1 2 3 4 5 6

NUMERICAL SIMULATION OF AEROSOL TRANSPORT IN THE URBAN BOUNDARY LAYER AND CANOPY

Victor Stepanenko[1,2,3]

[1]Lomonosov Moscow State University, Research Computing Center
[2]Lomonosov Moscow State University, Faculty of Geography
[3]Moscow Center of Fundamental and Applied Mathematics

Collaborators:

Andrey Glazunov[5], Evgeny Mortikov[1], Irina Repina[4], Natalia Chubarova[2], Pavel Konstantinov[2], Mikhail Varentsov[1,2], Timofey Samsonov[2], Andrey Debolskiy[1], Alexander Gavrikov[6], Arseniy Artamonov[4], Alexander Varentsov[2,1], Ilya Drozd[2], Vasiliy Lykosov[5]

Kick-off meeting, Laboratory of Urban Environment and Climate (LUEC), Faculty of Geography, Moscow State University, 25 January 2021

Outline

- Objectives, tasks, deliverables
- Background
- Research questions
- Numerical techniques and facilities
- EC and aerosol monitoring tower in the MSU campus
- Collaboration with other Tasks and WPs

Objectives, tasks, deliverables

Objective 3. Assessing the links and consequences of spatial and temporal variability of urban pollution in various spheres (atmosphere, hydrosphere and pedosphere) and find out proper feedback loops to quantify formation and **urban heat island – air pollution – boundary layer dynamics interactions and feedbacks, as well as for prediction and diagnosis of pollution and aerosol dispersion having various origin with spatial resolution down to the scale of individual streets and buildings**

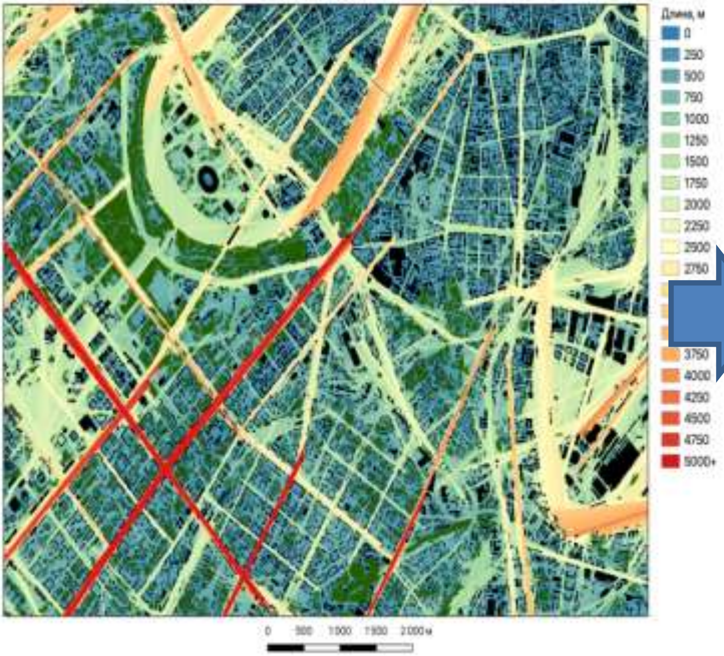
Deliverable 2. Patterns of transportation and accumulation of aerosols of various origin, in a wide range of sizes from nano- to microparticles in the urban canopy depending on background meteorological conditions

WP2. Task 2.2 Study of aerosols formation and transport in urban boundary layer based on hydrodynamic turbulence-resolving models

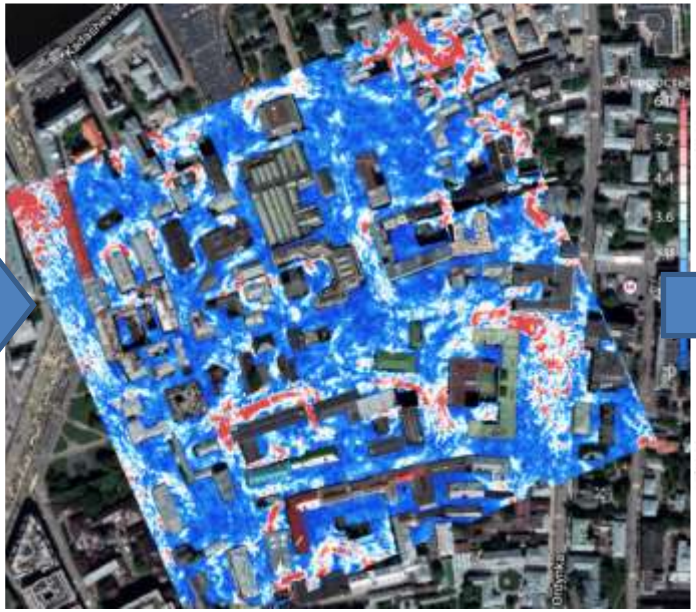
Research questions

- How the locally measured concentrations of *different* aerosols of *various* origins are related to concentrations over the city regions under *different* synoptic conditions?
- What is the vertical distribution of *different* aerosols of *various* origins under *different* synoptic conditions inside an urban canopy and above?
- What is the deposition of *different* aerosols of *various* origins on the soil surface in urban canopy under *different* synoptic conditions?
- What is the role of aerosol particles *dynamics* in their *interactions* in convective and stable boundary layers?
- Are there indices which may diagnose on a routine basis the vertical spread of surface-originated aerosols?

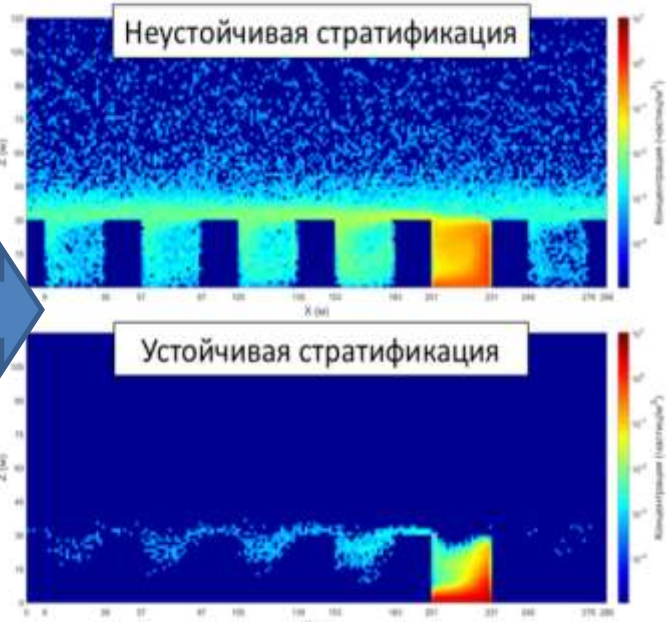
Computations and data-flow framework for modeling micrometeorological regime and aerosols on a scale from district to streets



GIS DATA
(color – the length of urban canyon)



Wind speed distribution in Moscow district



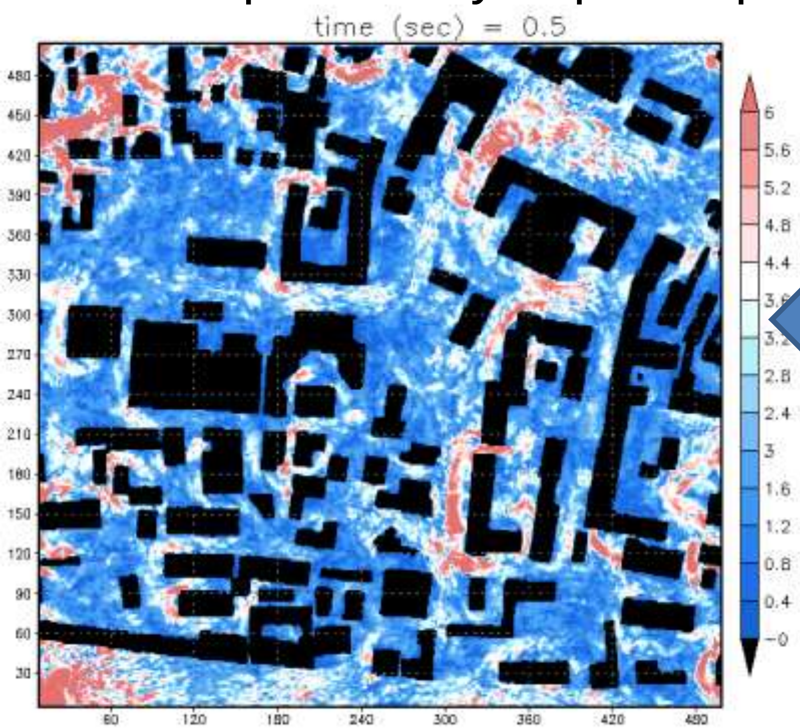
Aerosol concentration in a series of city canyons

Small-scale simulation of the urban boundary layer

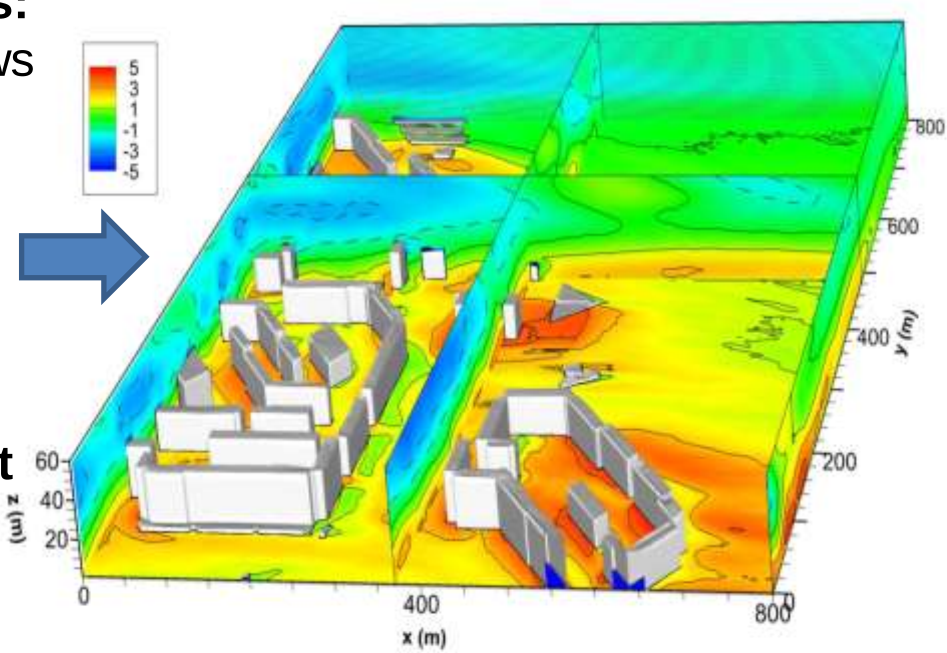
DNS – Direct Numerical Simulation,
LES – Large Eddy simulation,
RANS – Reynolds-averaged Navier–Stokes

- Immersed boundary method
- Unstructured grids (permitting the local grid refinements)
- Parallel realization on CPU and GPU
- Original subgrid models for LES
- Transport of heavy suspended particles and tracers

Lomonosov-2 supercomputer (MSU)

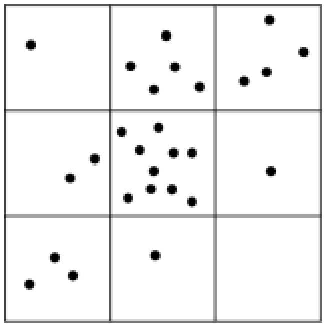


Applications: turbulent flows and pollution above different landscapes, especially **urban environment**



Aerosol transport modeling

Largangian approach



Trajectories of **individual particles** are tracked

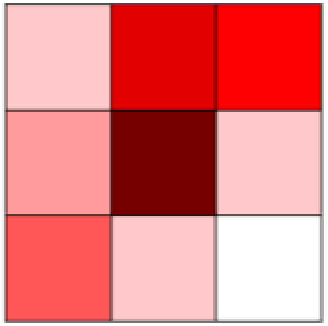
$$\frac{\mathrm{d}\boldsymbol{x}_p}{\mathrm{d}t} = \boldsymbol{u}_p, \frac{\mathrm{d}\boldsymbol{u}_p}{\mathrm{d}t} = \sum \boldsymbol{F}$$

$\boldsymbol{x}_p$ – particle location,

$\boldsymbol{u}_p$ – particle velocity

+: explicit solution of particles motion

Eulerian approach



Advection and diffusion of **concentration** is computed

$$\frac{\partial\langle s\rangle}{\partial t} + \langle u_i\rangle\frac{\partial\langle s\rangle}{\partial x_i} = \frac{\partial}{\partial x_i}K_s\frac{\partial\langle s\rangle}{\partial x_i} + Q_s$$

$\langle s\rangle$ – Reynold-averaged particle concentration

+: low computational cost

Largangian approach contains more information, because concentrations can be computed from particles trajectories, but not *vice versa*

t – time

$\boldsymbol{F}$ – external forces

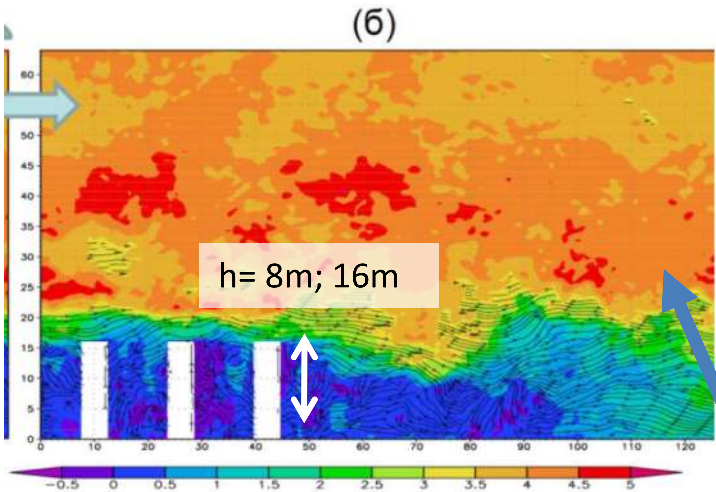
$\langle u_i\rangle$ – *i*-th Euleran velocity component

K_s – turbulent diffusivity

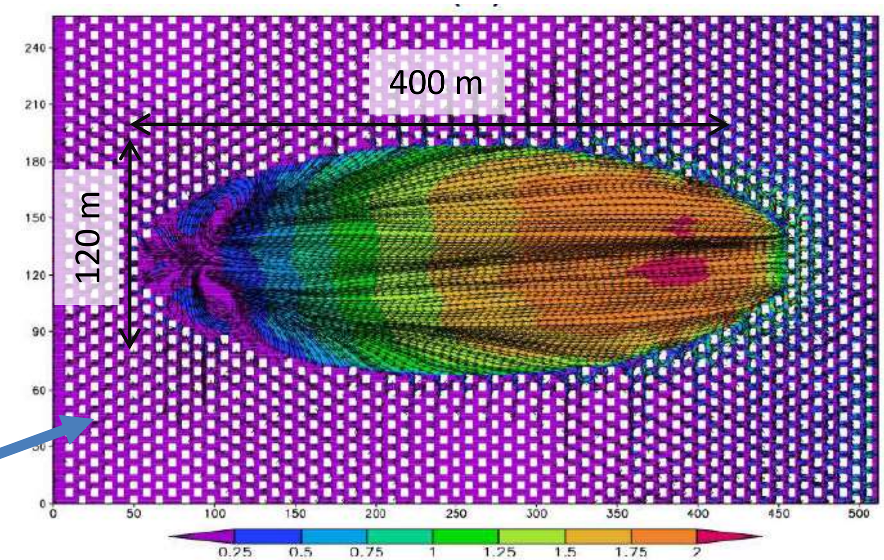
Q_s – sources and sinks

Aerosol transport modeling using Large Eddy Simulation

(Glazunov and Stepanenko, 2015; Glazunov et al., 2016, 2018)

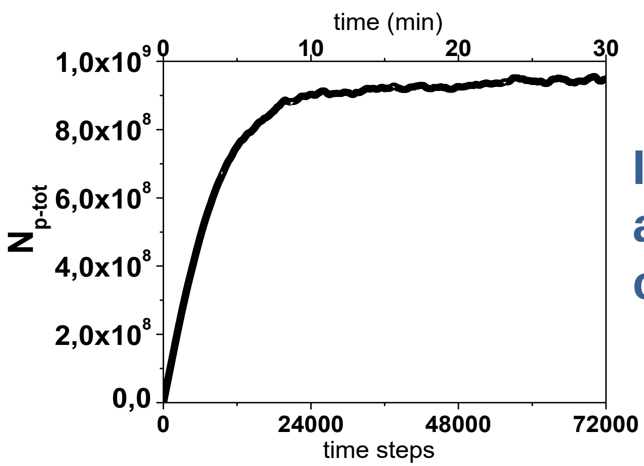


Velocity and streamlines over a clearing

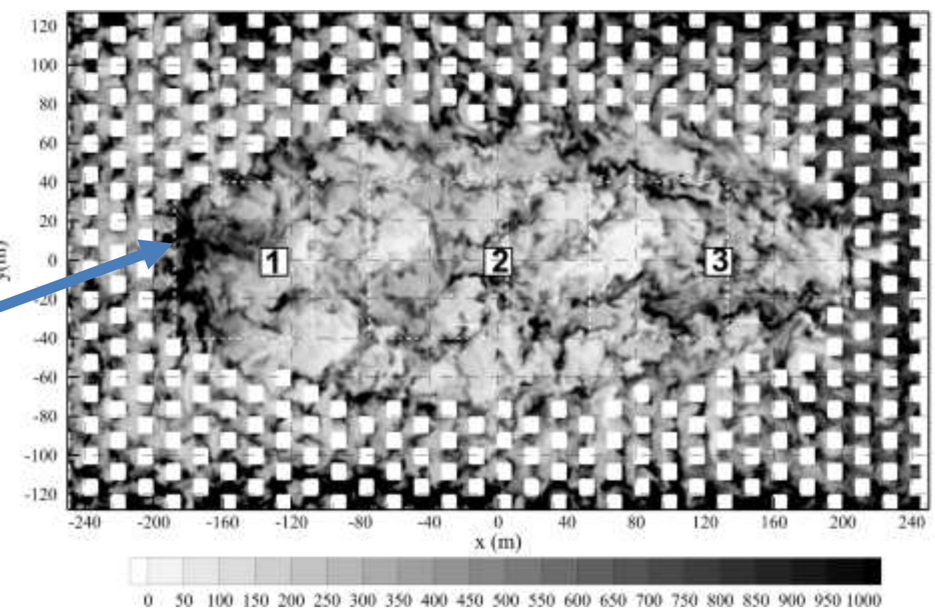


Mean velocity at the height z=0.25 m

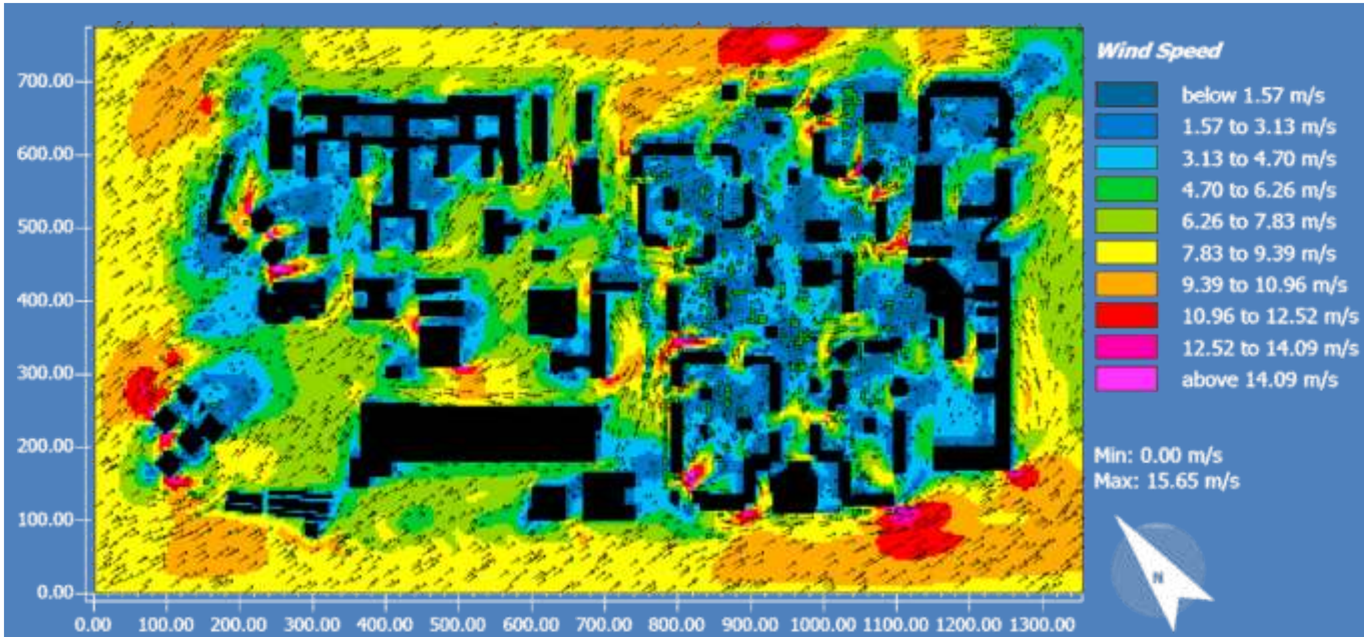
Number of particles during model runtime



Instantaneous aerosol concentration

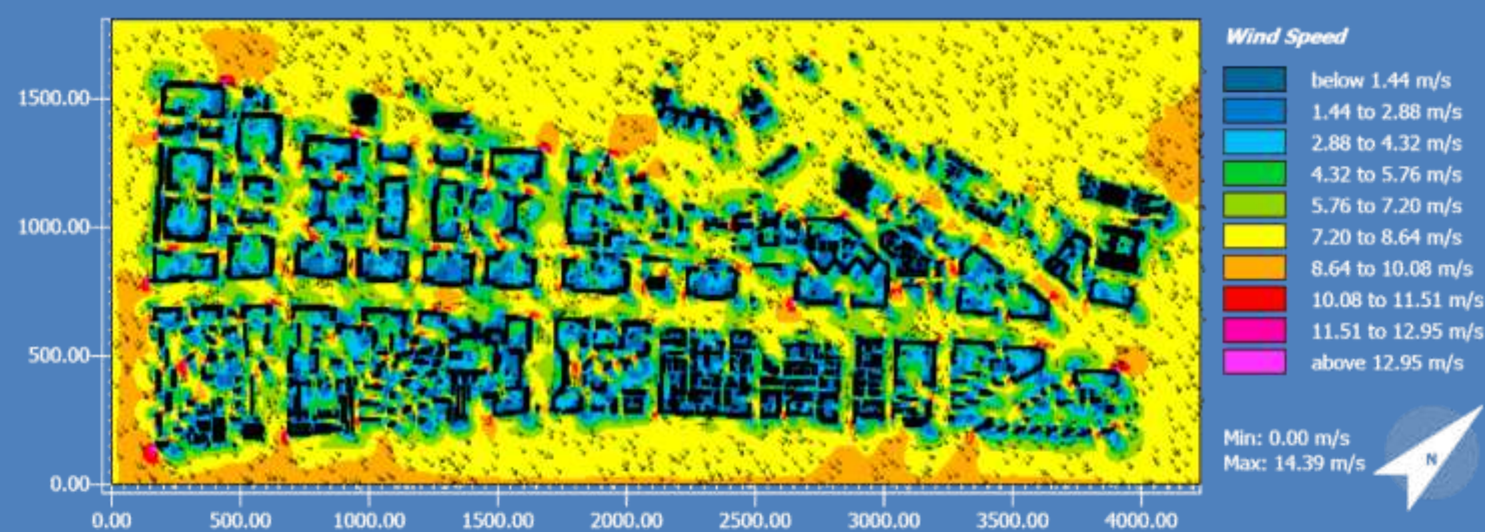


Microscale wind modeling for Moscow districts (ENVI-met RANS model)



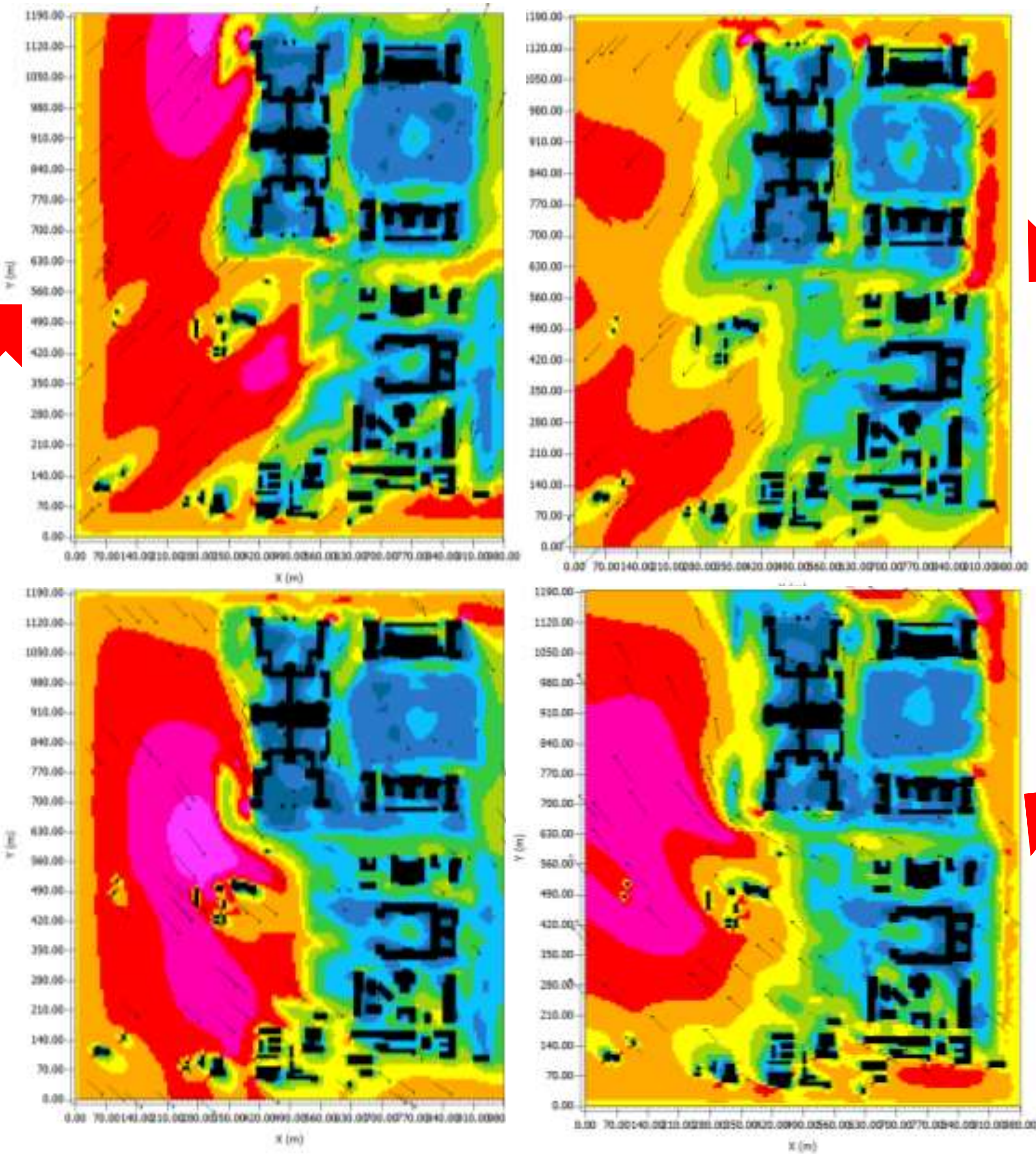
Pilot experiment on the Leninsky prospect – Miklukho-Maklaya st. Smart Urban Climate project

Trial experiment of Gagarinsky district, rough OSM (without topography corrections)

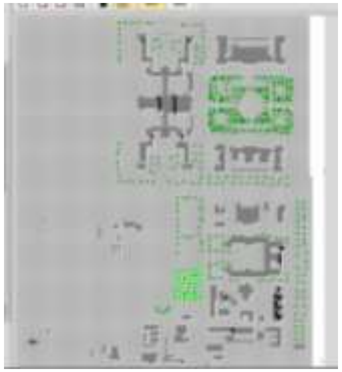


Wind speed and MSU-modeling domain

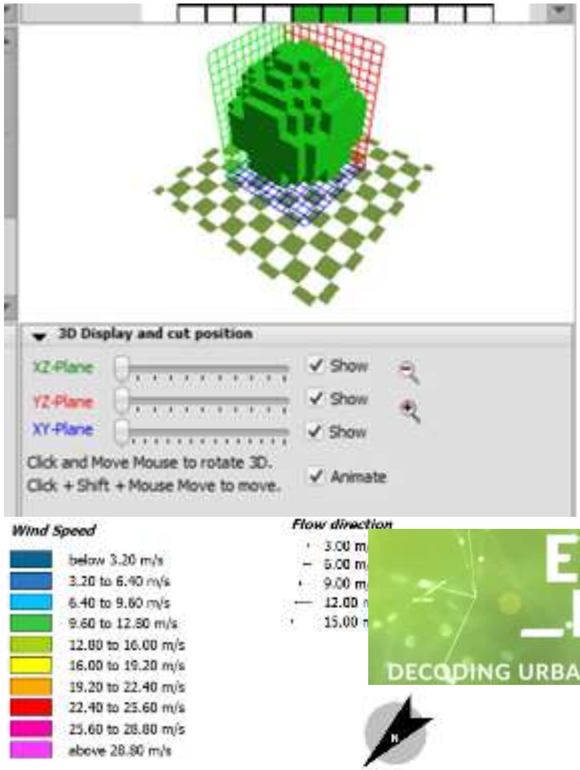
Nikolaeva et al., 2020



Digititalzation of MSU-domain



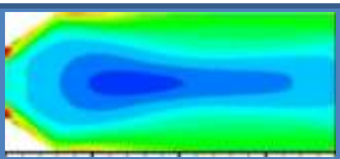
3D-tree modeling ventilation impact



ENVI_MET DECODING URBAN NATURE

Konstantinov et al., 2020

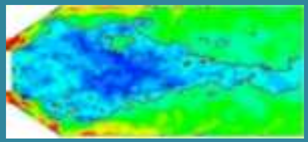
Interaction of modeling techniques



Reynolds-Averaged Navier-Stokes (ENVI-met, RCC MSU)

Largangian particles simulator

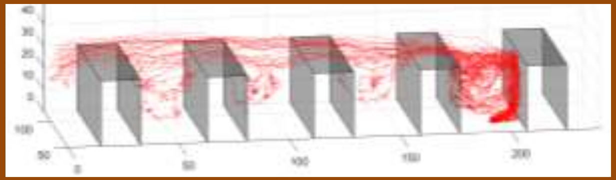
Validation of RANS by LES for typical and extreme synoptic conditions



Large Eddy Simulation (RCC MSU, INM RAS)

Largangian particles simulator

Fields of velocity and turbulence quantities for simulations of different aerosol types

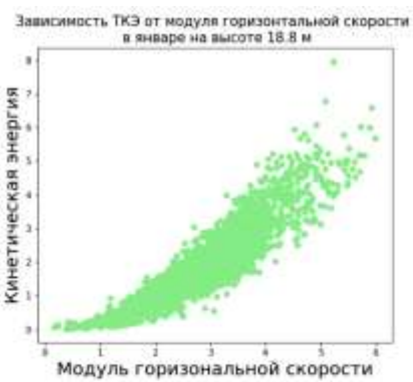


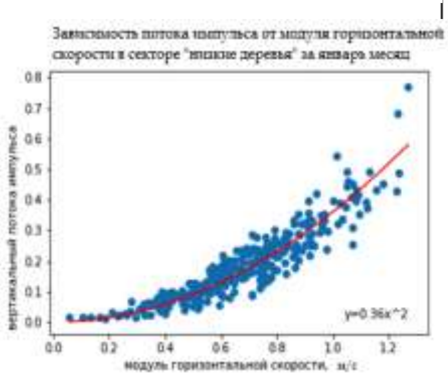
Largangian particles simulator (RCC MSU)

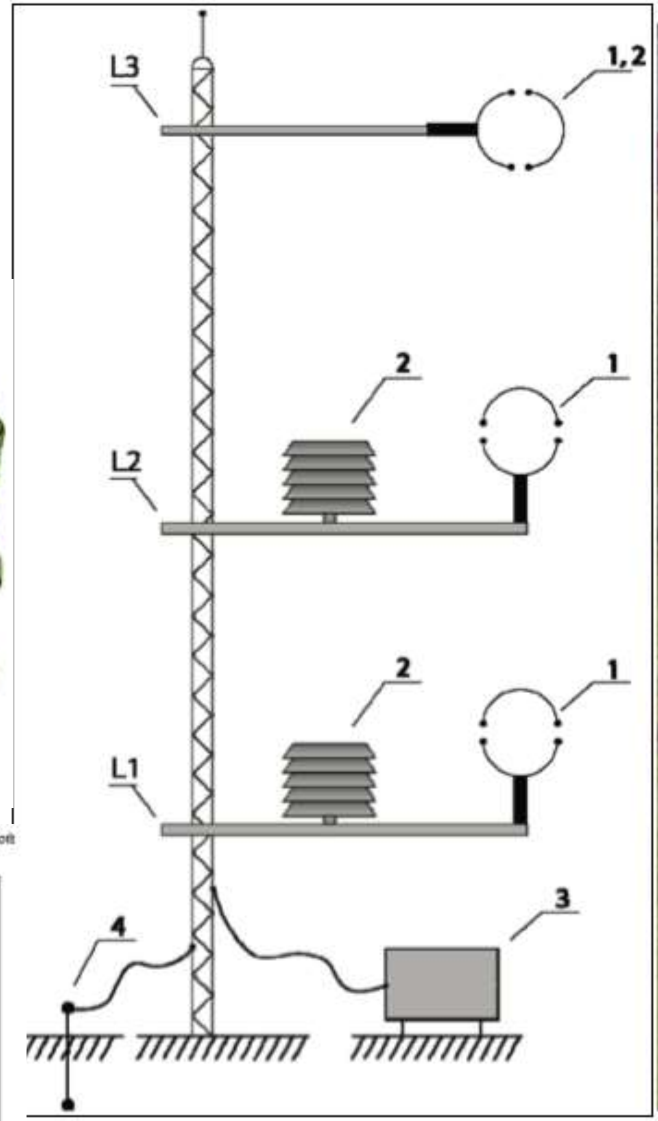
Computing resources are a bottleneck!

Existing EC tower in MSU campus

- Since the fall of 2019, a 22 m high eddy covariance tower
- 2 m, 11 m and 19 m of METEK sensors for momentum an heat



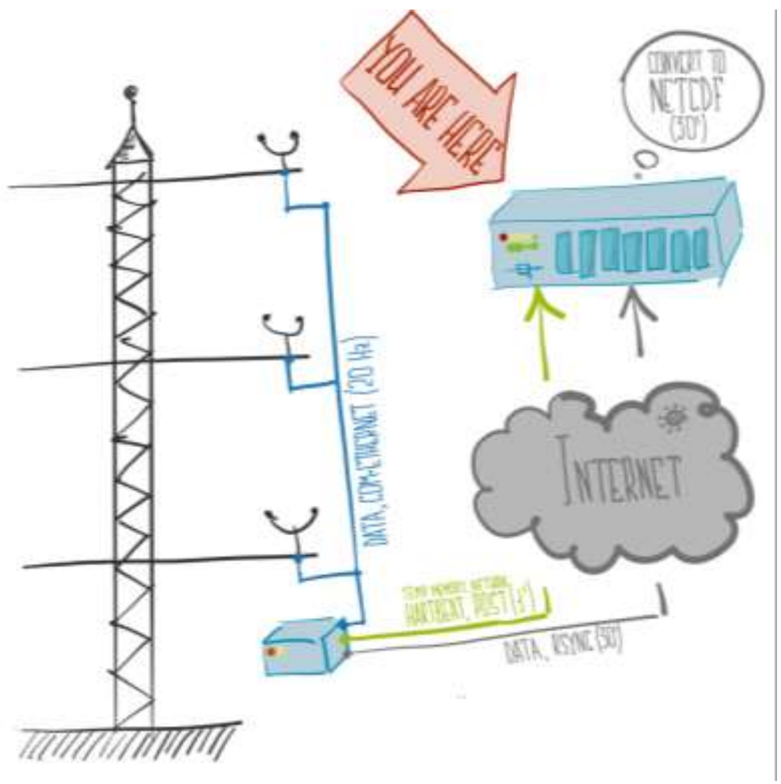


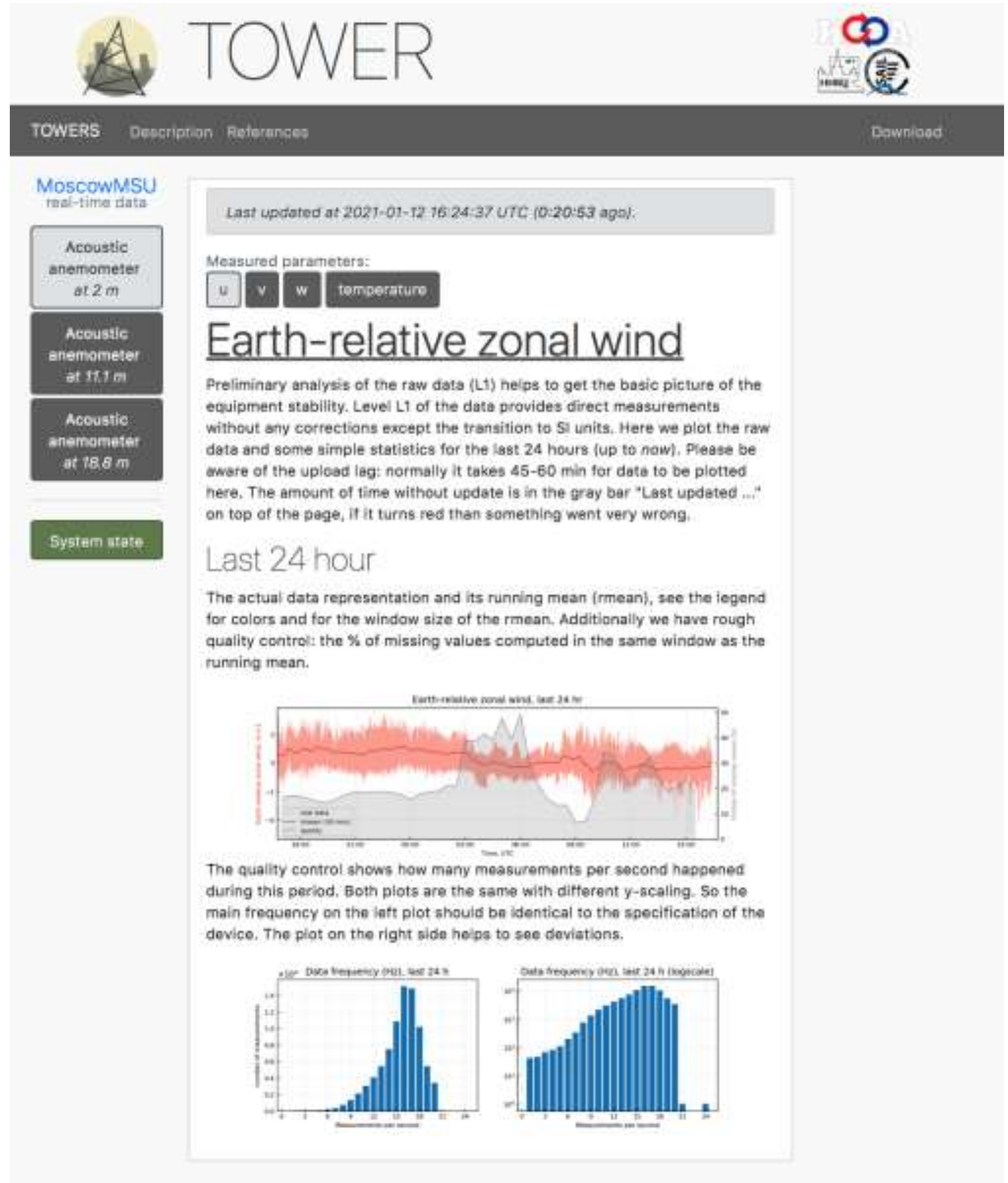


Website of the MSU tower

https://tower.ocean.ru/rtdata?tower=MSU&city=Moscow

- real-time online monitoring of system state
- online display of the latest 24 h data
- online screening of the latest data quality
- downloading of the raw data by registered users

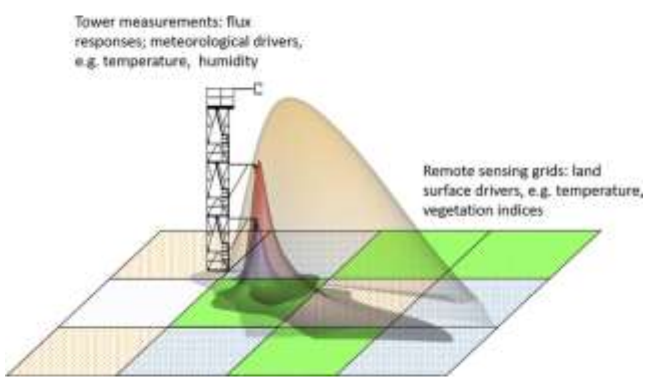


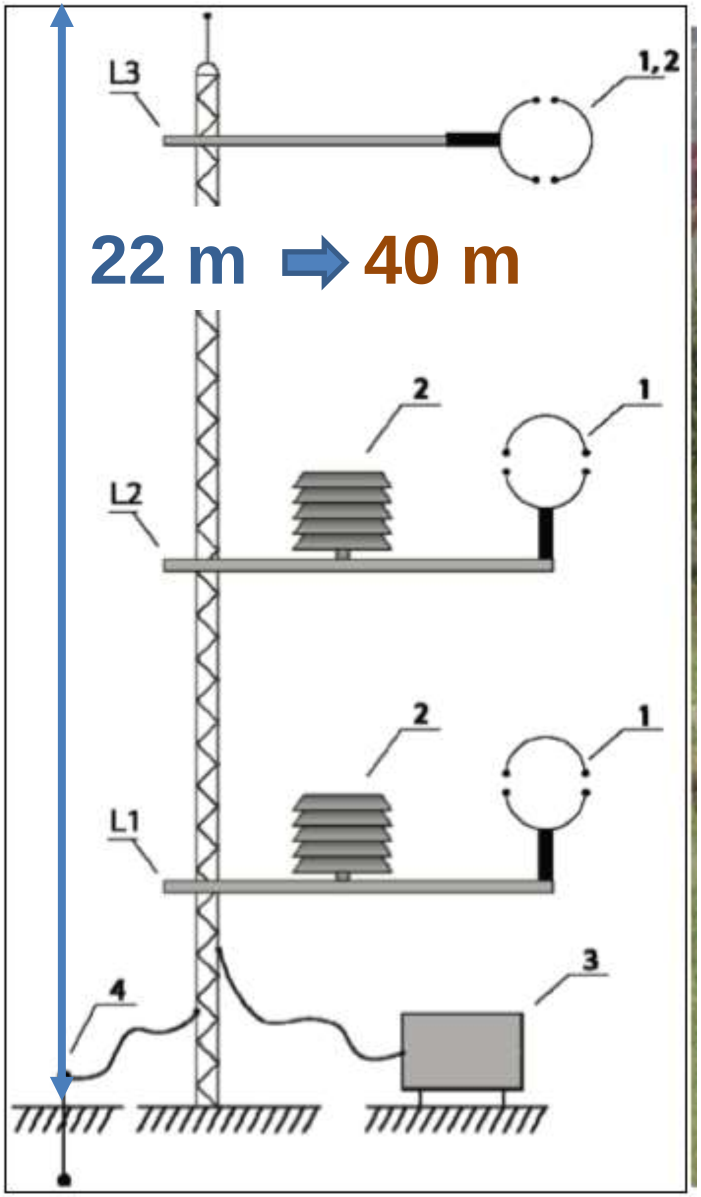


A prospect for a new tower in MSU campus

(towards FLUXNET and SMEAR standards)

- New tower of **~40 m** height (2-times higher than closest buildings)
- 3 levels of heat and momentum eddy covariance measurements
- 2-3 levels **PM10, PM2.5, PM1 concentration**
- Optimal choice of aerosol sensors on tower compliant to that used in MO MSU aerosol complex
- Optimal choice of mast construction and location in order not to disturb ongoing measurements
- Flux footprint analysis





Possible collaboration with other Tasks and WPs

- **WP2, Task 1, “Measurement of the physical-chemical properties of urban aerosols”**: the data on measured physical and chemical properties of aerosols, especially those of interest, will be used to setup numerical experiments;
- **WP3, Task 3.2**, **“Atmospheric urban aerosols in the city environment with account of its morphology, and their relationship with solar radiation and the urban heat island”**: numerical experiments allow to obtain fine scale spatial distribution of *different* aerosols in complex urban geometry, under contrasting background meteorological conditions, both typical and extreme in terms of wind and stratification;
- **WP4, “Creation of concept and methods of calculation of the mega-urban planetary boundary layer (PBL)”**: validating the newly developed theories for urban PBL development and their implications for aerosol distribution and transformations;
- **WP 6, “Interrelations and chemical (microparticles) transfer between urban atmosphere, soils and surface water”**: simulations of deposition of *different* aerosols on the soil and water surface in urban canopy under *different* background conditions.