

# ASSESSMENT OF KUTAISI CITY ATMOSPHERIC AIR POLLUTION WITH THE HIGH RISK-FACTOR PM<sub>2.5</sub> PARTICLE BY MEANS OF NUMERICAL MODELING

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## Abstract

*The spatial distribution and temporal variation of highly dangerous PM<sub>2.5</sub> particles in the atmosphere of Kutaisi, one of Georgia's most important tourist and recreational centres, has been studied using numerical modelling. This modelling was achieved through the combined integration of 3D non-steady nonlinear equations of mesoscale atmospheric processes and equations of air contaminant transfer and diffusion. The distribution of PM<sub>2.5</sub> emitted by motor vehicles into the air in Kutaisi in winter during a gentle background breeze has been modelled and analyzed numerically. Graphs showing the time-dependent changes in PM<sub>2.5</sub> concentration at different points in the city were plotted based on the calculated results. It was shown that, at a height of 2 m above the ground, the time change in the concentration of pollutants in the morning, evening and night hours is mainly determined by motor traffic intensity, while during the day it is mainly determined by local thermal and dynamic processes. The characteristics of the spatial distribution of PM<sub>2.5</sub> particles in the surface and boundary layers of the atmosphere have been obtained. The expected times and areas of high pollution have been identified. It has been demonstrated that pollution primarily occurs in the central part of the city and around highways passing through adjacent territories. Aerosol propagation in the upper part of the surface layer and in the boundary layer of the atmosphere mainly occurs in the direction of the background wind, with less dependence on local relief and the location of emission zones.*

**Keywords:** PM<sub>2.5</sub>, atmospheric pollution, numerical modeling, concentration, gentle breeze

## I. Introduction

Aerosol pollution of the atmospheric air is a phenomenon of high risk-factor for human health [1-6]. It is dangerous not only for population of heavily polluted industrial centers, but also for relatively clean separate regions and cities of Europe and Asia [4-6]. Microparticles PM<sub>2.5</sub> and PM<sub>10</sub> have especially negative effect on human health. They are absorbed through aspiration ways and frequently cause oncological, cardiovascular and other diseases. Investigations showed that in 2021 the global life shortening caused by air pollution comprised 1 year, while in some countries of Africa and Asia reached 1.2-1.9 years [4-5]. The problem of PM pollution of the atmosphere has been thoroughly examined in the fundamental work [8].

Air-protection measures carried-out in the XXI century by developed countries of the world have led to reduction of microparticle emission into atmosphere and improvement of air purity degree. Nevertheless, air pollution level in a wide range of cities still exceeds international standards [9-12]. In the cities with developed environmental pollution monitoring services, the

atmospheric air purity degree is assessed through analysis of operating supervision data [4, 6, 7]. In such places, where observation data are incomplete or insufficient, namely computer modeling of polluting agents propagation is one of the ways of environmental pollution level assessment [12-16].

Kutaisi is the second largest city of Georgia. It has very important administrative, international, medical and health-promoting, and touristic destination, due to which hundreds of thousand humans visit it every year. Based on the city function, study and assessment of environmental state, diagnostic forecast of pollution level and maintenance of high level of air purity are of special importance. PM2.5 and PM10 monitoring in the city has been started since 2018 and is implemented in 2 fixed surveillance points. According to obtained data, Kutaisi is not ranked among heavily polluted cities [11], though in some cases PM2.5 concentration in the air exceeds maximum permissible concentrations [10, 17]. At the same time, it should be noted that a monitoring carried out in two observation points is not enough to completely reflect the complete picture with urban air purity in terms of PM2.5. That is why, in order to overcome the above-mentioned problems, the propagation pattern and time behavior of PM2.5 generated by motor transport and emitted into atmosphere of Kutaisi and adjacent territories has been simulated and analyzed in the presented article using computer modeling of atmospheric propagation of admixtures.

## II. Research method

An equation describing atmospheric transfer and diffusion processes of admixtures in the area of complex orography may be written as follows [18]

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

here  $t$  is time,  $x, y$  and  $z$  – coordinates along parallel, meridian and directed upward vertically,  $\zeta = (z - \delta)/h$  – dimensionless vertical coordinate,  $\delta(x, y)$  – terrain height over sea level;  $h = H - \delta$  – tropopause thickness,  $H(t, x, y)$  – tropopause height;  $C$  – ingredients' concentration;  $u, v, w$  and  $\tilde{w}$  – wind velocity components along  $x, y, z$  and  $\zeta$  axes;  $w_0$  – precipitation rate of polluting ingredients;  $F(t, x, y, \zeta)$  – rate of ingredients atmospheric emission by the source;  $\mu$  and  $v$  – coefficients of horizontal and vertical turbulence. Wind velocity components, coefficients of turbulence in free atmosphere, surface and boundary layers of the atmosphere are calculated by means of equations and formulas given in [8, 9].

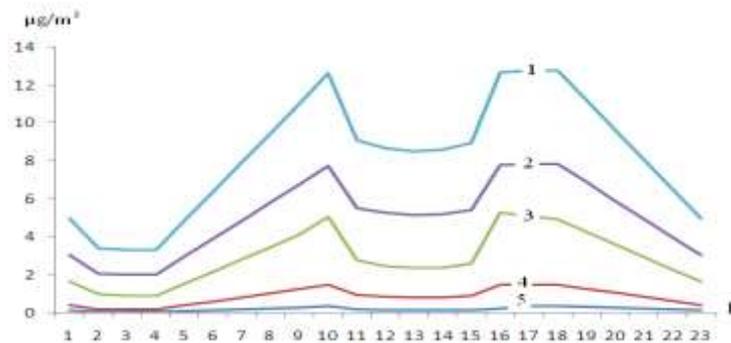
PM2.5 aerosol propagation has been numerically modeled at the  $13.4 \times 13.4 \times 9$  km<sup>3</sup> space domain (Fig. 1), with Kutaisi in its center. Orography height in the modeling area varies from 80 to 400 m. Numerical integration of equations of the mathematical model given in [19, 20, 21] has been made using relevant initial and boundary conditions. Numerical grid steps in horizontal direction equal to 200 m, and in vertical direction in free atmosphere – 300 m. Vertical steps in 100 m thick surface layer of the atmosphere vary from 0.3 m to 15m. Time step is 1 sec. Calculation have been made for 3-day period.

## III. Numerical modeling results

PM pollution of Kutaisi atmosphere in December has been modeled. There is a gentle breeze at 100 m height of surface layer of the atmosphere – wind velocity is 6 m/s. Above surface layer of the atmosphere there is a western wind, which velocity linearly increases with height and reaches 20 m/s at 9 km altitude. Relative atmospheric humidity is 50%. It is assumed that PM2.5 pollution of the atmosphere is caused by motor transport traffic in the city and its adjacent territories. Aerosol is emitted from the earth surface to 0.3 m height in 5 types of areas: at the territories of

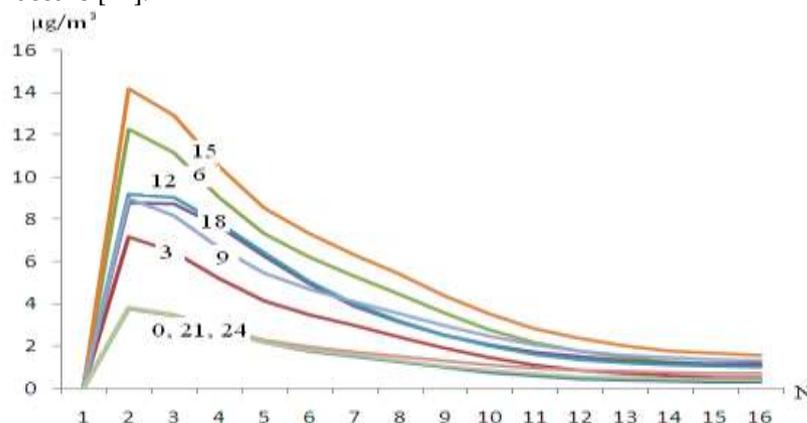
highways, central city streets, residential, industrial zones, adjacent villages and unpopulated territories. Emission rate is different depending on areas, periodical with 24-hour periodicity and proportional to motor transport traffic intensity. It is minimal in the interval of 0-4 h, afterwards linearly increases from 4 to 10 h, and is constant in time interval from 10 to 18 h. Within time period from 18 to 24 h emission rate linearly decreases and by 0 h becomes equal to existing emission rate. Maximum emission rate is 12.5  $\mu\text{g/s}$ .

In Fig. 1 there are shown the graphs of time change of PM2.5 concentration obtained via calculations for points with 5 basic types of pollution. It is seen from Fig. 1 that time change of concentration is qualitatively similar for points with all type of pollution and is characterized by 2 intervals of large values and 2 ones of small values. Large concentration values are obtained at 10 h and within time interval from 16 to 19 h, while small ones – in the intervals from 2 to 4 h and from 12 to 15 h.



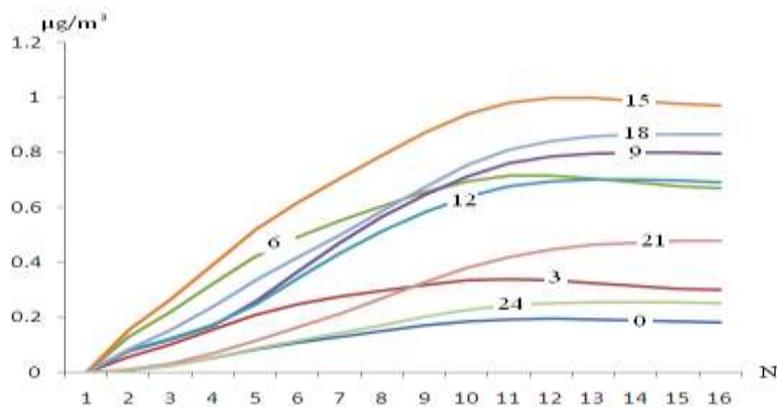
**Figure 1:** Time change of PM2.5 concentration obtained via calculations at the territories of highway (1), city central streets (2), industrial (3), rural (4) zones and unpopulated points (5) at the 2m height from earth surface

It should be noted that time change of concentrations in case of identical meteorological and pollution conditions, partially differ in quantity and quality terms from each other in winter and summer seasons [20,21]. While in summer season, the second concentration maximum is obtained around 20 h and further starts to reduce, in winter season the second concentration maximum is obtained by 16 h and is preserved for 3 hours. From 11 to 17 h an aerosol emission rate is constant. Despite this fact, a paraboloidal reduction of concentration in time takes place in points of all types, during which a minimal concentration value is obtained within 12-15 h interval of time. Physically, the mentioned change is associated with thermal interaction of underlying surface and air masses located nearby, during which a change of atmosphere stratification and air turbulization pattern occurs [21].

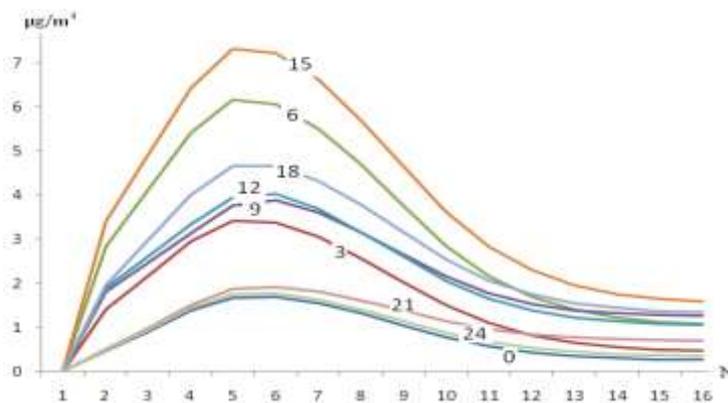


**Figure 2:** Vertical distribution of PM2.5 concentration in the point located at highway in surface layer of the atmosphere, when  $t = 3, 6, \dots, 24$  h ( $N$  is vertical numerical grid number)

In Fig. 2-4 there are shown PM2.5 concentration values obtained via calculation in surface layer of the atmosphere in vertical grid points located at highway, industrial and rural territories. It is seen from Fig. 2-4 that vertical distribution of concentration in the mentioned points substantially differs from each other. There is both qualitative and quantitative difference. At different points of time, maximum concentration values in points located at highway are within limits of 4-14  $\mu\text{g}/\text{m}^3$  and they are obtained in N = 2 point (0,3 m) of the vertical grid located in the close proximity to underlying surface. With a distance from earth surface the concentration decreases. This reduction is intense in the lower 10 m thick layer (N = 5). Above 10 m, concentration reduces more smoothly, at slow rate and at 100 m height (N = 16) its values don't exceed 2  $\mu\text{g}/\text{m}^3$ .



**Figure 3:** Vertical distribution of PM2.5 concentration in the point located at the territory of agricultural purpose in surface layer of the atmosphere, when  $t = 3, 6, \dots, 24$  h (N is vertical numerical grid number)



**Figure 4:** Vertical distribution of PM2.5 concentration in the point located at the territory of industrial purpose in surface layer of the atmosphere, when  $t = 3, 6, \dots, 24$  h (N is vertical numerical grid number)

There is an opposite vertical distribution of concentration in the points of agricultural purpose (Fig. 3). It is minimal in a close proximity to underlying surface (0-0,1  $\mu\text{g}/\text{m}^3$ ), increases with height and at 12, 18 and 21 h varies within limits of 0,2-1  $\mu\text{g}/\text{m}^3$  at 60 m height (N = 12). The mentioned growth of concentration is caused by ensuing horizontal diffusion of aerosol transferred upward vertically from severe pollution source.

The graph of vertical distribution of concentration in different points of time over the point located in industrial area is highly interesting (Fig. 4). It is similar to graph of Gaussian Distribution formula and is characterized by rapid growth of concentration in the lower part of surface layer

up to 15 m height ( $N = 6$ ). At this level its value reaches  $7,5 \mu\text{g}/\text{m}^3$ . Above 15 m concentration is reduced at relatively slow pace and at 100 m height concentration values drop to  $0,3\text{-}1,5 \mu\text{g}/\text{m}^3$ .

Fig. 5-7 show the fields of wind velocity and PM2.5 particles during a day with 3-hour intervals at 2, 100 and 600 m heights from earth surface. As is seen from these Figures, the effect of Kutaisi terrain on background flow doesn't cause noticeable change of local wind. There is a western wind in boundary layer of the atmosphere and its value in the surface layers varies within limits of 2-13 m/s. As for spatial distribution of concentration, it is qualitatively similar when  $h = 0$  and 3 h at 2 m height from earth surface, and the quantitative difference between them is negligible (Fig. 5). Concentration values at highways and urbanized territories of the city don't exceed  $5 \mu\text{g}/\text{m}^3$ , while PM2.5 concentration at rural areas and unpopulated territories is less than  $1 \mu\text{g}/\text{m}^3$ . Pollution level increases with rise of motor transport traffic intensity. By  $t = 6$  h, PM2.5 concentration at separate territories of Gamarjveba, Ukimerioni, City-Museum and Kakhianouri administrative units reaches  $10 \mu\text{g}/\text{m}^3$ . Concentration growth up to  $5 \mu\text{g}/\text{m}^3$  is obtained in the surrounding of highways and central avenues. When  $t = 0$  and 6 h (at night) concentration values at 100 m height reach 0,7 and  $1 \mu\text{g}/\text{m}^3$ , respectively, while at 3 h –  $0,5 \mu\text{g}/\text{m}^3$  (Fig. 5). As for higher levels (600 m), concentration values are within several hundredth of  $\mu\text{g}/\text{m}^3$ . Pattern of surface distribution of concentration shows that there is an intense carry-over of ingredients to the east, in direction of background wind.

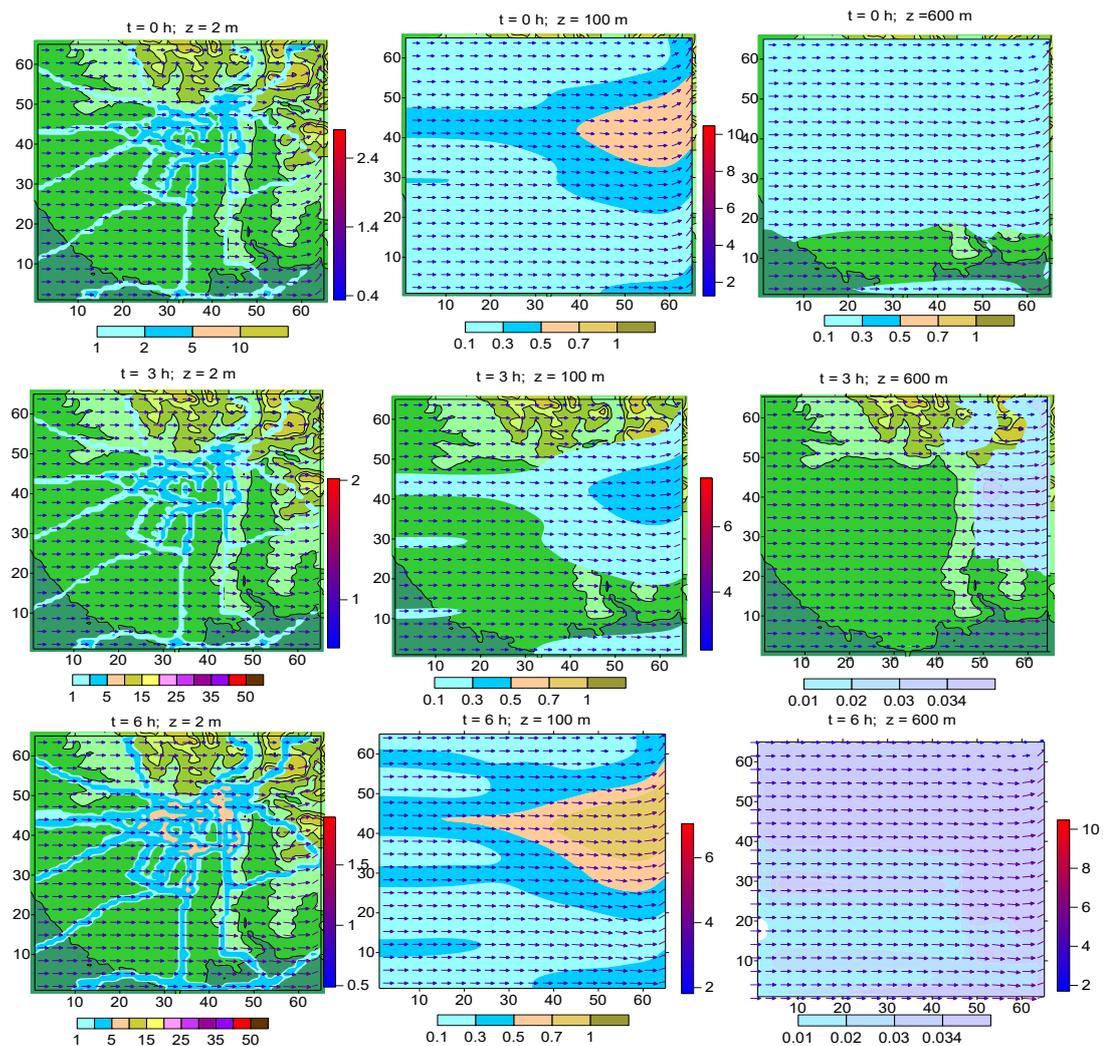
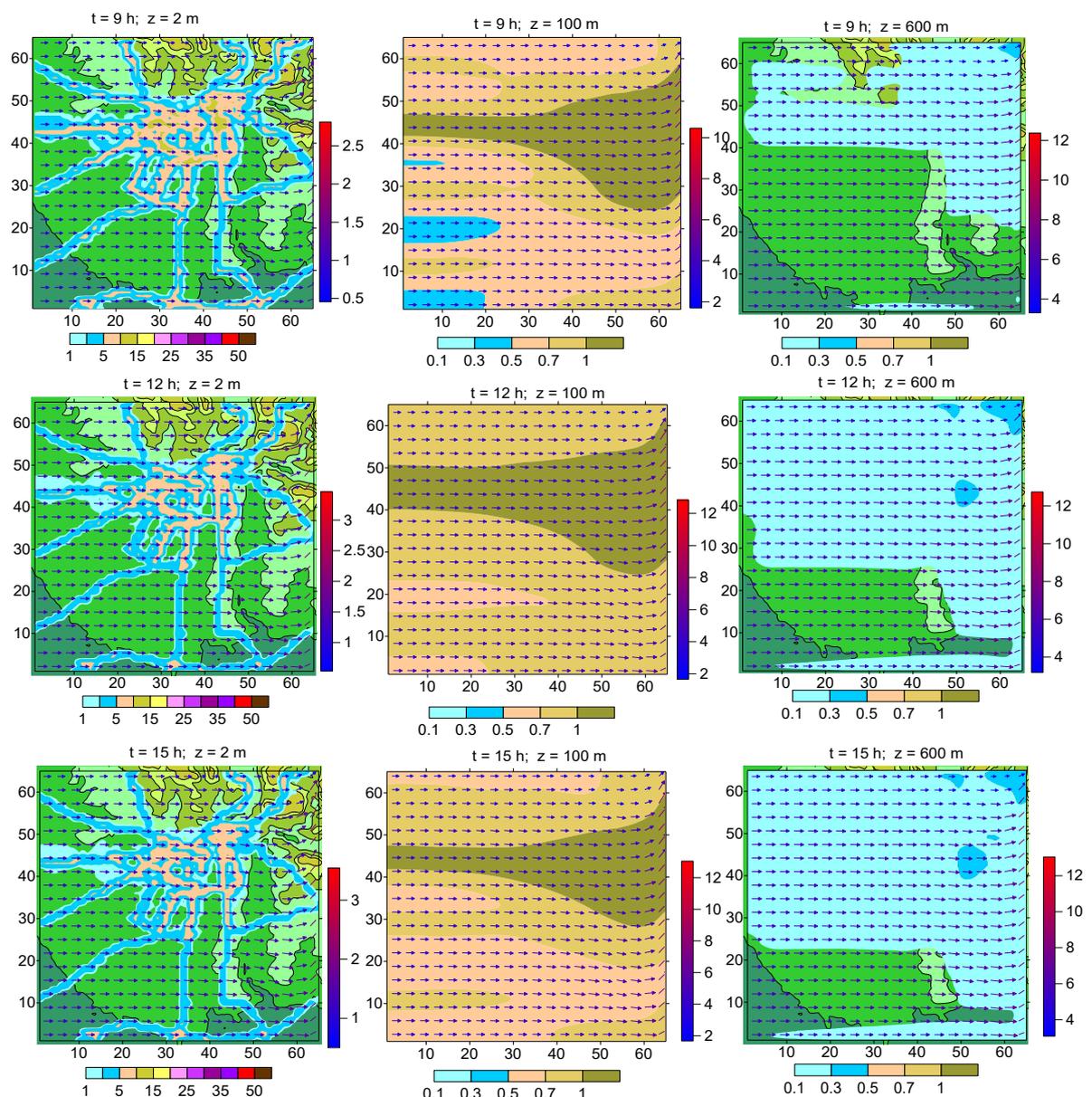


Figure 5: Distribution of PM2.5 concentration ( $\mu\text{g}/\text{m}^3$ ) and wind velocity (m/s) fields at 2, 100 and 600 m heights from earth surface, when  $t = 0, 3$  and  $6$  h

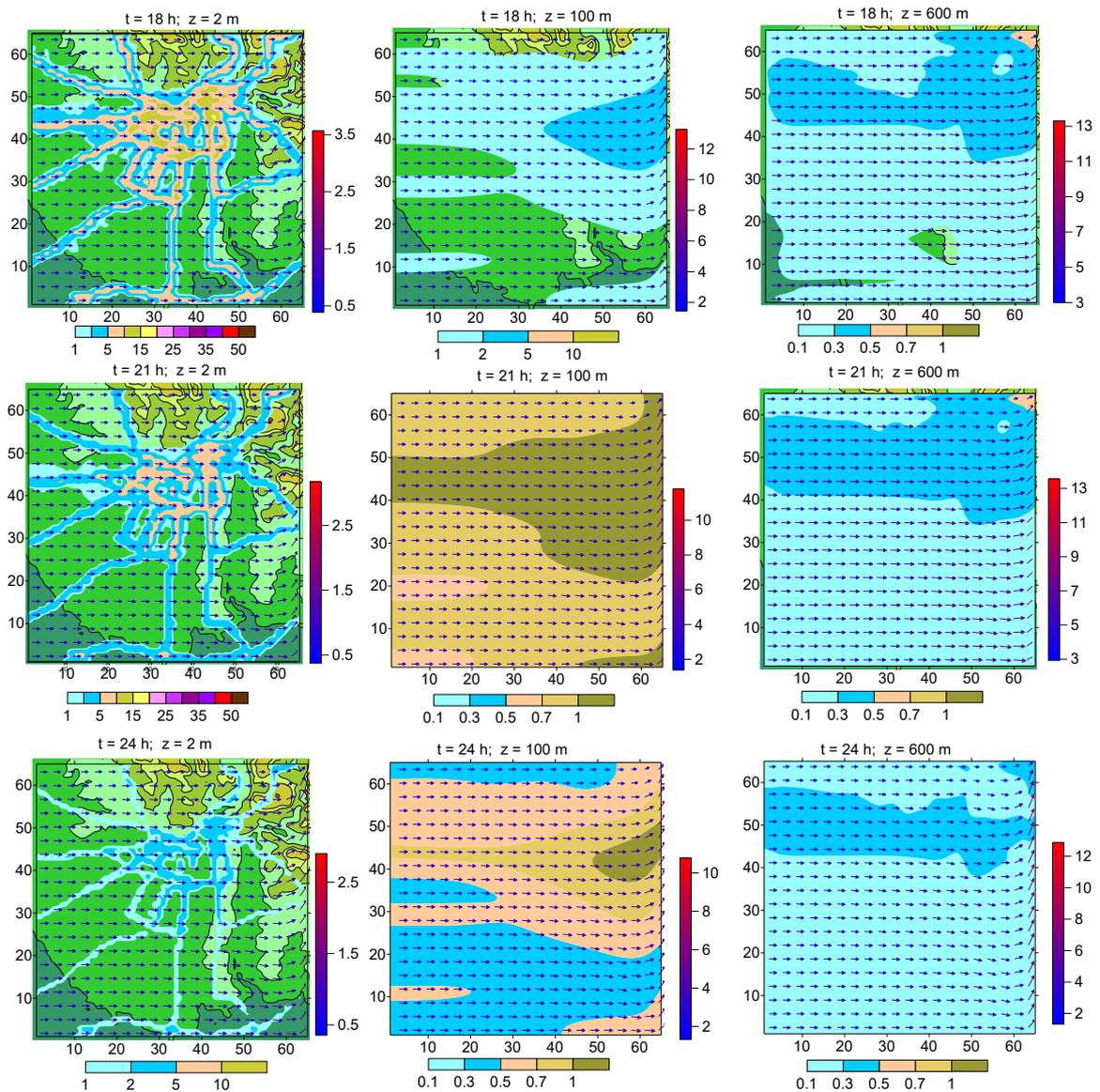
It is seen from Fig. 6 and 7 that in time interval from 9 to 18 h, concentration values at 2 m height from earth surface at urbanized territories of the city and in the vicinity of highways are mainly within  $5\text{-}15 \mu\text{g}/\text{m}^3$ . When  $t = 9$  and  $18$  h, concentration is high at some places of heavy motor traffic of Gamarjveba, City-Museum, Kakhianouri and Ukimetrioni administrative units. Maximal values at these territories reach  $10\text{-}15 \mu\text{g}/\text{m}^3$ .

From 9 to 15 h and then, within interval from 15 to 18 h, microaerosol content in the ground air reduces first, and afterwards increases and reach maximum –  $15 \mu\text{g}/\text{m}^3$ . After 19h, concentration starts to reduce. By  $t = 24$  h, the pattern of its spatial distribution at 2 m height from earth surface is similar to that obtained for  $t = 0\text{-}3$  h (Fig. 7). At higher levels, there is a definite qualitative and quantitative difference. At 100 m height, concentration increases after 18 h and by 21 h reaches maximal value –  $1,3 \mu\text{g}/\text{m}^3$ . After  $t = 21$ h, concentration reduces little by little. As for 600 m height, concentration values at this level are within  $0,1\text{-}0,3 \mu\text{g}/\text{m}^3$ , and decrease at slow pace with the passage of time



**Figure 6:** Distribution of PM2.5 concentration ( $\mu\text{g}/\text{m}^3$ ) and wind velocity (m/s) fields at 2, 100 and 600 m heights from earth surface, when  $t = 9, 12$  and  $15$  h

In Fig. 8 there is shown vertical distribution of PM2.5 concentration in surface layer of the atmosphere obtained via modeling in zonal section passing through the central part of the city. It is seen from Fig. 8 that PM2.5 propagation in atmospheric air occurs as a result of both turbulent diffusion and advection and convection processes. These processes form thermals in 10-20 thick



**Figure 7:** Distribution of PM2.5 concentration ( $\mu\text{g}/\text{m}^3$ ) and wind velocity (m/s) fields at 2, 100 and 600 m heights from earth surface, when  $t = 18, 21$  and  $24$  h

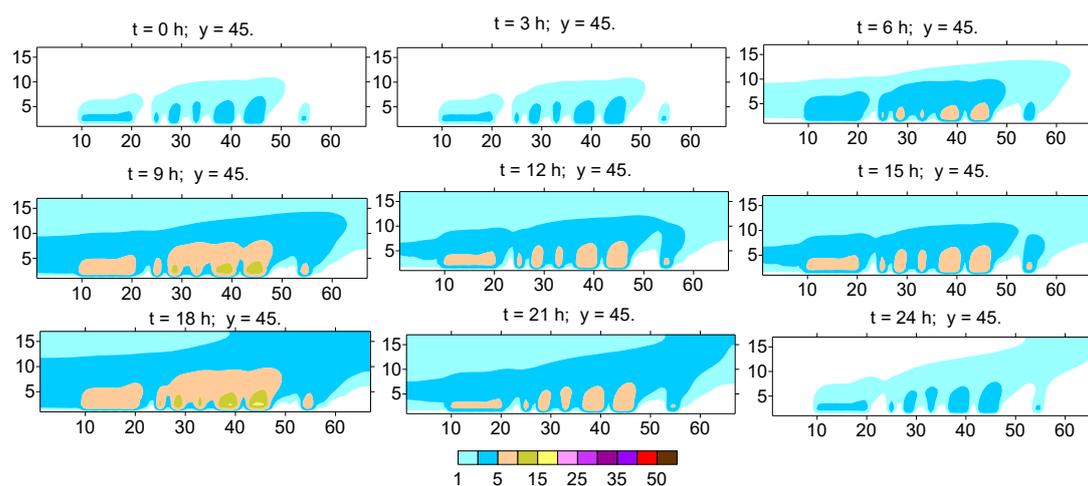
surface layer of the atmosphere, which are caught taken up to the upper part of surface layer of the atmosphere by background flows of eastern direction.

## IV. Discussion

Kutaisi atmosphere pollution with PM<sub>2.5</sub> – one of the most dangerous substances with high risk-factor has been studied in the work. Microparticles emitted into atmosphere by the motor transport represent pollution source when conducting numerical modeling. As far as there are no large industrial enterprises in the city, the mentioned assumption is quite acceptable in a first approximation. In future studies it would be reasonable to take into account background values of PM<sub>2.5</sub> concentration in the city and its adjacent territories, emission of small-size enterprises operating in the city and pollution caused by household activity. Improvement of modeling by means of reduction of the horizontal grid steps is scheduled also.

## V. Conclusions

Peculiarities of spatial distribution and time change of PM<sub>2.5</sub> generated by motor transport at the territory of Kutaisi in winter season during western medium-powered background wind have been investigated via numerical modeling. It has been shown that the relief of Kutaisi and adjacent territories causes no changes in wind direction. Patterns of spatial distribution of PM<sub>2.5</sub> concentration have been obtained as a result of modeling. Nature of time change of concentrations



**Figure 8:** PM<sub>2.5</sub> ( $\mu\text{g}/\text{m}^3$ ) distribution in surface layer of the atmosphere in vertical cross-section along the parallel passing through the city center

both in surface and boundary layers of the atmosphere has been established. It has been shown that during medium-powered background wind, the processes of diffuse and advective transfer promote admixtures' displacement from modeling area and atmosphere self-purification process. As a result, there is no formation of especially heavily polluted areas. City atmosphere is mainly polluted in the central urbanized parts of the city, where maximal concentration values don't exceed  $15 \mu\text{g}/\text{m}^3$ . Peculiarities of diurnal variation of vertical distribution and concentration of PM<sub>2.5</sub> emitted into atmosphere at the territories of city highways, industrial and agricultural areas have been investigated.

### CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

**Acknowledgments.** The scientific research has been funded and performed with financial support of the Shota Rustaveli National Science Foundation within the grant project FR-22-4765.

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