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Numeral investigation of the dependence of atmospheric pollution of city with a complex relief on the direction of background wind

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ABSTRACT

Dust propagation in the atmospheric air of Tbilisi city in case of western and eastern background light airs was numerically modeled and analyzed using the 3D regional model of the evolution of atmospheric processes and numerical integration of admixtures transfer-diffusion equation. The main differences and similarities appearing under conditions of background winds of both directions typical for the city are explored. The locations of high pollution areas are determined. Modeling made it possible to establish that in case of the eastern background light air the wind velocity field formed under the influence of the relief impedes dust removal from the city and forms over the large area of the city a zone with high pollution with a maximum concentration of 2-2.5 MAC. In case of the western background light air the wind velocity field promotes city atmosphere "self-purification" process and high pollution level is mainly registered during motor transport traffic "rush hour" situation. As a result of the calculations it is established that the dust propagation process conditionally runs by four stages and depends on the motor transport traffic intensity, city mains location and city micro-relief. From 6 AM to 9 AM the rapid growth of concentration takes place, from 9 AM to 6 PM – slight reduction or consistency of concentration, from 6 PM to 9 PM – concentration growth, while from 9 PM to 6 AM self-purification of the city air is observed.

Keywords: Atmosphere, Pollution, Numerical modeling, Concentration, Background wind, PM.

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INTRODUCTION

Researches [1-3] showed that the mortality rate caused by COVID-19 is relatively high at the urban territories with increased contamination of atmospheric air. As one of the reasons of rise in mortality, one may mention the spreading of COVID-19 virus hitting the dust particles, PM2.5 and PM10 [4, 5]. That is why, during viral pandemic, the study of aerosols propagation in the atmosphere of industrial centers and big cities, air purity protection and carrying-out the measures aimed to ecological safety are of special importance.

Tbilisi is an administrative center of Georgia and one of the major cities of the South Caucasus. While it isn't ranked among 500 cities worldwide mostly polluted by micro particles [6], but according to the data of National Environmental Agency of the Ministry of Environmental Protection and Agriculture of Georgia the concentrations of dust and micro particles often exceed maximum allowable concentrations [7].

Tbilisi city is a key junction point of the Great Silk Road connecting Europe and Asia, and routes connecting Russia with the Asia Minor. 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 that's why micro particles emitted from cars and dust raised up from underlying surfaces are the major pollution source. A dust hitting the atmosphere, along with a settled COVID-19 virus transfers throughout a city, accumulates at the particular territories, and creates a situation favorable for spread the hazardous for health infection.

The peculiarities of dust propagation at the territories of cities with complex terrain are explored in the present article. The dependence of atmospheric air pollution by dust on wind directions is studied using numerical modeling. Two main meteorological situations – eastern and western background winds – are considered. The modeling is conducted using the regional model of atmospheric processes in Georgia and numerical integration of equations of admixtures transfer and diffusion [8 -11].

STATEMENT OF THE PROBLEM

The 30,6x24 km^2 area of Tbilisi and surrounding territories is considered. In order to mathematically correctly describe the dynamic fields of atmosphere and meteorological parameters under conditions of complex terrain of the city a relief-following coordinate system (t, x, y, $(t, x, y, \zeta = (z-\delta)/h)$) is used. Here t is time, x and y are coordinates directed along parallel and meridian, ζ is a vertical non dimensional coordinate, $\delta(x, y)$ is a relief height above sea level, h = H - δ – troposphere thickness, $H(t, x, y)$ – tropopause height. The equation for dust concentration transfer and diffusion in the selected coordinate system will be written in the following form

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

where, C is concentration of dust; u, v, w and $\tilde{w}$ are wind velocity components along the x, y, z and ζ axes, w_o is dust deposition rate, $F(t, x, y\ \zeta)$ the rate of dust dissipation in the atmosphere by the source, μ and ν are coefficients of horizontal and vertical turbulence. Wind velocity components and coefficients of turbulence in the free atmosphere and surface layer of atmosphere are calculated by means of numerical integration of equations given in [9,10].

Dust propagation in the free atmosphere and surface layers of atmosphere is modeled through numerical integration of equation (1), using respective initial and boundary conditions. Numerical grid steps along the x and y axes equal to 300 and 400 m, and vertical non dimensional step in the free atmosphere is 1/31 and is equal to about 300 m. In the 100 m thick surface layer of atmosphere a vertical step varies from 0.5 to 15 m, while time step is 1 sec.

Calculations are made for 3-day period. The cases of western and eastern background light airs under dry weather conditions of June are considered. Background wind velocity equals to 1 m/sec at 100 m height above the ground, and 20 m/sec – in the tropopause (9 km altitude). Relative atmosphere humidity is 50%.

It is assumed that atmosphere is polluted by a dust originated at city mains and cities due to motor transport traffic. Its quantity changes in time and is determined according to assessment of continuous surveillance materials and transport traffic intensity. In Fig. 1 the relief of Tbilisi is shown. Pollution source distribution is marked in dark blue. They are mainly located at the central city mains and urbanized territories.

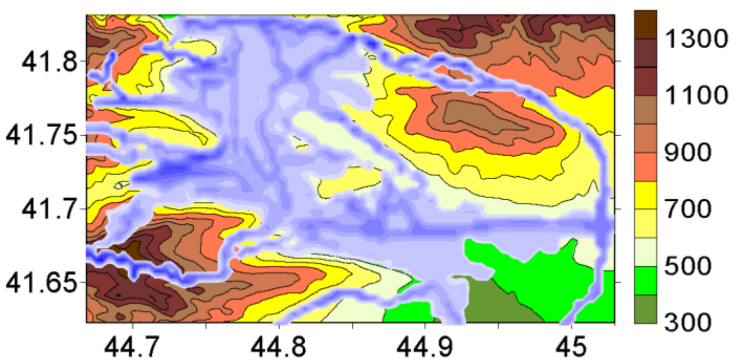

Fig.1. *Tbilisi city terrain heights (m) and pollution source distribution (blue zone and lines). Actual geographic coordinates are placed on the axes*

3. RESULTS OF NUMERICAL MODELING

In Fig. 2 and 3 there is shown the spatial distribution of dust concentration and wind velocity at 2, 100 and 600 m heights from the earth surface for t = 0, 3 and 6 h in case of eastern and western background light airs, obtained via calculations. Concentration is given in units of one-off maximum allowable concentration (MAC = 0,5 mg/m^3). It is seen from Fig. 2 and 3 that dust concentration spatial distributions, in case of eastern and western background light airs have both similar properties and significant distinguishing signs. Among similar properties are: concentration values starting with t = 0 h gradually reduce and reach minimum magnitude, when t = 6 h; maximum value of concentration equals to 0.7 MAC and is obtained in the surface layer of atmosphere, when t = 3 h; concentration values at the upper limit of the surface layer of atmosphere (at 100 m height from the earth surface) are higher or equal to those obtained at 2 and 100 m altitudes above the ground; the dust quantity taken out from the modeling area by dynamic and diffusion processes surpasses the quantity dissipated by vehicles, and due to this fact the process of atmosphere self-purification takes place in the time interval from t = 0 to 6 h. Distinguishing signs are: pollution level at the central and densely populated urbanized territories in case of eastern background light air is less than that of peripheral part. On the contrary, in case of western background light air a maximally polluted zone is obtained at the central and densely populated urbanized territories; the horizontal diffusion process and related dust transfer process are more intense in case of eastern background light air.

The differences in spatial distribution of concentration result from the influence of complex terrain. In case of eastern background light air, high mountains located in the western part of modeling area inhibit air flows free movement to the west and impede dust removal from city territory (Fig. 1, Fig. 2). At the same time, the relief generates a local-scale anticyclonic swirl, which cause dust relocation from the central part to peripheral areas by means of divergent velocity field. As a result, the dust concentration in the surface layer of the atmosphere and in the vicinity of main pollution sources is less than concentration obtained in the surroundings of recreational zones and sources with less pollution capacity. In case of western background light air there is a lowland territory in the south-eastern part of the city and there are no high orographic obstacles (Fig. 1). At that, the relief causes the wave disturbance of wind velocity only. As a consequence, a dust available in the air easily moves out of main pollution zones, its concentration is getting smaller in the central and peripheral parts of the city and remains slightly high along some city mains (Fig. 3).

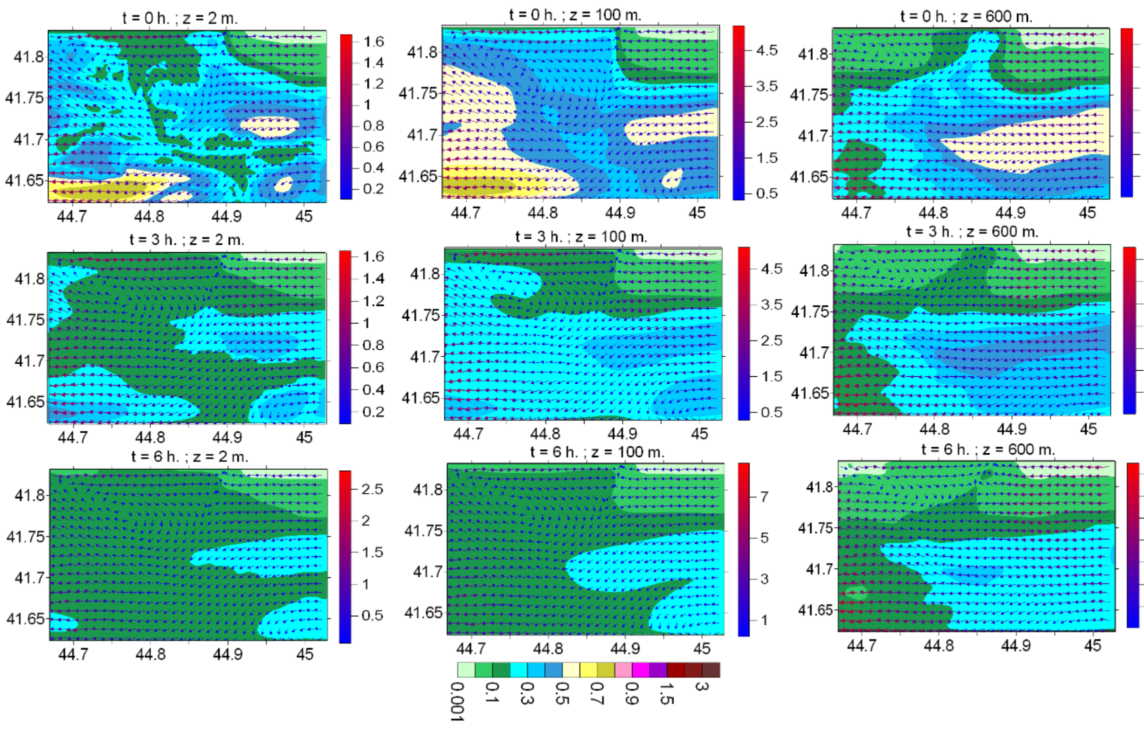

Fig. 2. *Distribution of wind velocity (m/s) and dust concentration (MAC) in case of eastern background light air, when t = 0, 3 and 6 h at 2, 100 and 600 m height from the earth surface*

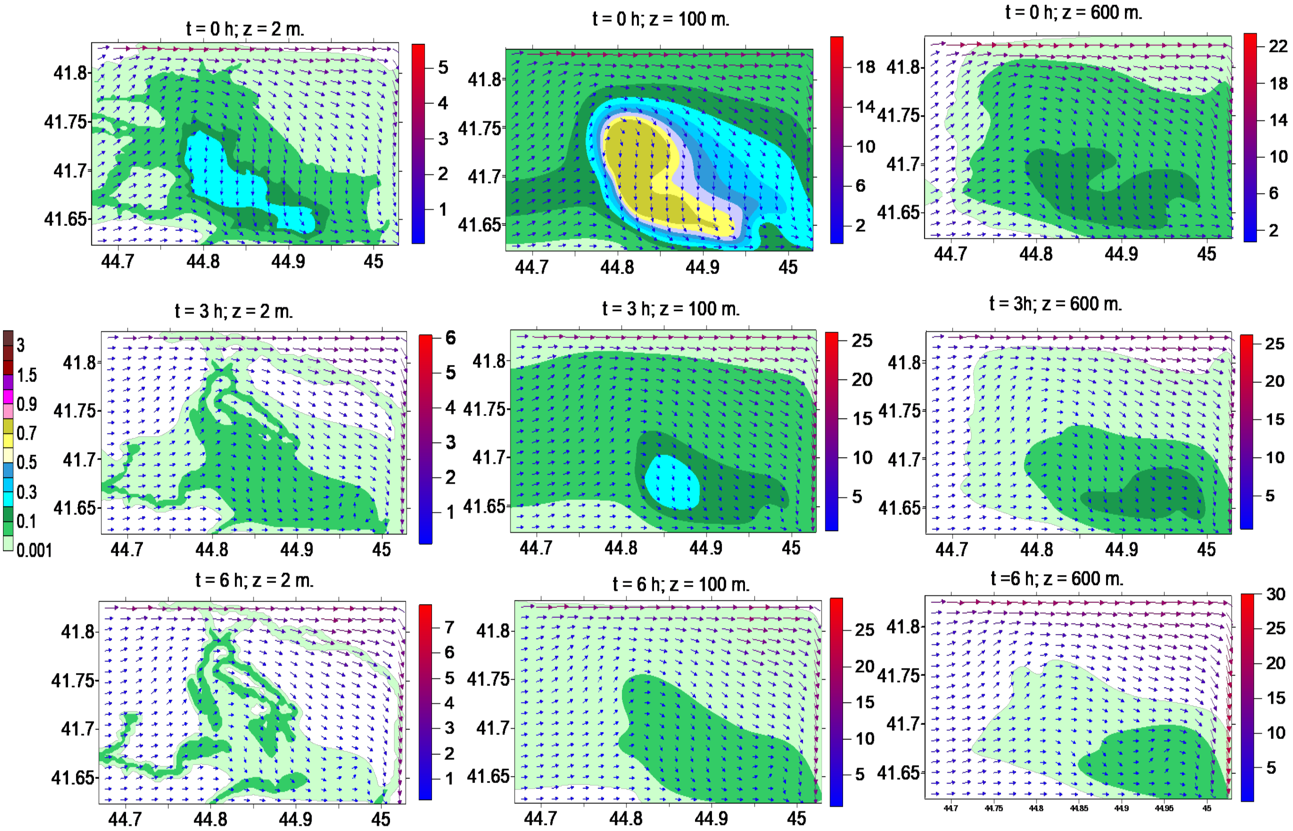

Fig. 3. *Distribution of wind velocity (m/s) and dust concentration (MAC) in case of western background light air, when t = 0, 3 and 6 h at 2, 100 and 600 m height from the earth surface*

In the process of numerical modeling the intensity of transport traffic is changed during day: from 6 AM to 9 AM the motor transport traffic intensity increases, from 9 AM to 11 AM intensity is constant and corresponds to the first "rush-hour" situation, from 11 AM to 5 PM period, traffic intensity slightly reduces. Along with traffic intensity change the quantity of dust hitting the atmosphere changes, as well, and this dust extends over the whole city and its adjusting territories by means of advective, convective and turbulent diffusive mechanisms. Dust spatial distributions obtained in this period through modeling in case of eastern and western light airs are shown in Fig. 4 and 5, respectively. It is clearly seen from the figures that in the lower part of the atmospheric boundary layer the dust propagation process has a qualitative difference. In case of western background wind, the mountains encircling the city from three sides, impede free movement of background flow to the west and together with underlying surface thermobaric field change develop local convergence and divergence zones of wind velocity, which are distributed in such a way that form the enclosed area of motion. Respectively, the dust taking-out from city territories inhibits and the level of city pollution increases (Fig. 4). Concentration growth takes place up to the midday. In the interval of t = 12-15 h a quasistationary state of the dust concentration is established. This time the concentration is high at main highways of every district of the city and its value varies within a range of 1-1.5 MAC. The level of pollution at the urbanized territory adjacent to the central part of the city is within 0.5-0.8 MAC in average.

Free taking-out of dust takes place in case of western background wind. As a result, from 6 AM to 9 AM time interval, on separate sections of highways located in the central and south-eastern parts of the city a relatively slight growth of dust concentration is obtained (Fig. 5). After 9 AM the level of city pollution drops until the second "rush-hour" (6 PM). From the midday to 6 PM the dust pollution level is non-uniformly distributed and 1 MAC concentration is obtained in the surroundings of several crossroads. Dust pollution level at 100 and 600 m height above the ground increases together with the rise of ground-level dust concentration.

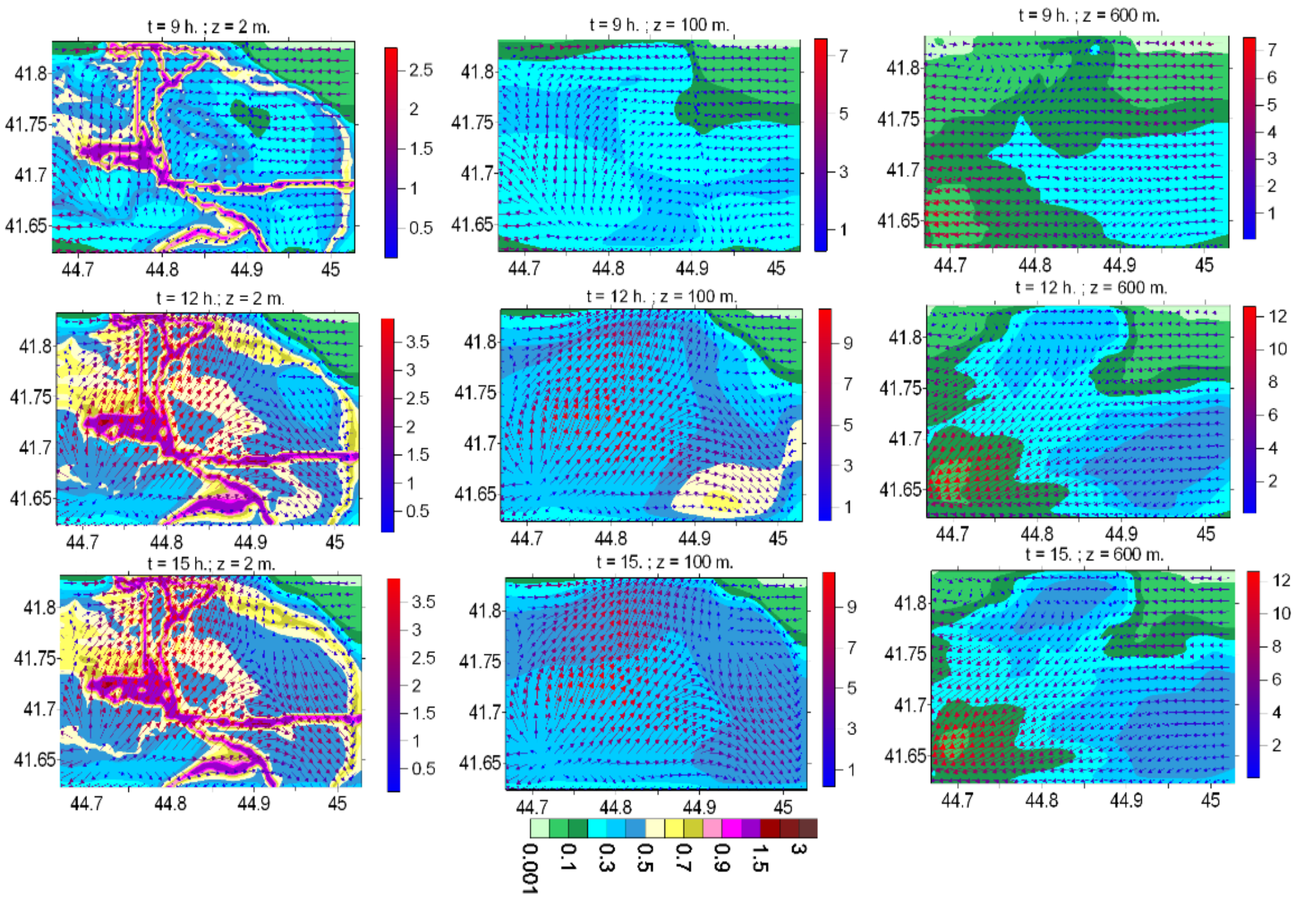

Fig. 4. *Distribution of wind velocity (m/s) and dust concentration (MAC) in case of eastern background light air, when t = 9, 12 and 15 h at 2, 100 and 600 m height from the earth surface*

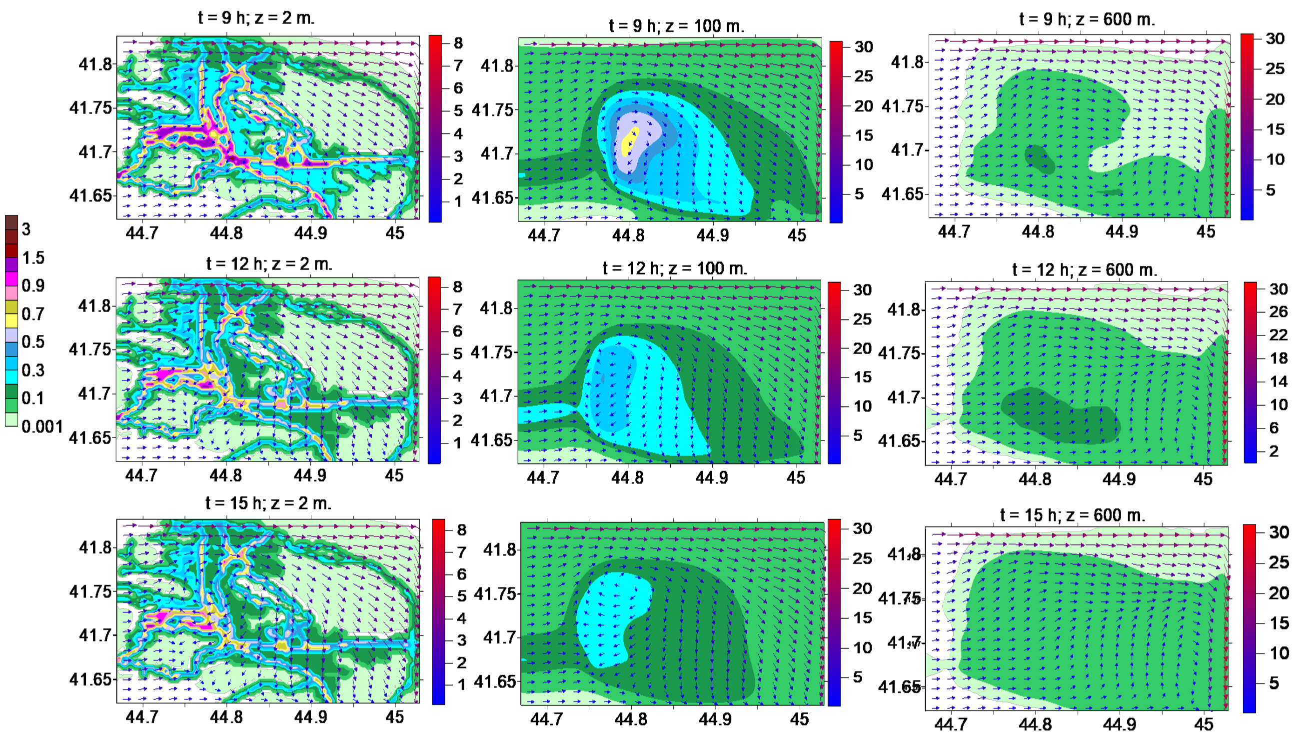

Fig. 5. *Distribution of wind velocity (m/s) and dust concentration (MAC) in case of western background light air, when t = 9, 12 and 15 h at 2, 100 and 600 m height from the earth surface*

In case of eastern background wind, in the second half of the day, from 6 PM to 9 PM, despite the second "rush-hour" situation with motor transport traffic, a quasistationary distribution of pollution is settled at 2 m height from the earth surface (Fig. 6). Wherein, there is no significant change in values of concentration, however partial extension and deformation of pollution zones takes place. At that, the "excessive" dust emitted during "rush-hour" situation extends towards the upper part of surface layer of the atmosphere that causes a substantial increase of concentration at 100 and 600 m height when t = 21h. Maximum values of concentration in the city center, in the southern part of modeling area are within a limit of 1.5-2.5 MAC. At 100 m height, the concentration is roughly equal to 1 MAC in the southern part of the city.

The dust propagation process in case of western background light air runs differently. The impact of "rush-hour" situation on atmosphere pollution becomes appreciable in the second part of a day. Calculations show that starting with 6 PM the concentration growth takes place not only in the central part of the city, but at the peripheral territories as well (Fig. 7). By 9 PM, the concentration at 2 m height from the earth surface reaches 2 MAC and afterwards it starts to reduce.

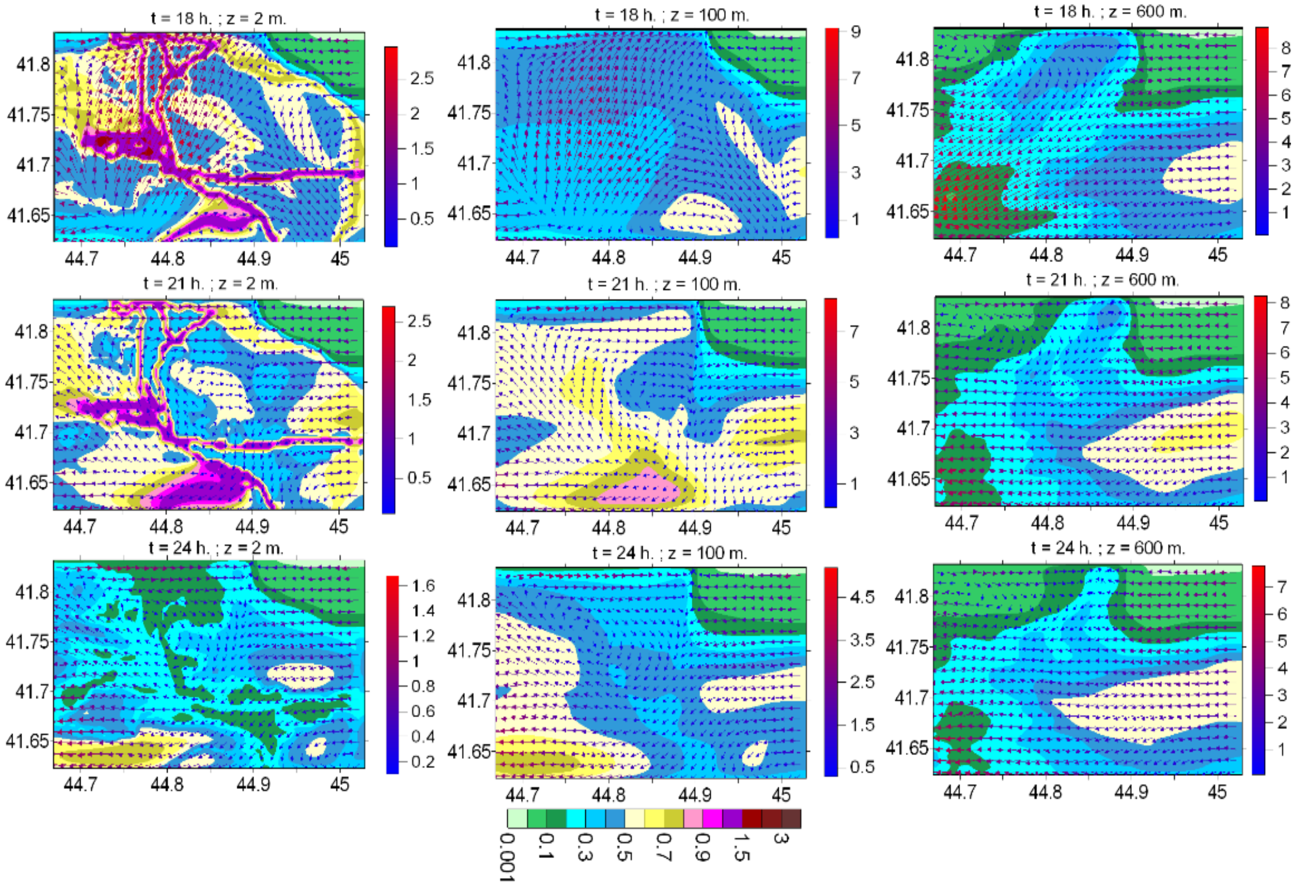

Fig. 6. *Distribution of wind velocity (m/s) and dust concentration (MAC) in case of eastern background light air, when t = 18, 21 and 24 h at 2, 100 and 600 m height from the earth surface*

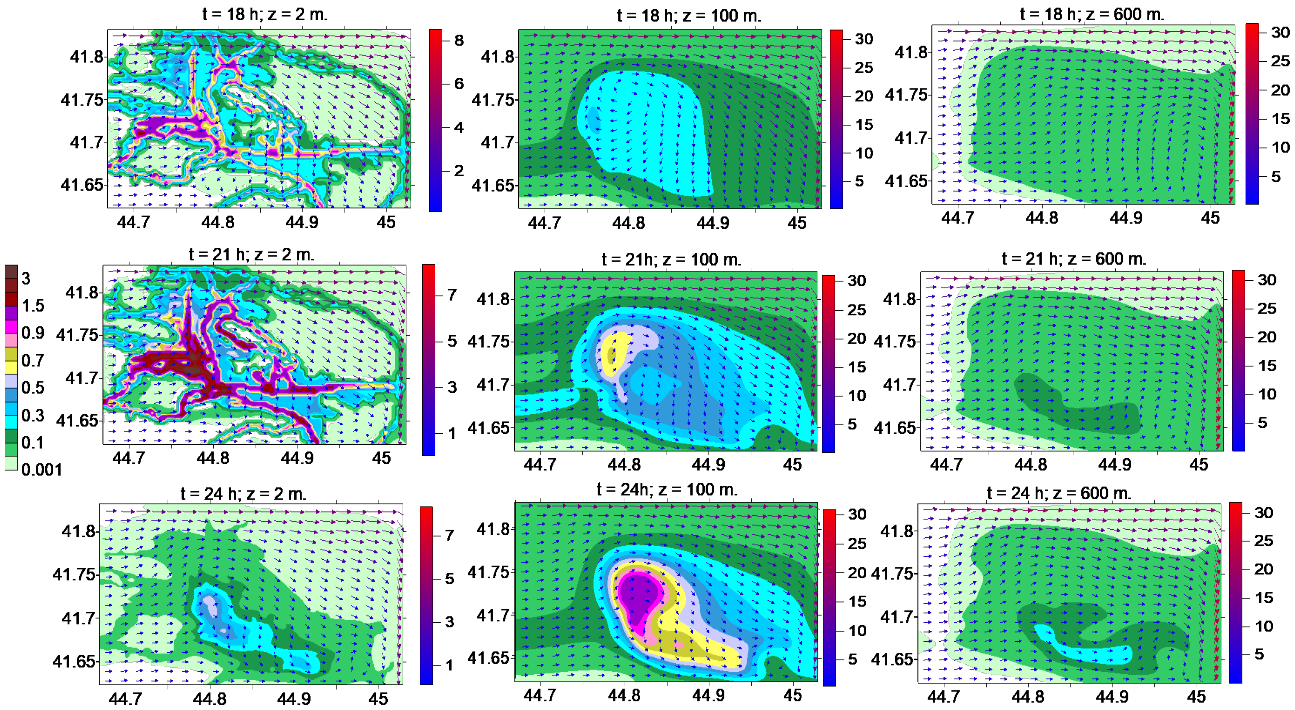

Fig. 7. *Distribution of wind velocity (m/s) and dust concentration (MAC) in case of western background light air, when t = 18, 21 and 24 h at 2, 100 and 600 m height from the earth surface*

The processes of dust vertical transfer in the surface layer of the atmosphere are different, as well. In case of eastern background light air, the dust concentration change occurs synchronously at 2 and 100 m height, while during western background wind this process runs with 3-hour phase delay.

CONCLUSION

Change of kinetics of distribution of the dust generated by motor transport at the territory of Tbilisi is explored using numerical modeling for main two meteorological situations: in case of eastern and western background light airs. Daily change of dust spatial distribution is studied. Via modeling there are obtained concentration values, which are within a limit of magnitudes obtained via routine observations. Through analysis of the fields of wind velocity and dust concentration there is established that the spatial distribution of heavily polluted areas depends on the motor transport traffic intensity and city mains disposition, on one hand and on local circulation systems formed through diurnal temperature variation in the surface layer of the atmosphere.

There are explored those main differences and similar properties that are originated in case of background winds of both direction peculiar for the city. By means of modeling there is established that in case of eastern background light air the wind velocity field formed under the influence of terrain impedes the process of dust taking-out from the city and creates the area of high dust pollution level at the large territory of the city with 2-2.5 MAC maximum concentration. As for western background light air, the wind velocity field promotes the “self-purification” process of city atmosphere and high level of dust pollution is registered during “rush-hour” situation with motor transport traffic. At that, in a period of the second “rush-hour” situation the concentration significantly increases in the central part of the city and in the surroundings of connecting avenues.

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