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Numerical Modeling of Kutaisi City Atmospheric Air Pollution with PM2.5 Particles in Winter During Ground Level Calm and Background Eastern Wind in the Free Atmosphere

[1,2]Aleksandre A. Surmava, [2]Vepkhia G. Kukhalashvili, [1]Natia G.Gigauri, [1]Liana N. Intskirveli, [3]Leila V. Gverdtsiteli

[1] Institute of Hydrometeorology of the Georgian Technical University, Georgia
[2] M. Nodia Institute of Geophysics of the I. Javakhishvili Tbilisi State University, Georgia
[3] Georgian Technical University, Georgia

e-mail: l.inwkirveli@gtu.ge

ABSTRACT

Spatial distribution and time change of PM2.5 particles dissipated in the atmosphere as a result of motor transport traffic in Kutaisi city has been studied using computer modeling. This modeling has been made through combined integration of equations of time evolution of meso-scale atmospheric processes and admixtures' transfer-diffusion, using the relevant initial and boundary conditions. Such meteorological situation has been considered, during which wind velocity in surface layer of the atmosphere equal to 0, while there is background eastern wind in the free atmosphere. Atmospheric pollution is caused by microparticles dissipated in the air during motor transport traffic. The wind fields formed in boundary layer of the atmosphere resulting from interaction of terrain and background flows in winter and fields of concentrations of microparticles transferred by wind and dissipated in the air at different heights from the earth ground have been plotted using numerical modeling data. Areas of relatively severe and mild contamination have been determined, peculiarities of vertical distribution of concentrations have been analyzed. It has been showed that the shapes of vertical distribution of concentrations in surface layer of the atmosphere are similar of temperature distributions in to dry thermals.
Key words: *PM2.5, microparticles, concentration field, atmosphere, numerical modeling, calm.*

Introduction

It has been showed by numerous studies that solid and liquid microparticles – PM2.5 and PM10, which hit the atmosphere as a result of emissions from industrial facilities, agricultural activities and motor transport operation are ranked among atmosphere polluting substances with high risk-factor extremely hazardous for health [1-5]. Due to very small sizes (diameters are $\leq 2.5\ \mu$ and $\leq 10\ \mu$) they easily penetrate human organism, cause various illnesses and frequently even a death [6-7]. The ecological problems caused with atmospheric pollution with PM has been thoroughly studied in the fundamental work [8].

As a result of practical air-protecting measures carried out in the XXI century, number of microparticles emitted in the air has been significantly decreased. As a consequence, PM2.5 concentrations have been reduced in the air and atmosphere purity degree has been improved. Though, the air contamination level in number of large and small cities still exceeds the European Union standards [9-14].

Kutaisi, the second largest city of Georgia, with 147 thousand habitants is ranked among the small cities. Despite the small size it has a great international medicinal-health promoting and touristic importance. Resort Tskaltubo, historical monuments: Gelati monastery complex – a monument of UNESCO cultural heritage, Bagrati Cathedral, Palace of Geguti, Martvili and Motsameta monasteries, touristic attractions – Sataplia and Prometheus caves, Kinchkhi, Martvili, Balda canyons etc. are located in the city suburbs. Hundreds of thousands of people visit it every year. Based on this fact, study and assessment of environmental state, diagnostic forecast of pollution level, maintenance of high degree of air purity have of paramount ecologic importance. It should be noted that a monitoring carried out in two air quality observation points existing as of today is unable to estimate real picture air of purity in the city.

In order to cope with the above-mentioned problem, the pattern of propagation and time change of PM2.5 particles generated by the motor transport and emitted in the air in Kutaisi city and at the adjacent territories has been simulated and analyzed in the presented article by means of field measurements and computer modeling of admixture propagation in the atmosphere.

Research method

Propagation of dust and PM microparticles discharged by the motor transport to the air of Georgian cities has been numerically simulated through combined integration of 3D equations of meso-scale atmospheric processes and equation of a passive polluting admixture propagation in Caucasus [15-24].

Numerical modeling results

PM2.5 propagation has been modeled in 13.4×13.4×9 km^3 space domain of complex terrain (Fig. 1), with city of Kutaisi located in its center. Orography height of the modeling area varies from 80 to 400 m. Numerical modeling of the mathematical model equations [17, 18] has been made using relevant initial and boundary conditions. Numerical grid steps in horizontal direction equal to 200 m, while in vertical direction in the free atmosphere – 300 m. Vertical steps in 100 m thick surface layer of the atmosphere vary from 0.3 to 15 m. Time step is 1 sec. Calculations have been made for 3-day period.

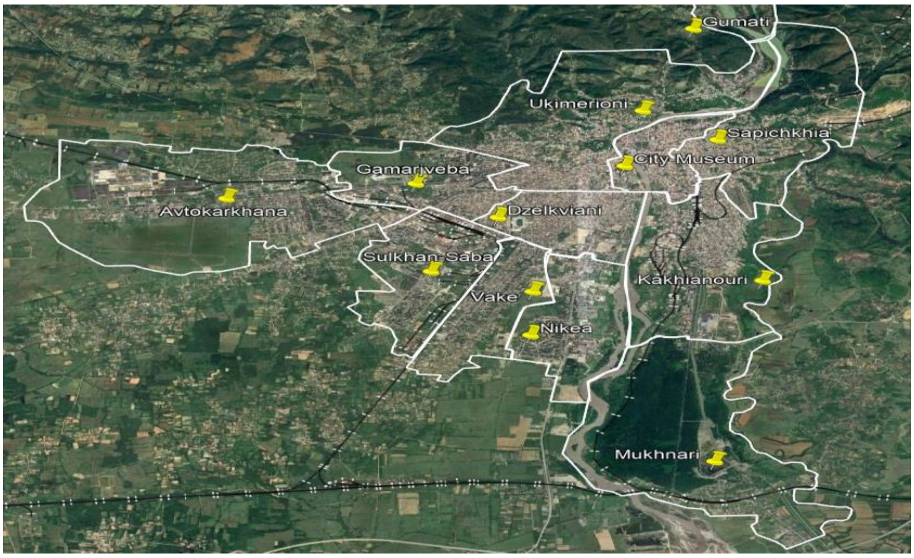

Fig. 1. Administrative units and urban development scheme of city of Kutaisi.

A case of Kutaisi atmosphere pollution with PM2.5 in December has been modeled. There is a calm at 100 m height in surface layer of the atmosphere – background wind velocity is 0 m/sec. There is an eastern wind above the surface layer and its velocity linearly increases with height and reaches 21 m/sec at 9 km height. Atmospheric relative humidity equals to 50%.

It has been obtained via calculations that microaerosol pollution of atmospheric air occurs due to motor transport traffic from underlying surface at 0.3 m height. PM2.5 particles are emitted in the atmosphere at 5 types of areas: at highways, city central streets, residential, industrial zones, and unpopulated territories of surrounding villages. Emission rate is periodical with 24-hour period and proportional to motor transport traffic intensity. Emission rate is maximum and constant in time interval from 10 to 18 h, minimal in the interval of 0-4 h, linearly increases from 4 to 10 h, linearly decreases within time period from 18 to 24 h and by 0 h becomes equal to existing emission rate. Maximum emission rate is 12.5 µg/s.

Fig. 2 shows graphs of PM2.5 concentration time change obtained via calculations for 5 basic types of pollution points. It is seen from Fig. 2 that time change of concentration is similar for all types of observation points and is featured by 2 intervals of large values and 2 ones of small values. Large concentration values are obtained approximately within time intervals from 11 to 13 h and 16 to 19 h, while small ones – in the intervals from 0 to 5 h and from 13 to 16 h. It should be noted that time change of concentrations in case of identical meteorological and contamination pollutions is qualitatively similar and quantitatively different for summer [18] and winter seasons (Fig. 2).

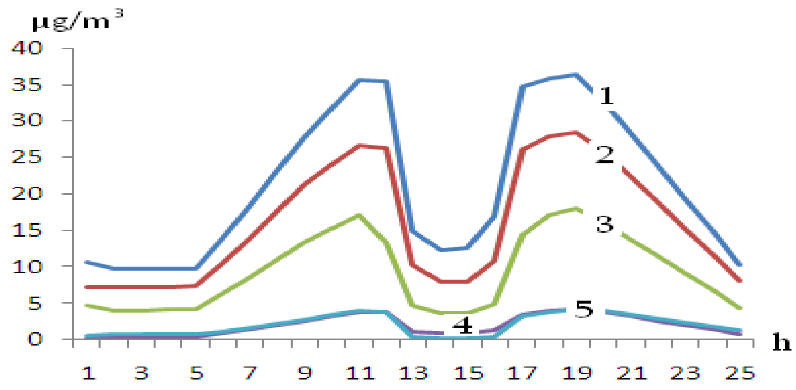

Fig. 2. Time change of PM2.5 concentrations obtained via calculations at highway (1), city central streets (2), industrial (3), rural (4) zones and unpopulated points (5) at the 2m height from earth surface.

The difference lies in the period of high pollution onset. In summer [17], compared to winter, the maximal pollution level is obtained approximately 2-3 hours earlier in the first half of the day, and 2-3 hours later in the second half. The mentioned effect is associated with time change of thermal stability of the atmosphere. In summer, soil surface and adjacent surface layer of the atmosphere are rapidly cooled early in the morning, so vertical temperature gradient $\gamma = \partial T / \partial z$ (T is temperature, z – vertical coordinate) is reduced, while thermal stability coefficient $S = \gamma_a - \gamma$ (γ_a - dry adiabatic gradient) is increased respectively. As a consequence, ground-level air layer becomes more dynamically stable and less turbulized. Reduction of turbulence is accompanied by intense accumulation of emitted aerosols in the lower part of the surface layer and rise of pollution level. The similar process takes place in summer in the second half of the day, approx. within interval of 19-20 h. Despite the fact that quantity of substances emitted in the atmosphere is identical in the same types of points located in different parts of the city, their concentrations in these points obtained via calculation differ from each other (Fig. 3). In the lower part of surface layer, it equals to 2-10 mkg/m^3 at highways and industrial zones of the city, while at unpopulated rural territories it is 0.2–4 mkg/m^3. The similar dependence is obtained for other types of observation points as well.

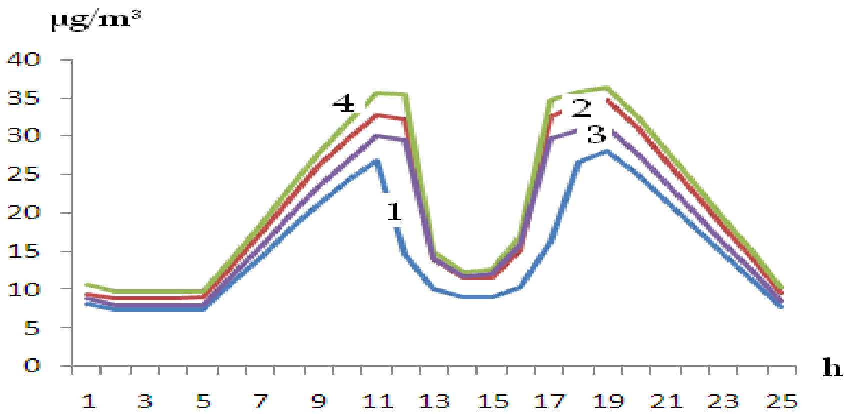

Fig. 3. Time change of PM2.5 concentration in the eastern, western, northern and southern parts of the city, in four points located at highway, at 2 m height from earth surface

Vertical distribution of concentration differs from each other in different types of points. Concentration value is maximal at the highway and in the vicinity of city central streets in the close proximity to surface layer of the atmosphere and hyperbolically reduces with height increase (Fig. 4). In this case, concentration value in the close proximity to the surface layer varies within 13-48μg/m^3, while at 100 m height – within 0.1-7 μg/m^3.

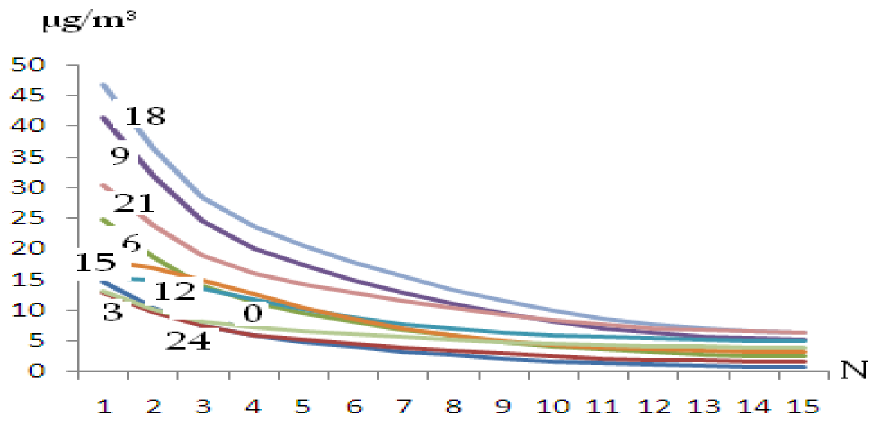

Fig. 4. Vertical distribution of PM2.5 concentration (μg/m^3) in points located at the highway in surface layer of the atmosphere, when t = 0, 3, 6,..., 24 h. (N is a number of vertical numerical grid)

In points placed at the territory of industrial area, vertical distribution of concentration is of parabolic shape (Fig. 5). Its vertex is located at N = 4-6 levels (at 5-15 m height from earth surface), while branches are down-directed. Concentration maximum values in these points vary within 4-20 μg/m^3. At 100 m height concentrations approximately equal to 1-7 μg/m^3.

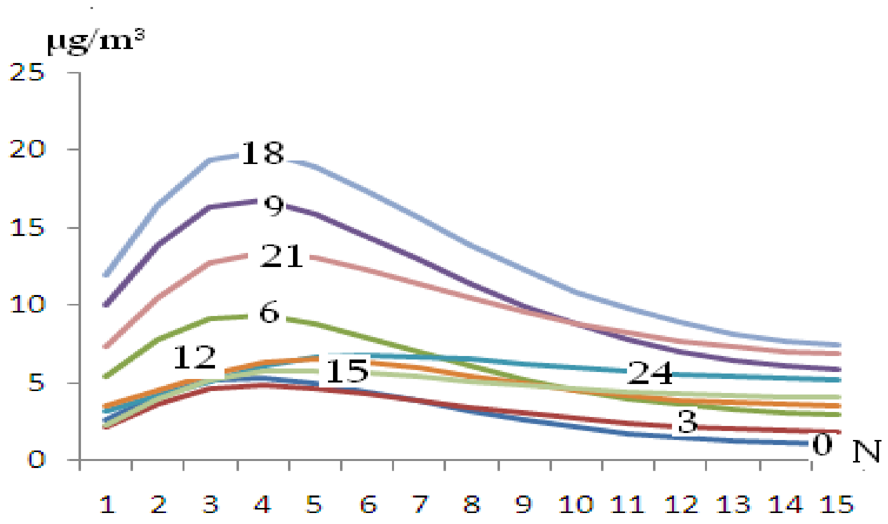

Fig. 5. Vertical distribution of PM2.5 concentration (μg/m^3) in points located at the territory of industrial purpose in surface layer of the atmosphere, when t = 0, 3, 6,..., 24 h. (N is a number of vertical numerical grid)

As for observation points placed at the territory of agricultural purpose, the concentration here is small at 2 m height, then increases with height and reaches maximum values at 10-15 m heights (N = 5-6). At high altitudes, small decrease of concentration is obtained. At 100 m height, concentration value is minimal, when t = 0h, and maximal when t = 18 and 21h. By t = 24h, concentration value at 100 m height is approx 4 μg/m^3.

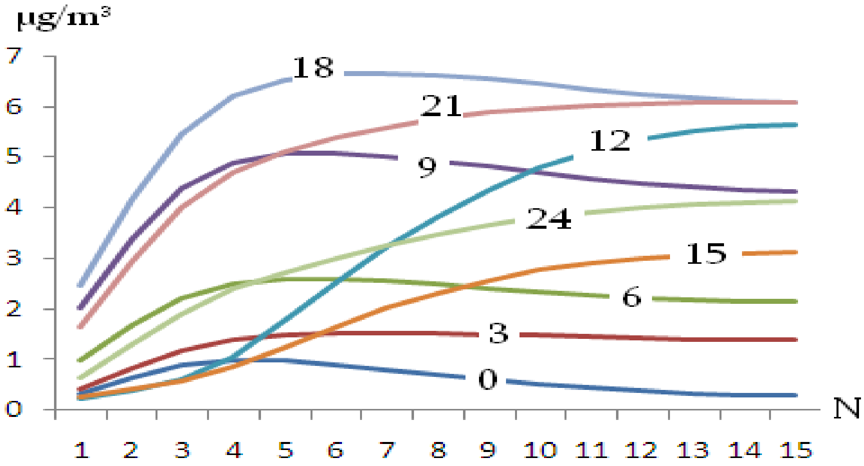

Fig. 6. Vertical distribution of PM2.5 concentration (μg/m^3) in points located at the territory of agricultural purpose in surface layer of the atmosphere, when t = 0, 3, 6,..., 24 h. (N is a number of vertical numerical grid)

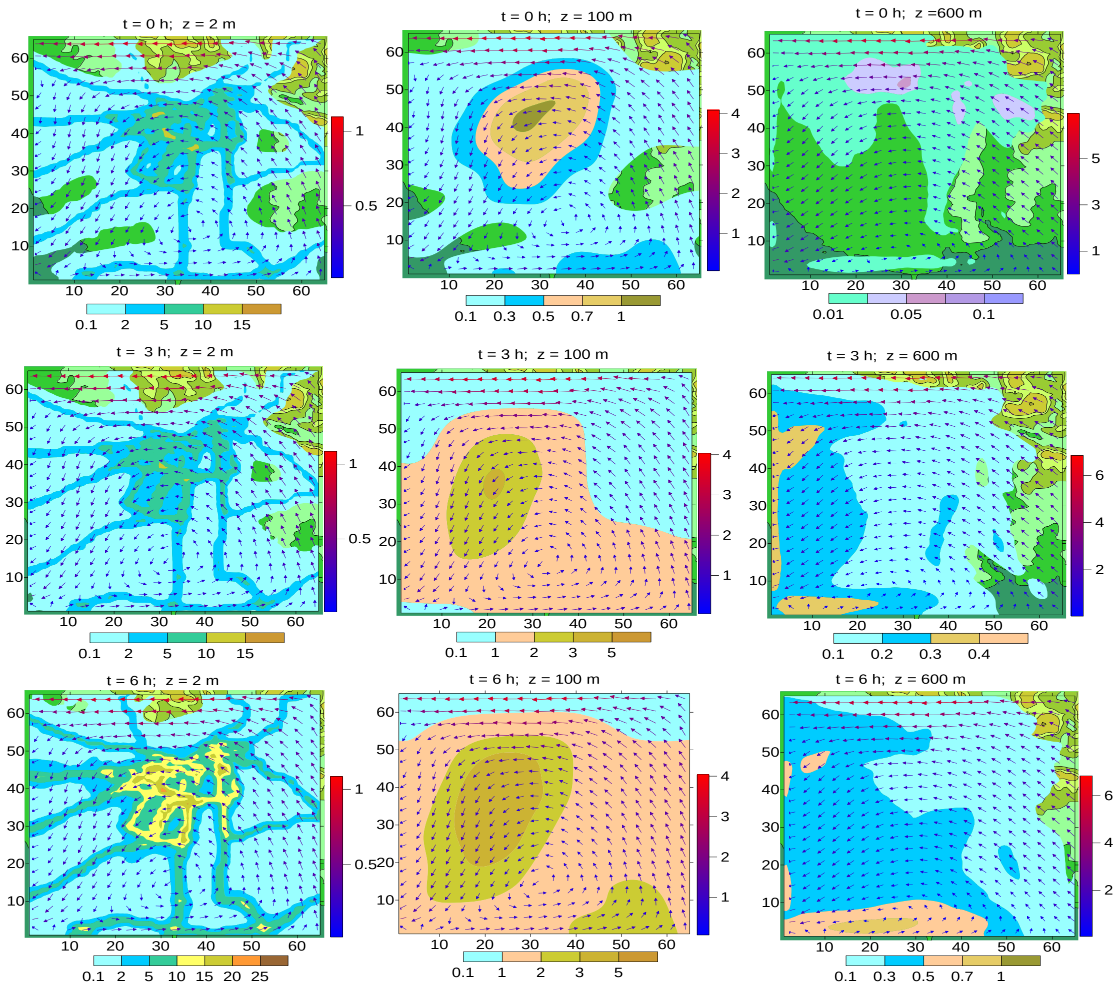

Fig. 7. Distribution of PM2.5 concentration (μg/m^3) and wind velocity (m/sec) fields at 2, 100 and 600 m heights from earth ground, when t = 0, 3 and 6 h.

In Fig. 7-9 there is shown spatial distribution of wind velocity and PM2.5 concentrations fields, obtained via numerical modeling within 1 day. It is seen from the figures that in case of constant background eastern wind, interaction of terrain and underlying surface with background flow in free atmosphere generates quasi-stationary cyclonic vortex of local scale. This vortex is formed in the center of southern part of the region. The vortex is clearly manifested in 100 m thick surface sub-layer of the atmosphere and gradually weakens at higher levels of boundary layer of the atmosphere.

PM2.5 concentration within interval of 0-3 h, at 2 m height in surface layer of the atmosphere exceeds 0.1 $\mu g/m^3$ in the major part of area (Fig. 7). Concentration values at urbanized territories of the city and in the vicinity of motoring highways vary within 2-10 $\mu g/m^3$. At small territories of Dzelkviani and Vake administrative units (AU), concentrations reach 10-14 $\mu g/m^3$. From t = 3h concentration begins to increase at the substantial areas of the city center. By t = 6h concentration value in the central areas of the city and in the vicinity of highways is 10-15 $\mu g/m^3$, and even exceeds these figures in some observation points. At 100 m height from earth surface, concentration of polluting microaerosols propagated to the south-eastern part of the modeling area mainly varies within interval of 1-5 $\mu g/m^3$. At higher levels (600 m), concentration doesn't exceed 1 $\mu g/m^3$.

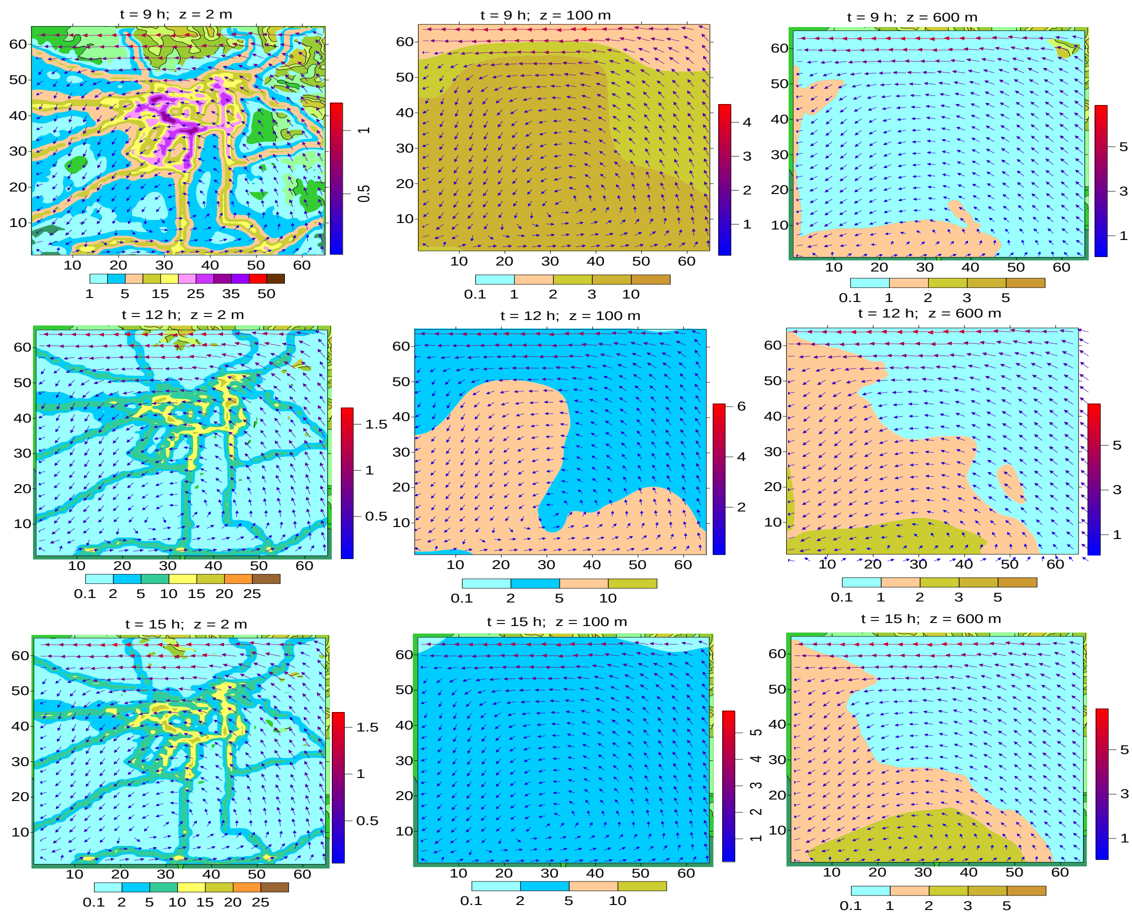

Fig. 8. Distribution of PM2.5 concentration ($\mu g/m^3$) and wind velocity (m/sec) fields at 2, 100 and 600 m heights from earth ground, when t = 9, 12 and 15 h.

After 6 AM, ground-level concentrations of PM2.5 begin to increase with motor traffic intensity. Concentration build-up is especially high at the central avenues passing through the territory of Avtokarkhana, Gamarjveba, Sulkhan-Saba, City-Museum and Sapichkhia AUs (Fig. 8). Concentration values at the mentioned territories at 2 m height from the earth surface reach 25-30 $\mu g/m^3$. At their adjacent territories, concentrations gradually decrease with distance from the emission source and become equal 10-20 $\mu g/m^3$ first, and afterwards, 1-5 $\mu g/m^3$ at larger distances.

Intense air pollution takes place in the upper parts of surface layer of the atmosphere. Convective and vertical diffusive motions take place here, due to which concentration synchronically increases with ground-level concentration. As a result, by 9AM, concentration value at the upper limit of surface layer of the atmosphere (100 m) equals to 3-10 μg/m^3 at quite large territory.

After 9AM, especially within interval of 9-15 h, vertical turbulent diffusion and convective transfer are strengthened and, as a consequence, maximum concentration of microaerosols reduces to 10-15 μg/m^3 at urbanized territories of the city. At 100 and 600 m heights, pollution level reduces, as well – to 2-5 and 2-3 μg/m^3, respectively.

After 3PM, intensive build-up of concentration begins in the eastern and western parts of the central district of the city: at the territories of City-Museum, Kakhianouri, Gamarjveba, Sulkhan-Saba and Nikea AUs (Fig. 5). Concentration build-up is associated with thermal stability increase. At large territories of the central parts of the city concentration values are 25-35, while in populated and industrial areas of suburbs – 10-25 μg/m^3. High values of concentration are not maintained over a long period of time. It starts to intensively decrease from t = 20h and this process lasts until 3AM. The mentioned decrease is caused by quantity reduction of emitted microaerosols caused by vehicle traffic intensity.

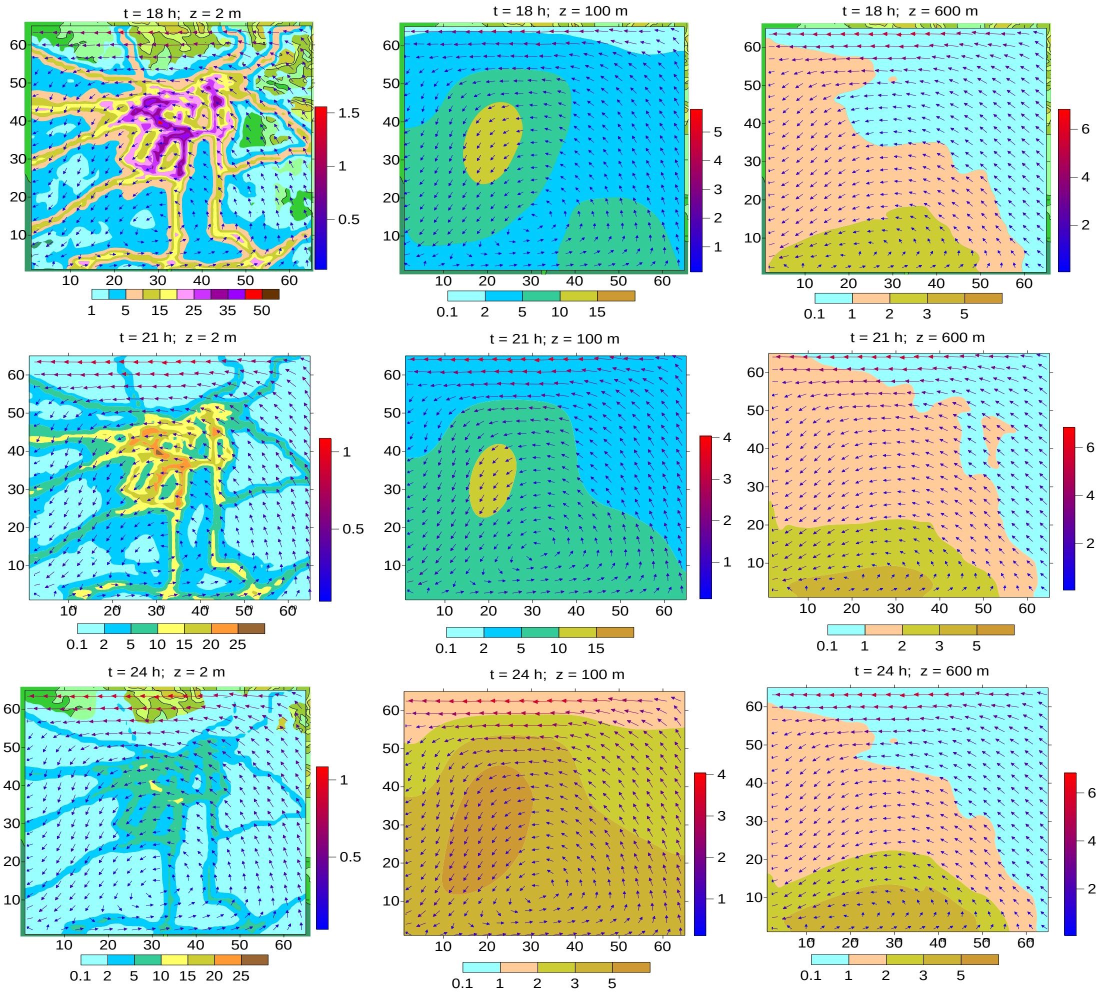

Fig. 9. Distribution of PM2.5 concentration (μg/m^3) and wind velocity (m/sec) fields at 2, 100 and 600 m heights from earth ground, when t = 18, 21 and 24 h.

Conclusion

Features of spatial distribution and time change of PM2.5 particles formed by motor transport at the territory of Kutaisi in winter during ground-level background calm and western wind in the free atmosphere has been studied. It has been obtained via calculations that in winter season, interaction of regional terrain with background western wind generates meso-scale cyclonic vortex of wind velocity. Formed dynamic and thermobaric fields have an influence on spatial distribution of aerosols emitted in the atmosphere due to motor transport traffic. Patterns of spatial distribution of PM2.5 concentration has been obtained resulting from modeling, time behavior of concentrations has been established both in surface and boundary layers of the atmosphere. It has been shown that vertical distribution and time change of concentration depends on both aerosol emission rate and motor transport traffic intensity, as well as on kinematics of surface layer of the atmosphere and local circulation system formed due to diurnal variation of thermal regime on the underlying surface. High and average pollution levels in the city and at adjacent territories and change in their position within a day have been established.

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ქ. ქუთაისის ატმოსფერული ჰაერის PM2.5 -ნაწილაკებით დაბინძურების რიცხვითი მოდელირება ზამთარში მიწისპირა შტილისა და თავისუფალ ატმოსფეროში ფონური აღმოსავლეთის ქარის დროს

ა. სურმავა, ნ. გიგაური, ვ. კუხალაშვილი, ლ. ინწკირველი, ლ. გვერდწითელი

რეზიუმე

რიცხვითი მოდელირებით გამოკვლეულია ქ. ქუთაისის ტერიტორიაზე ავტოტრანსპორტის მიერ წარმოქმნილი PM2.5–ის სივრცული განაწილებისა და დროში ცვლილების თავისებურება ზამთარში მიწისპირა ფონური შტილის და თავისუფალ ატმოსფეროში დასავლეთის ქარის დროს. გამოთვლებით მიღებულია, რომ ზამთრის სეზონში მეზომასშტაბის რეგიონის რელიეფის ურთიერთქმედება ფონურ დასავლეთის ქართან წარმოშობს მეზომასშტაბის ქარის სიჩქარის ციკლონურ ცირკულაციას. ფორმირებული დინამიკური და თერმობარული ველები ახდენენ გავლენას ატმოსფერუში ავტოტრანსპორტის მოძრაობის შედეგად გაფრქვეული აეროზოლის სივრცულ განაწილებაზე. მოდელირების შედეგად მიღებულია PM2.5 – ის კონცენტრაციის სივრცული განაწილების სურათები, განსაზღვრულია კონცენტრაციების დროში ცვლილების ხასიათი, როგორც ატმოსფეროს მიწისპირა ფენაში ასევე სასაზღვრო ფენაში. ნაჩვენებია, რომ კონცენტრაციის ვერტიკალური განაწილება და დროში ცვლილება დამოკიდებულია როგორც აეროზოლის გაფრქვევის სიჩქარეზე და ავტოტრანსპორტის მოძრაობის ინტენსივობაზე, ასევე ატმოსფეროს მიწისპირა ფენის კინემატიკაზე და ქვეფენილ ზედაპირზე თერმული რეჟიმის დღეღამური ცვლილებით ფორმირებულ ლოკალურ

ცირკულაციურ სისტემაზე. განსაზღვრულია ქალაქის და მიმდებარე ტერიტორიებზე მაღალი და საშუალო დაბინძურების დონეები და მათი მდებარეობის ცვლილება დღეღამის განმავლობაში.

საკვანძო სიტყვები: PM2.5, მიკრო ნაწილაკები, კონცენტრაციის ველი, ატმოსფერო, რიცხვითი მოდელირება, შტილი.

Численное моделирование загрязнения атмосферного воздуха г. Кутаиси частицами PM2.5 в зимний период при штиле на суше и фоновом восточном ветре в свободной атмосфере

А. Сурмава, Н. Гигаури, В. Кухалашвили, Л. Инцкирвели, Л. Гвердцители

Резюме

С помощью численного моделирования на территории г. Кутаиси исследованы особенности пространственного распределения и временных изменений микрочастиц PM2.5, генерируемых зимой автотранспортом в районе города во время приземного фонового штиля и западных ветров в свободной атмосфере. Расчеты показали, что в зимний сезон взаимодействие рельефа мезомасштабного региона с фоновым западным ветром формирует циклоническую циркуляцию мезомасштабных скоростей ветра. Формирующиеся динамические и термобарические поля оказывают влияние на пространственное распределение аэрозолей, выбрасываемых в атмосферу транспортными средствами. В результате моделирования получены графические изображения пространственного распределения концентраций PM2.5, а также определен характер изменения концентраций во времени как в приземном слое атмосферы, так и в пограничном слое. Показано, что вертикальное распределение концентрации и ее изменение во времени зависят как от скорости рассеивания аэрозоля, так и от интенсивности дорожного движения, а также от кинематики приземного слоя атмосферы и местной циркуляционной системы, формируемой суточными изменениями термического режима. Определены высокие и средние уровни загрязнения в городе и прилегающих территориях, а также их изменение в течение суток.

Ключевые слова: PM2.5, микрочастицы, поле концентрации, атмосфера, численное моделирование, штиль.