t, x, y)$ is tropopause height; t is a time.

The equation for propagation of a contaminant in the atmospheric in the taken coordinate system will be written in the following form

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

where C is the dust concentration; u, v, and $\tilde{w}$ are the components of wind velocity along x, y and ζ axes; w_0 is a rate of dust particle sedimentation determined according to Stoke's formula; μ and ν are the kinematic coefficients of horizontal and vertical turbulence; ρ is a density of the standard atmosphere. The values of the component of the wind velocity and turbulence coefficients in the surface layer and the free atmosphere are defined through regional models [7] [8]. The Equation (1) is solved numerically both in the free atmosphere and surface layer. The thickness of the surface layer is equal to 100 m.

3. Discussion

Calculations are made on a rectangular numerical grid with 300 and 400 meters horizontal steps along the latitude and longitude, respectively. The vertical non-dimensional step in the free atmosphere is 1/31. In the 100 m thick surface layer of the atmosphere, the vertical step varies from 2 to 15 meters.

Tbilisi city is confined with high ridges from three sides, while in the south-eastern direction a low-laying area is located. Mtkvari river gorge spreads throughout the length of the city. There are several small gorges, mountains and hills within its boundaries. Terrain height varies from 70 m to 1.5 km in the modeling area. A case of stationary background eastern light air under dry weather conditions of June is considered. Relative atmospheric humidity is 50%.

It is assumed that the atmosphere is polluted by the dust originated as a result of vehicle traffic at city mains and streets. Its quantity changes in time and is determined according to fixed surveillance data and vehicular traffic intensity. The mentioned data are used as initial and vertical boundary conditions in the numerical integration process.

Tbilisi city terrain is shown in **Figure 1**. The pollution source distribution is marked in dark blue. These sources are located in central city mains and urbanized territories.

In **Figure 2** there is shown a spatial distribution of dust concentration and wind velocity obtained via calculation at 2, 100 and 600 m height over the ground at t = 0, 3 and 6 h of the first day. Concentration is given in units of MAC, and wind velocity—in m/sec. As it is seen from **Figure 2**, at 2 m height from the underlying surface the dust pollution level gradually drops starting with 0 h of midnight.

Concentration becomes minimal by 6 AM. At this time concentration value in the city and its surrounding territories varies within a range of 0.001 - 0.2 MAC. Concentration 0.1 MAC is obtained at the large territory of the city, in both urban and recreational zones and unsettled territories. At 100 and 600 m, height concentration is less variable. Its value in the 600 m thick atmospheric layer varies within a limit of 0.1 - 0.3 mg/m^3.

After t = 6 h, the quantity of dust hit an atmosphere starts to increase along with the rapid growth of vehicular traffic intensity. The quick pollution of the urban atmosphere takes place. When t = 9 h, dust concentrations at 2 m height over a ground increase directly in the vicinity of polluting sources and nearby, along with city mains (**Figure 3**). In parallel, an advective, convective and

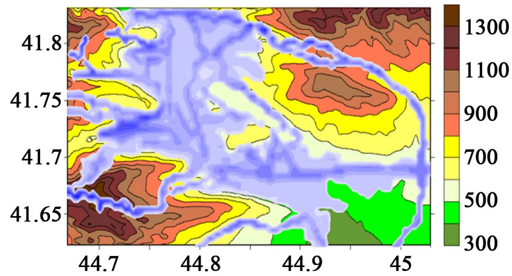

Figure 1. Tbilisi city terrain height (m) and pollution source distribution. Real geographical coordinates are given at axes.

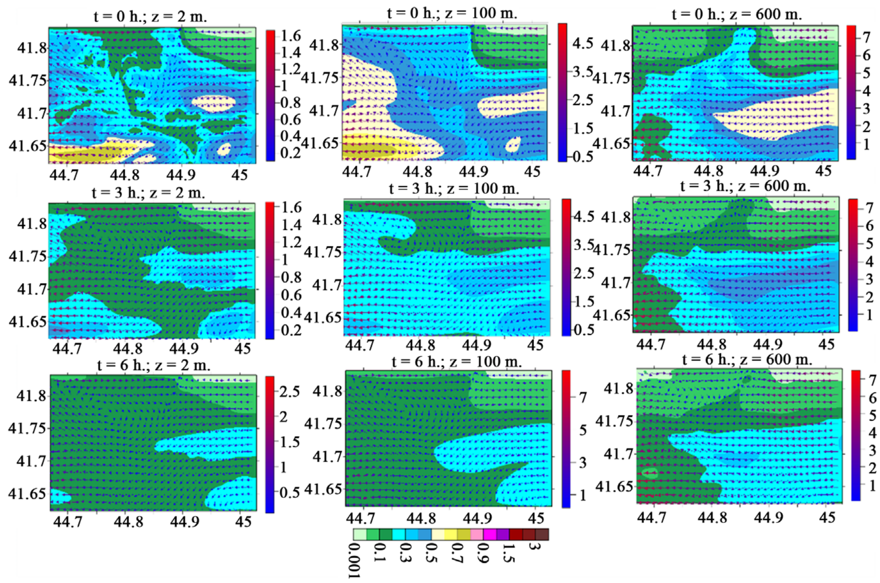

Figure 2. Wind velocity (m/sec) and dust concentration (MAC) distribution, when $t = 0$, 3 and 6 h at 2, 100 and 600 m height over ground.

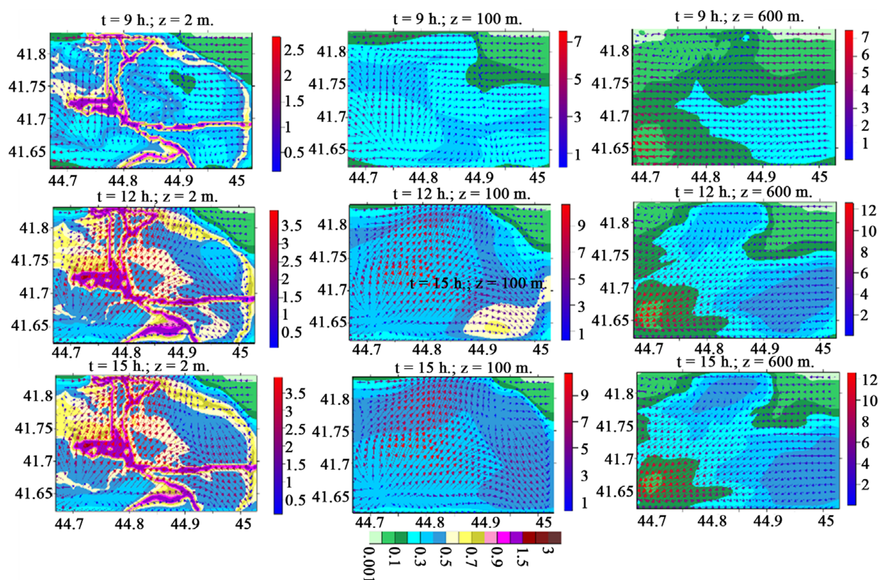

Figure 3. Wind velocity (m/sec) and dust concentration (MAC) distribution, when $t = 9$, 12 and 15 h at 2, 100 and 600 m height over ground.

diffusive dust transfer occurs, which depends on the directions of local ground winds.

The maximum dust pollution level is obtained from $t = 12$ to 21 h period of a day. City center, Vake, Saburtalo and Ortachala, *i.e.* areas directly bordered with city mains are among zones of the heavy concentration of dust. The concentration varies within a limit of 0.9 - 1.2 MAC in these territories. In urban areas distanced from city mains, a dust concentration varies within a range of 0.5 - 0.9 MAC. As for recreational zones and unsettled territories, where pollution sources don't exist, pollution occurs through the mechanism of advective and diffusive transfer. As a result, a ground-level concentration varies within limits of 0.3 - 0.5 MAC. The dust originated nearby earth surface distributes upward and at $t = 12$ h a dust concentration reaches 0.7 MAC at 100 m height.

From $t = 15$ h to 21 h of a day the concentration spatial distribution pattern doesn't experience significant qualitative changes (Figure 4). Only a small quantitative change takes place. At 2 m height, a heavy pollution zone area decreases in the central part of a city and at the territory of Vake and Saburtalo, while it increases in Ortachala and southern suburban part of the city. Concentration is getting bigger in the vicinity of Tbilisi by-pass road and Tbilisi Sea. Forms of isolines and their deformation are very complicated and are directly caused by spatial and time variations of local wind velocity formed under influence of city terrain.

At 100 m height over ground, maximum pollution is obtained when $t = 21$ h and it covers a considerable part of the modeling area. Its formation is associated with mountain-and-valley circulation processes caused by the daily thermal regime under complex terrain conditions, due to which an intense ascension of heated air mass and vertical transfer of considerable part of dust takes place

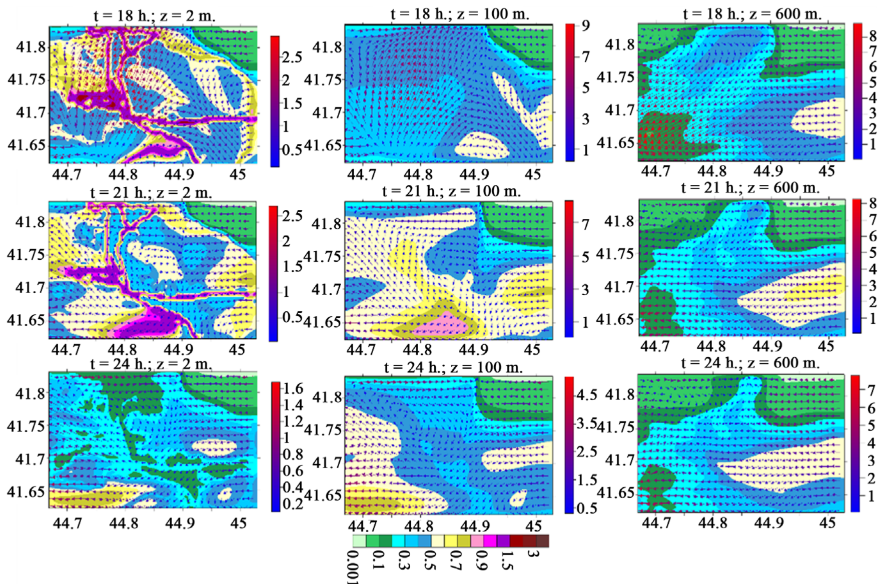

Figure 4. Wind velocity (m/sec) and dust concentration (MAC) distribution, when $t =$ 18, 21 and 24 h at 2, 100 and 600 m height over ground.

during a day. The maximum value of concentration obtained by this moment is within 0.5 - 0.7 MAC.

After $t = 21$ h an atmospheric pollution level drops, as far as vehicular traffic intensity and related dust dispersion in the atmosphere are getting smaller. When $t = 24$ h, such spatial distribution of concentration is obtained that is close to the distribution existing for the moment when $t = 0$ h, *i.e.* the dust accumulated in the city atmosphere transfers from this territory, and self-purification of city atmosphere takes place. The further calculations showed that a quasi-periodical change of dust concentration in the urban atmosphere takes place in the case of stationary background wind.

Experimental measurements of dust concentration at 2 m height were conducted at several points of a city. Data comparison showed that the difference between concentrations obtained experimentally and via modeling didn't exceed 30%.

4. Conclusion

The kinematics of the atmospheric, a daily pattern and spatial distribution of the dust formed by motor transport at Tbilisi territory are investigated. Based on the analysis of the wind velocity and dust concentration fields it is obtained that spatial distribution of heavily polluted areas depends on the location of city mains, on one hand and local circulation systems formed due to dynamic influence of terrain and daily change of thermal regime at the underlying surface, on the other. The location of heavily polluted areas and their time variation during light background eastern winds is established. A comparison of concentration values obtained via modeling with experimental measurement data showed a good agreement.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Samet, J.M., Zeger, S.L., Dominici, F., Curriero F., Coursac, I., Dockery, D.W., Schwartz, J. and Zanobetti A. (2000) The National Morbidity, Mortality, and Air Pollution Study. Part II: Morbidity and Mortality from Air Pollution in the United States. Research Report, 94; Health Effects Institute, Cambridge, MA. https://doi.org/10.1097/00001648-200611001-00004

[2] Pope, C.A., Burnett R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K. and Thurston G.D. (2002) Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution. *Journal of the American Medical Association*, **287**,

1132-1141. https://doi.org/10.1001/jama.287.9.1132

[3] Katsouyanni, K., Touloumi, G., Spix, C., Schwartz, J., Balducci, F., Medina S., *et al.* (1997) Short Term Effects of Ambient Sulfur Dioxide and Particulate Matter on Mortality in 12 European Cities: Results from Time-Series Data from the APHEA Project. *BMJ*, ***314***, 1658-1663. https://doi.org/10.1136/bmj.314.7095.1658

[4] WHO (2016) Mortality and Burden of Disease from Ambient Air Pollution-WHO. https://www.who.int/gho/phe/outdoor_air_pollution/burden/en/

[5] Wikipedia. List of Most Polluted Cities by Particulate Matter Concentration. https://en.wikipedia.org/wiki/List_of_most-polluted_cities_by_particulate_matter_concentration

[6] Garemosdabindzureba. (In Georgian) http://nea.gov.ge/ge/service/garemos-dabindzureba/7/biuleteni/

[7] Surmava, A.A., Mishveladze, B.A. and Davitashvili, T. (2009) Numerical Modeling of the Pollution Transfer in the Caucasus Atmosphere from Hypothetical Source in Case of the Background Western Wind. *Journal of the Georgian Geophysical Society*, **13B**, 15-21.

[8] Gigauri, N.G. and Sumava, A.A. (2017) Spatial Distribution of the Local Meteorological Fields and Dust Concentration in Kakheti Atmosphere in Case of the Northern Background Wind. *Journal of the Georgian Geophysics Society*, **20**, 11-23.