Numerical simulation of particle transport in urban boundary layer

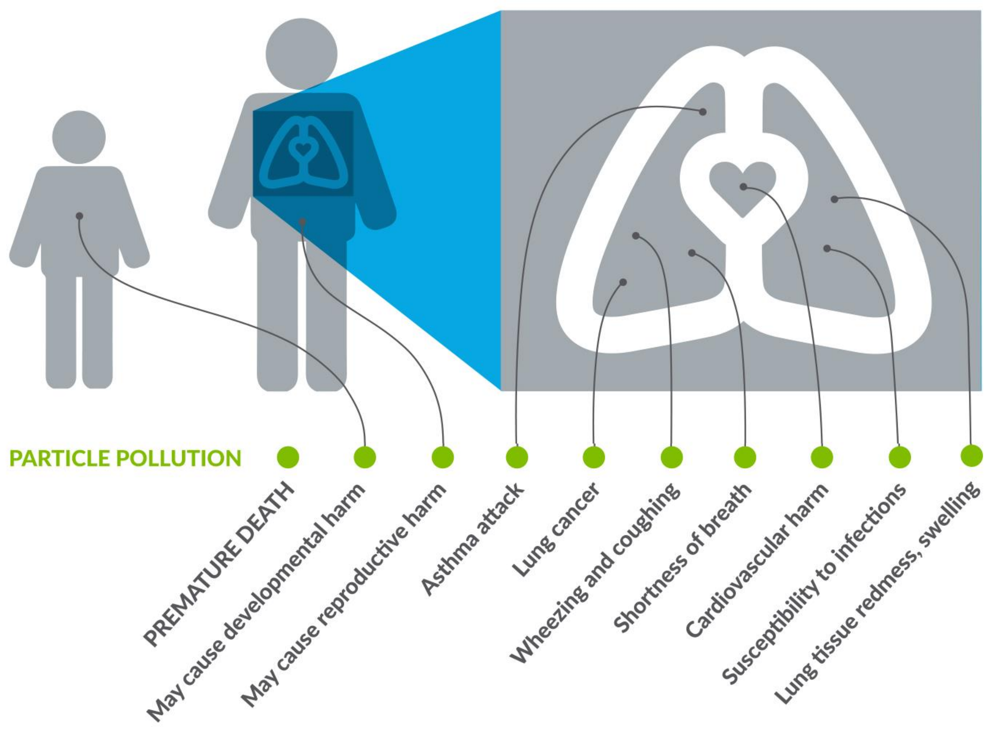
Численное моделирование переноса взвешенных частиц в пограничном слое атмосферы над урбанизированной территорией

A.I. Varentsov (jdeadfox17@gmail.com)**, V.M. Stepanenko, E.V. Mortikov, P.I. Konstantinov** – Lomonosov Moscow State University
А.И. Варенцов, В.М. Степаненко, Е.В. Мортиков, П.И. Константинов – МГУ имени М.В. Ломоносова

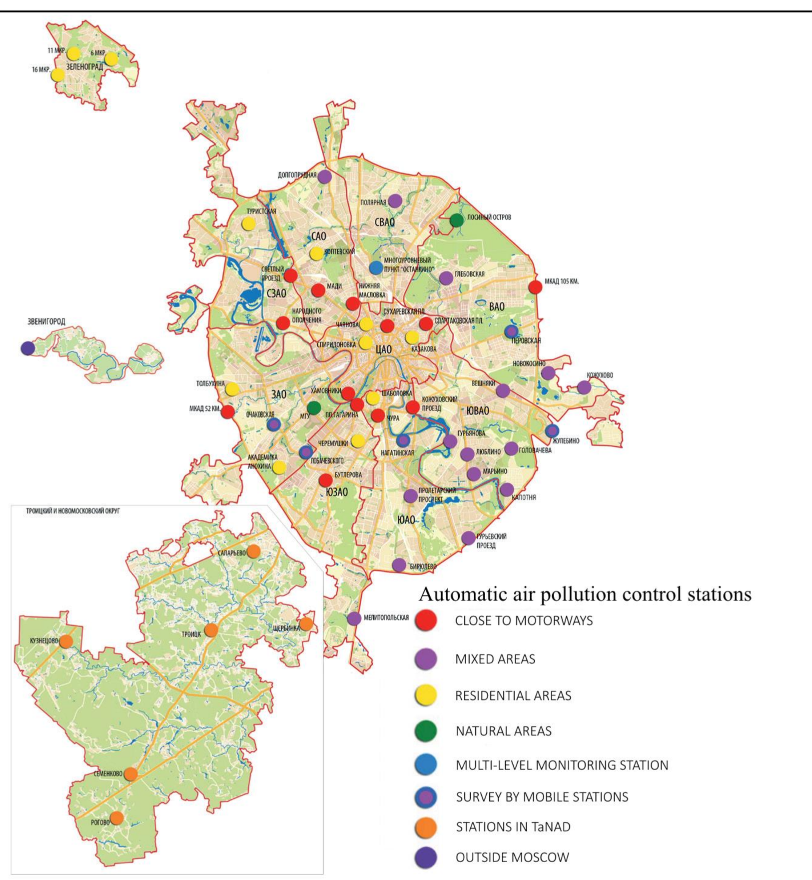
Abstract: This paper presents the development of the Lagrangian model of the aerosol particles transport in the urban boundary layer of the atmosphere with a high spatial resolution. The developed numerical physico-mathematical model is implemented in a program code, successfully verified on idealized analytical solutions and applied in a realistic turbulent flow over complex urban geometry. The influence of atmospheric stratification, particle size and lifetime on the process of particle transport is estimated.

Аннотация: В данной работе представлено развитие лагранжевой модели переноса аэрозольных частиц в городском пограничном слое атмосферы с высоким пространственным разрешением. Разработанная численная физико-математическая модель реализована в программном коде, успешно верифицирована на идеализированных аналитических решениях и применена в условиях реалистичного турбулентного потока над городской застройкой. Оценено влияние стратификации атмосферы, размеров и времени жизни частиц на процесс их переноса.

1. Motivation



Health effects of particulate matter pollution



Layout of AAPCS on the territory of Moscow and the Moscow region (2017)

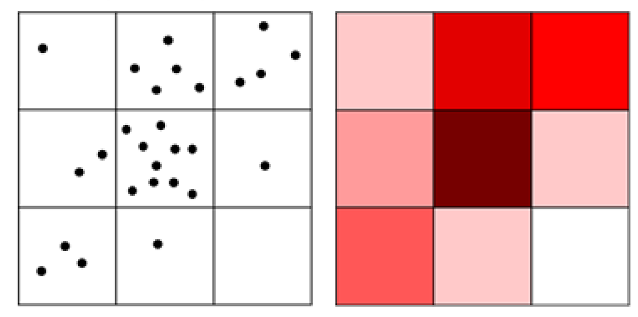
Urban aerosols monitoring problems:

- Negative impact of high aerosol concentrations and bioaerosols on health and environment
- Irregular distribution of urban aerosol emitters
- Advanced obstacle geometry and flow field
- Insufficient spatial resolution of contact measurement networks
- Impossibility of remote sensing inside urban areas

Objective: Development of a tool for calculating aerosol dispersion in urban geometry with high spatial resolution

Model type choice

Lagrangian | Eulerian



Particles ✓ | Concentrations ✗

+: explicit account of forces acting on particles

+: Lagrangian approach is more informative

2. Particle advection model: physics and work algorithm

Motion equations

Newton's second law; F_D – medium resistance force; Turbulent eddies; Interaction with surfaces

$$\frac{d\boldsymbol{u_p}}{dt} = \frac{\boldsymbol{g}(\rho_p - \rho)}{\rho_p} + F_D(\boldsymbol{u} - \boldsymbol{u_p})$$

$$\frac{d\boldsymbol{x_p}}{dt} = \boldsymbol{u_p}$$

$\boldsymbol{u_p}$ – particle velocity, ρ_p – particle density, $\boldsymbol{u}$ – flow velocity, ρ – medium (flow) density

Turbulence parameterizations
1. Gaussian model
2. Discrete random walk model
3. Random displacement model

Algorithm: Reading input data → Domain and grid initialization → Particle creation (emission) → Particle velocity calculation → Interaction with surfaces → Calculation of new positions of particles → Next iteration $t_{n+1} = t_n + \Delta t$ → Decay of particles with a finite lifetime → Particle creation (emission)

C++ implementation

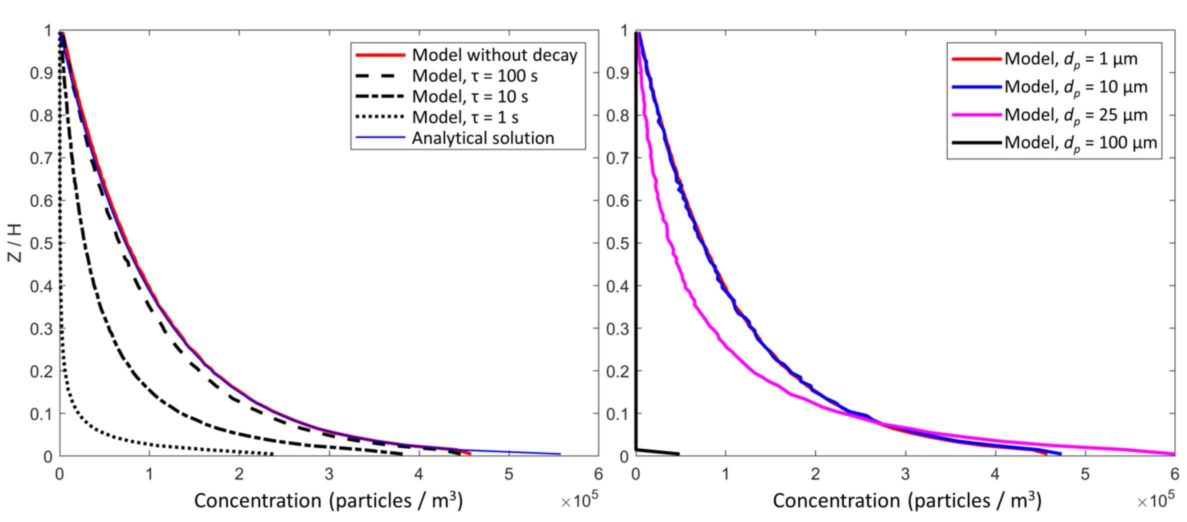
Input data (fields of meteorological values):
- can be set analytically
- can be imported from meteorological models

3. Results of simulations

Verification on analytical solutions

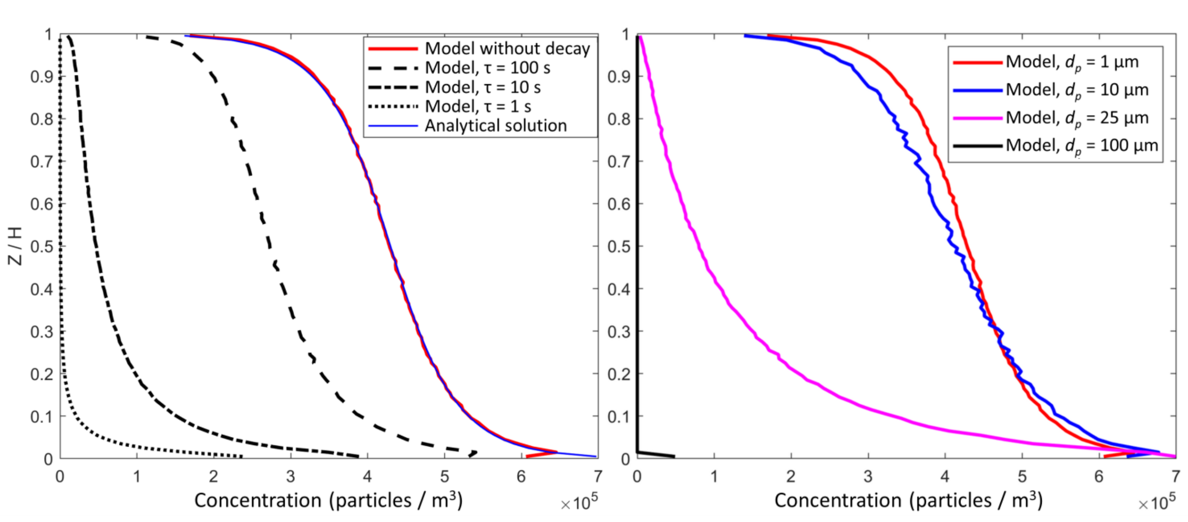
1. Boundary layer: $K_s = u_* kz$

d_p = 1 µm, different lifetime | different d_p, infinite lifetime



2. Couette flow: $K_s = u_* k \frac{h}{\pi} \sin\left(\pi \frac{z}{h}\right)$

d_p = 1 µm, different lifetime | different d_p, infinite lifetime

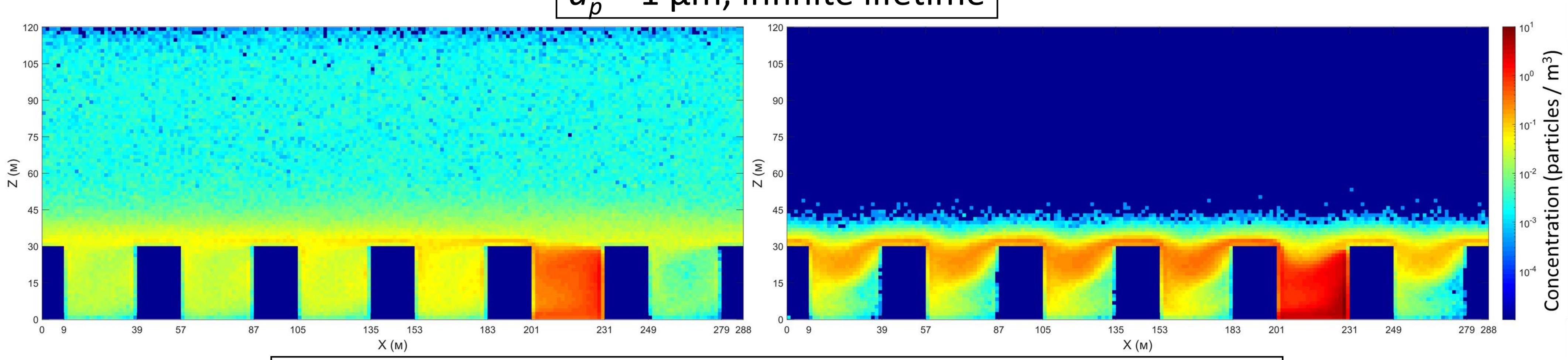


In the cases of both analytical solutions, there is a high agreement between the exact and numerical solutions

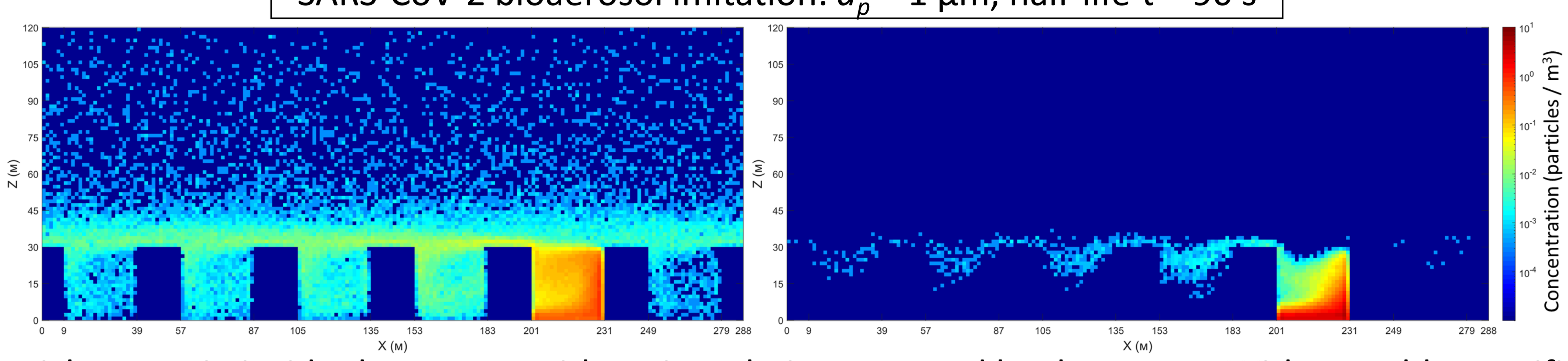
Close to real conditions: series of urban canyons

Unstable stratification | Stable stratification

d_p = 1 µm, infinite lifetime



SARS-CoV-2 bioaerosol imitation: d_p = 1 µm, half-life τ = 90 s



Most particles remain inside the canyon with emitter, being captured by the vortex. With unstable stratification, particles spread over the entire domain, but in the case of a limited lifetime the concentrations can be very small

4. Conclusions

- The 3D microscale Lagrangian model of particle transport was developed and implemented in the program code.
- The procedure for comparing the model with two exact analytical solutions was performed, which showed a high degree of agreement.
- The influence of stratification and wind speed in the atmospheric boundary layer on the transport of particles with different size and lifetime under the conditions of a typical urban geometry is investigated.

5. Perspectives

- Integration with large eddy simulation models
- More particle properties accounting
- More accurate turbulence parameterizations