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NUMERICAL MODELING OF PM2.5 PROPAGATION IN TBILISI ATMOSPHERE IN WINTER.

I. A CASE OF BACKGROUND NORTH LIGHT WIND

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Summary: *PM2.5 propagation at Tbilisi territory in winter period in case of background north light wind is numerically modeled and analyzed through combined integration of 3D regional model of atmospheric processes evolution and equation of admixtures transfer-diffusion. Motor transport moving at city streets and trunk lines is a main source of atmosphere pollution. There are investigated the main peculiarities, which characterize the process of microaerosols spatial distribution under rugged terrain conditions. PM2.5 high concentration zones are established at the territory of city, time intervals, when high air pollution forms or air self-purification takes place, are determined. Temporal and spatial variations of PM2.5 concentration in the lower part of atmospheric boundary layer are studied. It is established that 25 mkg/m^3 and higher concentration is obtained from 11AM to 1PM and from 7PM to 10PM in the surroundings of Ponichala situated in the eastern part of the city.*

***Key Words*:** PM2.5 concentration, atmosphere pollution, numerical modeling.

Introduction

Atmospheric air pollution may be one of the contributing factors of COVID-19 pandemic [1]. PM2.5 and PM10 microparticles present in the air are especially dangerous from this viewpoint. They have double negative effect ability. On one side, they easily penetrate into human body and cause pulmonary and cardiovascular diseases [2-4]. On the other, as virus carriers they promote COVID-19 virus penetration into organism and complication of current cardiologic, pneumonic, urological and other diseases that is highly dangerous during pandemic. Studies carried out in 70 cities of China showed that there is a direct link between number of COVID-19 diseases and time variation of PM2.5 concentration level [5, 7]. That is why, under current conditions, study of large cities atmosphere pollution with PM2.5, and temporal and spatial variation of its concentration is a very topical problem, which is urgent for Tbilisi, as well, where an acute pandemic situation exists for the second straight year.

Brief statement of the problem

There are no large industrial facilities in Tbilisi. However, thousands of vehicles move up and down in its narrow streets and trunk roads of a rugged terrain. That is why, an assumption is made in this work that the main source of atmosphere pollution with PM2.5 is represented by microaerosols getting on air resulting from motor transport traffic. Spatial distribution of pollution source and city orography are shown in Fig. 1.

In Fig. 2 there is shown a time variation of PM2.5 emission rate at 0,5 m height from the earth surface in 1 m^3 volume in case of 3000 veh/h traffic intensity at trunk road. It is obtained through experimental measurements, analysis of National Environment Agency data obtained from observation points and results of carried-out numerical experiments. At that, it is assumed that time variation of PM2.5 atmospheric emission rate at other trunk roads is similar to those shown in Fig. 2 and is proportional to motor transport traffic intensity.

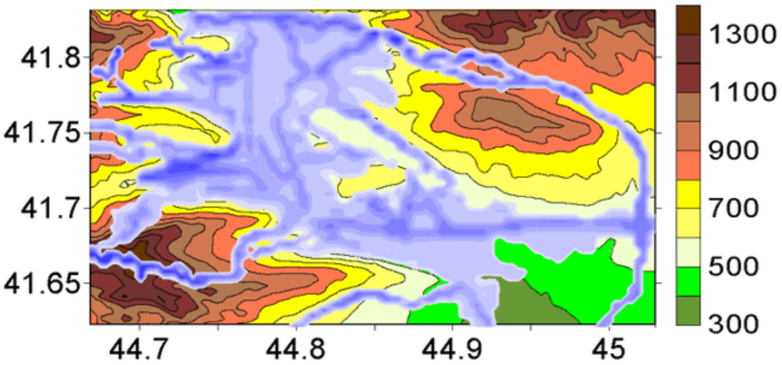

Fig. 1. Tbilisi city orography (m) and spatial distribution of pollution sources (dark blue areas).

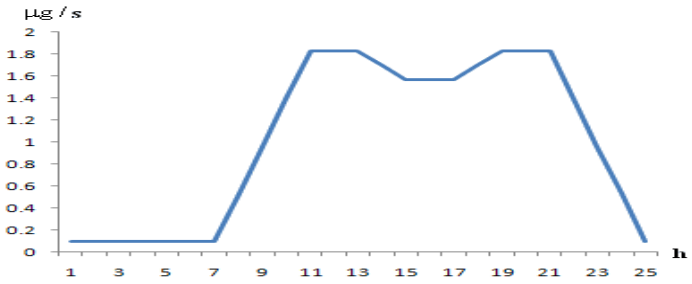

Fig. 2. Temporal variation of PM2.5 emission rate in 1 m^3 volume area at road with maximum traffic intensity (3000 veh/h)

Numerical model of development of meso-scale atmospheric processes in Caucasus and polluting ingredients propagation is used for study of time variation of PM2.5 concentration and its spatial distribution [8, 9]. Equation used during modeling, which describes the process of atmospheric propagation of passive admixtures at territories with a rugged terrain, can be written as follows:

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

where t is time, x and y – coordinates plotted along parallel and meridian, $\zeta=$ ¿ – dimensionless vertical coordinate, $\delta(x,y)$ – terrain height above sea level; $h=H-\delta$ - troposphere thickness, $H(t,x,y)$ – tropopause height, C – ingredients concentration; u, v, w and $\widetilde{w}$ – wind velocity components along x, y, z and ζ axes; w_o – dust precipitation rate; $F(t,\ x,y,\ \zeta)$ – dust discharge into atmosphere by a source; µ and ν – factors (coefficients) of horizontal and vertical turbulence. Wind velocity components and turbulence factors can be calculated through numerical integration of equations given in [7, 8] and formulas determining turbulence factors.

Dust propagation in free atmosphere and surface layer of the atmosphere is modeled via numerical integration of equation (1), using the corresponding initial and boundary conditions. Numerical grid steps along x and y axes are equal to 300 and 400 m, and vertical dimensionless step in free atmosphere is 1/31 that roughly corresponds to 300 m. Vertical step in 100 m thick surface layer of the atmosphere varies from 0,5 to 15 m. Time step is 1 sec. Calculations are made for 3 day-and-night periods. Cases of background north light wind (BNLW) and background eastern light wind (BELW) under dry weather conditions of January are considered. Wind velocity varies from 1 m/sec (at 100 m from earth surface) to 20 m/sec (in tropopause at 9 km altitude). Relative atmospheric humidity is 50%.

Analysis of modeling results

In Fig. 3 there are shown the fields of wind velocity (m/sec) and PM2.5 concentration (mkg/m^3) obtained through numerical integration in the surface layer of the atmosphere – at 2, 100 m and boundary layer – at 600 m altitude, when t = 3 h and 6 h in case of background south light wind with 1 m/sec value. It is seen from Fig. 3 that terrain effect in surface and boundary layers of the atmosphere causes wavelike disturbance of wind velocity directed from the north to the south, a main stream of which follows the course of Mtkvari valley. Wind velocity value varies within limits of 1-6 m/sec.

Wind field promotes taking out of PM2.5 particles available in the city from urban territories towards south-eastern direction and reduces surface wind pollution. In the course of the first 6 hours of a day, at 2 m height from a ground spatial distribution of concentration is qualitatively uniform: concentration in the outskirts of the city is 0,01-0,1 mgk/m^3, at urbanized territories and in the eastern part of the city concentration values are mainly within limits of 0,1-1 mgk/m^3. Concentration value 5-10 mgk/m^3 is obtained in two parts of the city only – westward, in the surroundings of avenues situated in Vake-Saburtalo districts and in the eastern part – along the Kakheti highway.

Concentration values at 100 m height from a ground at 3 and 6 in the morning differ from each other. While at 3 in the morning concentration over the city is mainly within 0,1-1 mgk/m^3, by 6AM a pollution zone forms over the eastern part of the city, where PM2.5 concentration reaches 25 mgk/m^3. In atmospheric boundary layer (600m) PM2,5 concentration is less than 0.1 mgk/m^3 in the major part of the city, and varies within limits of 0.1-1 mgk/m^3 in the eastern part of the city.

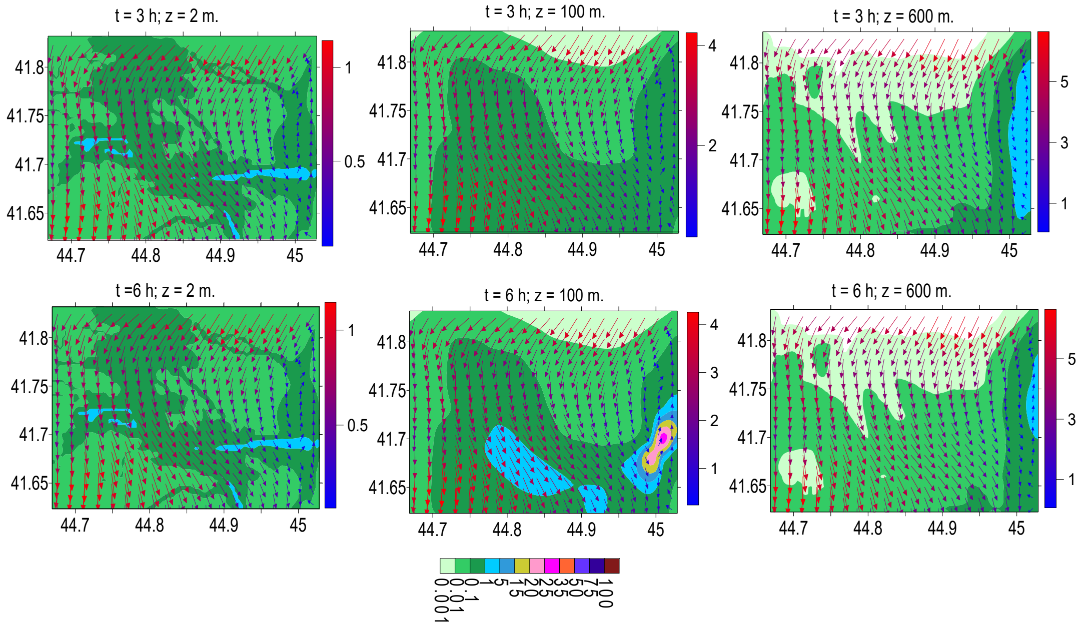

Fig. 3. Wind velocity (m/sec) and PM2.5 concentration fields (mkg/m^3) in surface and boundary layers of the atmosphere, when t = 3 and 6 h

In time period of a day, when t = 9-15h, microaerosols concentration increase takes place almost in all modeling areas (Fig. 4 and 5) along with increase of motor transport traffic intensity and related growth of PM2.5 emission rate (Fig. 2). Remarkable increase is obtained at 9AM, when a rate of aerosols discharge into atmosphere becomes maximal. At this point PM2.5 concentration in the eastern part of Kakheti Highway at 2 m height from the ground becomes maximal and reaches 25-30 mkg/m^3. In some areas of TEMKA, Vake, Saburtalo and Ponichala, at relatively small territories, concentration is within limits of 15-20 mkg/m^3. At that, formation of low pollution zones (0.1-1 mkg/m^3) in the central and peripheral parts of the city should be mentioned.

From 9AM to 3PM, despite the fact that a maximum amount of microaerosols is emiited into atmopsphere, PM2,5 concentration little by little reduces at almost entire territory of the city. In this time range, maximum concentration values are within limits of 5-15 mkg/m^3 at 2 m height. Relatively high pollution level is obtained at upper boundary of surface layer of the atmosphere (100 m). At this altitude, in the major part of a space, concentration varies within a limit of 1-5 mkg/m^3, while in the south-eastern part, at quite large area concentration is within a range of 5-15 mkg/m^3, when t = 12h. At 100 m height air pollution level increases from t = 9 to 12 h and drops when t=12-15h.

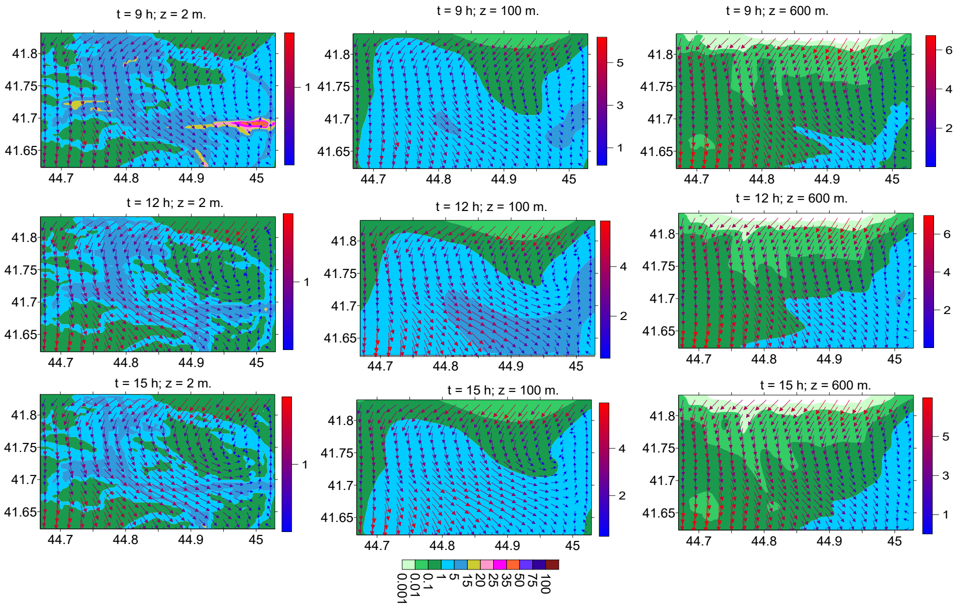

Fig. 4. Wind velocity (m/sec) and PM2.5 concentration fields (mkg/m^3) in surface and boundary layers of the atmosphere, when t = 9, 12 and 15 h

It is obtained via calculations that along with onset of the second "rush hour" of motor transport traffic, atmospheric pollution with PM2,5 increases in the central districts of the city at 2 m height from the ground. When t = 18h, concentration is especially high in the eastern part of Kakheti Highway and northern part of Vazha-Pshavela Avenue. Concentration values reach 20 mkg/m^3 in these places, while at quite large area concentration is within 5-15 mkg/m^3 range.

In time period from t=18 h to 21 h, a ground-level concentration in Vake, Saburtalo, Gldani districts drops by 10 mkg/m^3, while along Kakheti Highway the decrease is relatively small. In the vicinity of the upper boundary of surface layer of the atmosphere, aerosols concentration in time period from t = 18h to 24 h first increases a little, and then reduces. Studies conducted after 24 hours showed that in case of constant background wind the process of atmosphere pollution is of quasi-stationary nature.

Temporal variation of concentration in 4 points of densely populated city areas and 2 points in the outskirts of town is shown in Fig. 6. It is seen from Fig. 6 that time variation of concentration has 2 maximums. One maximum is reaches round t = 11h and another near t = 21 h. The process of concentration growth corresponding to the first maximum runs during 4 hours – from t = 7h to 11 h, while in case of the second maximum it lasts 7 hours – from t=15h to 22 h.

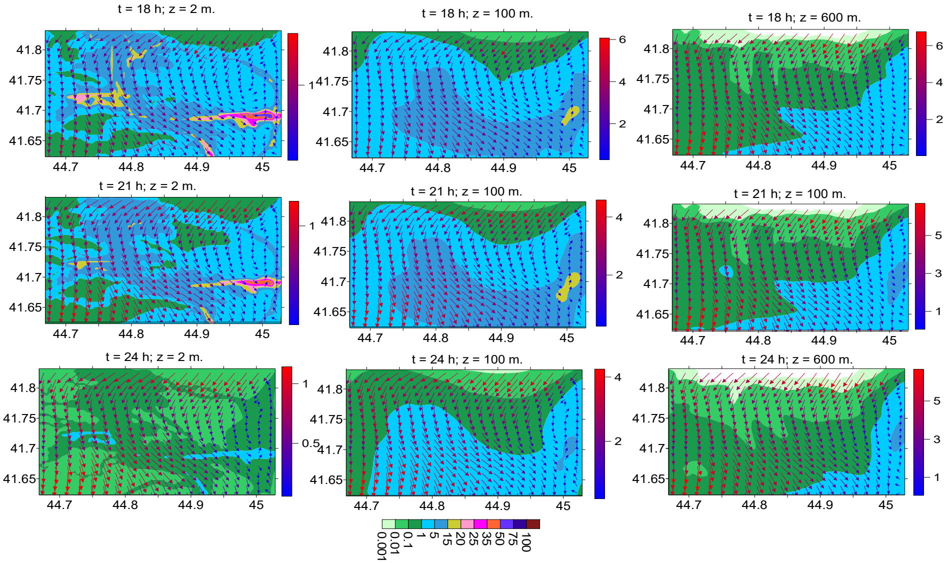

Fig. 5. Wind velocity (m/sec) and PM2.5 concentration fields (mkg/m^3) in surface and boundary layers of the atmosphere, when t = 18, 21 and 24 h

Vertical distribution of PM2,5 for different points of time is shown in Fig. 7, where the concentration isolines of 3 cross-sections drawn along the parallel in the surface layer of the atmosphere are shown. It is seen from Fig. 7 that in time period from 3AM to 6AM a vertical distribution of PM2.5 concentration in the lower part of surface layer of the atmosphere is uniform. The latter is caused by coincidence of vertical turbulent and convective transfers in the field of formed local anticyclone. After t = 6h, an uniform structure of aerosols vertical distribution is damaged with increase of motor transport traffic intensity. Vertical turbulent diffusive flows of aerosol are formed, which promote territory ventilation and taking out of pollution from territory of the city. The only exceptions are two zones in the surroundings of Vake and Ponichala. In these zones, a high pollution zone is formed from t = 9h to 21 h in 50 m thick lower part of the atmosphere on leeward side of orographic resistance.

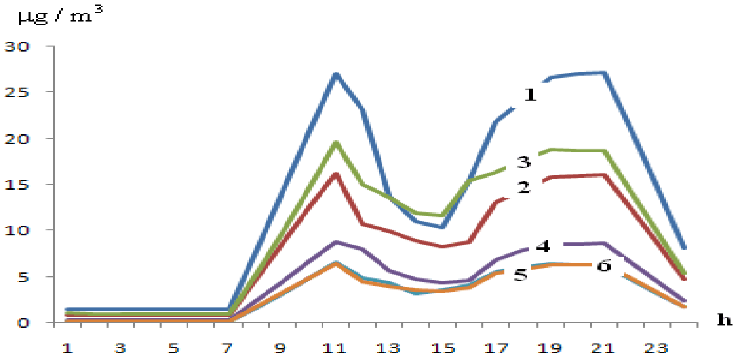

Fig. 6. Temporal variation of PM2.5 concentration in 6 points of modeling area: 1 – Ponichala; 2 – Vazha-Pshavela Ave., 3 – Akhmeteli Theater; 4 – Freedom Square; 5 – Tskhneti; 6 – Digomi

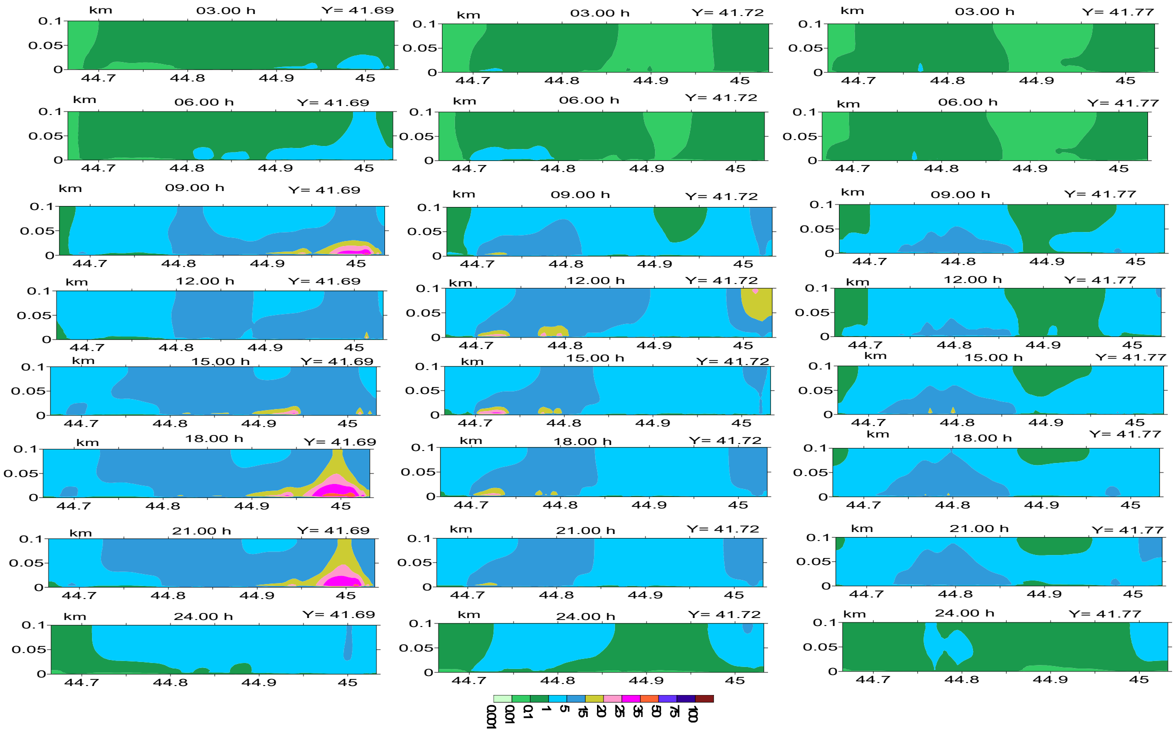

Fig. 7. PM2.5 concentration isolines in three vertical cross-sections drawn along the parallel in 100 m thick lower layer of the atmosphere

Conclusion

Carried-out calculations showed that in case of background north light wind a city orography promotes city ventilation and Tbilisi atmosphere pollution with PM2.5 is not high at all. The only exceptions are two zones – Vake and Ponichala districts, where concentrations round t = 11 and 21 h reach and even exceed 25 mkg/m^3. In time period from midday to 6PM the concentration values obtained via calculation are significantly less than measurement data [10]. In other points of time the observation data are also higher than those obtained through calculations. The mentioned fact is presumably related to the circumstance, that a background level of pollution, which is not established for Tbilisi atmospheric air, is not taken into account in the model.

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References

1. Bourdrel T., Annesi-Maesano I., Alahmad B., et al. The impact of outdoor air pollution on COVID-19: a review of evidence from in vitro, animal, and human studies. // Eur Respir Rev 2021; 30:200242 [https://doi.org/10.1183/16000617.0242-2020].

2. Yixing Du, Xiaohan Xu, Ming Chu, Yan Guo, Junhong Wang. Air particulate matter and cardiovascular disease: the epidemiological, biomedical and clinical evidence. // J Thorac Dis. 2016 Jan; 8(1): E8–E19. Doi: 10.3978/j.issn.2072-1439.2015.11.37

3. Adaji E. E., Ekezie W., Clifford M., Phalkey R. Understanding the effect of indoor air pollution on pneumonia in children under 5 in low- and middle-income countries: a systematic review of evidence. // Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-018-3769-1

4. Gonzalez-Barcala F.J., Pertega S., Garnelo L., Castro T.P. , Sampedro M., Lastres J.S., San M.A., Jose Gonzalez, Bamonde L., Valdes L., Carreira J.-M., Silvarrey A.L. Truck traffic related air pollution associated with asthma symptoms in young boys: a cross-sectional study. // Public Health, 127, 2013., 10.1016/j.puhe.2012.12.028.

5. Wang B., Liu J., Fu S., et al. An effect assessment of airborne particulate matter pollution on COVID-19: a multi-city Study in China. //medRxiv 2020; preprint [https://doi.org/10.1101/2020.04.09.20060137].

6. Zhu Y., Xie J., Huang F., et al. Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. // Sci Total Environ 2020; 727: 138704.

7. Copat C., Cristaldi A., Fiore M., Grasso A., Zuccarello P., Signorelli S. S., Conti G. O., Ferrante M. The role of air pollution (PM and NO_2) in COVID-19 spread and lethality: A systematic review. // Environmental Research. Volume 191, December 2020, 110-129 https://doi.org/10.1016/j.envres

8. Surmava A., Intskirveli L., Kukhalashvili V., Gigauri N. Numerical Investigation of Meso - and Microscale Diffusion of Tbilisi Dust. // Annals of Agrarian Science, v. 18, No. 3, 2020, pp. 295-302.

9. Surmava A., Kukhalashvili V., Gigauri N., Intskirveli L., Kordzakhia G. Numerical Modelling of Dust Propagation in the Atmosphere of a City with Complex Terrain. The Case of Background Eastern Light Air. // Journal of Applied Mathematics and Physics, v. 8, No.7, 2020, pp. 1222-1228. https://doi.org/10.4236/jamp.2020.87092.

10. Gigauri N., Kukhalashvili V., Surmava A., Intskirveli L., Pipia M. Spatial distribution of PM10 and PM2.5 concentrations in the atmosphere of Tbilisi according to regular observations and experimental measurements. // Scientific Reviewed Proceedings of the IHM, GTU, vol. 131, 2021, pp. 44-50, (in Georgian).