Microscale simulation of wind speed in urban areas during extreme weather events (case study of Moscow)

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Abstract. This study is primarily based on the goal to make a model of the MSU campus to investigate wind speed distribution. As a case study, a squall event on the 29\(^{th}\) of May 2017 is chosen. The event caused human casualties, which required much research. To validate the results, they have to be tested for their stability. In this work this goal is met by varying wind directions. Later the wind maps were achieved as the results were overlaid to reflect the variability of the wind speed distribution. Moreover, the results of this work are possible dangerous areas of a campus which can be obtained as a result of simulating hazardous wind speeds. The wind directions are varied to match 4 primary directions. The heights of interest are chosen to be 1.5 m and 12.5 m, they represent the pedestrian level and the level of half the average tree height, respectively. The simulation software used is ENVI-met. This work shows whether this software is suitable for modeling hazardous events, how stable the results are, and whether the new user is able to successfully use the possibilities offered by ENVI-met to achieve the needed goals. With the results of simulations for stability tests and dangerous area outlining, spatial distributions of the wind speed are analyzed both quantitively and qualitatively.

1. Introduction and motivation

Each year the urbanization level in the world is increasing \([14]\). More and more people live in cities, more people are now subjected to specific conditions of urban microclimates, may it be urban heat islands or wind tunneling, or a specific regime of air pollutant dissipation \([8]\).

Urban meteorology has been experiencing substantial development in the preceding 60 years. The advancements could be traced to the developments in the computation capacities as well as better understanding and modeling of microscale interactions. These interactions greatly influence the urban microclimate and include plant to air, soil to air, building to air, and other interactions.

The lack of forecasting of hazardous events in urban agglomerations poses a great risk for the population. Moreover, the grave consequences of such lack of forecasts could be seen in the tragic events of the squall in Moscow on the 29\(^{th}\) of May 2017, when several people were killed by falling trees and debris \([7]\).

Over the years, the damage from various hazardous hydrometeorological events in Russia has increased. Some may argue that the increase can be attributed to the increasing cost of property and goods. Another argument may be that there are more people living in previously uninhabited places,
which leads to a greater probability of a damaging event. But there is also a possibility that the number of these events, as well as their severity, has increased over the last years.

May all the above reasons be equally important and valid or not, there is an increasing need to accurately predict areas prone to damage. However, the forecast can be surely made for synoptic scales. The microclimatic scale is not yet covered by the weather predictions because of the needed scope of supercomputer calculations. For Moscow (and especially for the MSU campus area) some meso- and microclimate modeling studies were performed previously for the urban heat island [4,11,12,13], as well as for the thermal comfort conditions [5].

This work is primarily based on the need to test whether it is possible to forecast the distribution of wind speeds in urban conditions. The research is based on the conditions of the squall that Moscow experienced on the 29th of May 2017 [7].

A squall is an event of rapid and short-lived (acute) increase in the windspeed to more than 15 m/s. To differentiate squalls from wind gusts, squalls are usually considered to be more than 1 minute long. Sometimes squalls can reach hurricane-force wind speeds, which can lead to damage to the infrastructure.

In general, the most favorable conditions for squall development are [1]:

- A cold front near the top of a wave disturbance moving at speeds of 10 m/s or more
- A cold front and an occluded front moving by themselves at speeds of 10 m/s or more
- A small trough in the warm sector of a cyclone
- The frontal part of a high-altitude baric trough or the frontal part of a cold center in middle troposphere

Between 1997 and 2018 Moscow experienced several squall events. In total, the wind speed of more than 21 m/s was recorded in Moscow for 14 times [9].

One of such examples is the squall event in Moscow on 29th of May 2017. The recorded squall could not be traced to a typical supercell genesis, yet it was produced by a rapidly progressing cold front with speeds of around 100 km/h. The decrease in the observed temperature was 10°C in 12 minutes, and the maximum observed wind gust speed was 28.3 m/s.

The Moscow agglomeration was positioned in the warm sector of a large extratropical cyclone centered over the Barents Sea. During the previous night and in the morning the cyclone center was moving in a south-easterly direction, so that towards the middle of the day the center had shifted from Karelia to Yaroslavl, just north of Moscow. Considering the location in the warm sector, the air temperature observed before the squall had reached 26.4°C by 15 hours local time (UTC+3).

As the studied squall was not accompanied by a thunderstorm or high values of the upper level clouds, it is reasonable to suggest that the squall was initiated by a cold front. The above-mentioned cold front was clearly visible by satellite observations. The rapidly moving cold front was traversing Moscow between 15 and 16 hours local time.

Coincidentally, the traverse of the cold front aligned with the time of maximum heating of the area, which led to a collection of hazardous weather events.

The squall was accompanied by a significant and rapid decrease in the observed air temperature. As such, at 15:39 the air temperature was registered at 25.0°C and at 15:52 the air temperature had already dropped to 14.9°C. At the same time, the wind gusts increased, with the maximum gust registered at 15:40 at a speed of 28.3 m/s. The average wind speeds also increased significantly, nearly doubling from 5.9 m/s at 15:38 to 10.2 m/s at 15:48.
To investigate the spatial differentiation of the windspeed field, the territory of the MSU campus was chosen, since it is both well-known to the researchers and consists of various types of land use and has varying building heights.

The advantage of the chosen territory is also in the various types of land use represented on the studied territory. The land use includes buildings of various heights, different vegetation types (dense tree cover of both conifers and deciduous species, as well as open spaces with grass cover).

The goals of the work are:

- To develop an ENVI-met model for the area of research
- To test the stability of the modelling outputs
- To graph the wind speed map for 4 primary wind directions (0, 90, 180, 270)
To highlight the hazardous zones for the MSU campus
To investigate the dependence of the local wind speed variability on the mesoscale wind speed

The input data consisted of wind speed (maximum gust speed) and direction (245°), temperature and humidity from observations of the MSU meteorological observatory (located within the studied area). To test the stability of the outputs, the wind direction was slightly varied in the runs (up to 10° in each direction). As a result, there are 5 maps of wind speeds with close wind directions. The similarity of the outputs indicates stability of the modeling scenarios.

To detect hazardous zones, the area was studied for significant wind speed increases (based on the maps of modelling outputs). An important issue to be considered is the interaction of the trees and atmosphere at great wind speeds. The trees decrease the wind speed significantly, exposing themselves to great wind pressure, which can lead to the tree falling.

2. Materials and methods

To investigate the positions of the zones of possible hazards, a model of the territory was developed using the ENVI-met software [15]. The ENVI-met complex is based on a three-dimension non-hydrostatic microclimate model. A typical spatial resolution of the model is 0.5-10 meters, and the resolution in time is up to 15 seconds. A crucial advantage of the used model is modelling of the interactions between the atmosphere, soil, vegetation, and buildings. A possibility of modelling every single tree or building plays a significant role in the precise forecast of the main meteorological parameters. The used forecast parameters include wind direction and speed, air temperature, humidity, turbulence, radiation flows, bioclimatology, and particle diffusion and dispersion.

The ENVI-met complex was developed in 1994 by the University of Mainz (Germany) [3]. The main difference between the models that are used to forecast the synoptic processes and daily weather and the used complex is the space and time resolution. A typical simulation is usually encompassing a time scale of a couple to a couple dozen of hours.

A significant advantage of the model over the others is the possibility to specifically edit every plant and every aspect of the studied buildings. Therefore, this complex can be used not only to forecast hazardous events, but also to model the properties of the buildings, may it be wind stress, heat distribution, or albedo.

One of the notable features of the ENVI-met model is the possibility to have a telescopic scale of the lower modelling cells, which increases the resolution in the layers that most people are in (close to the ground).

2.1 Sensitivity test

To test the sensitivity of the model, there are usually a variety of tests performed that have practically the same input, but one of the variables is slightly changed over the course of different simulations. In the case of this work, only the sensitivity to errors in the wind direction was tested. This decision was made due to the goals of the work. It is focused on the wind speed distribution, rather than on the temperature or humidity. The primary goal of the stability tests was to see that simulations with similar inputs produce similar results and do not vary greatly if the inputs are slightly changed.

As the basis for the stability tests, data from the MSU observatory was used. The maximum recorded wind gust reached a speed of 28.3 m/s. The observed wind direction was 245°. Other than the wind speed and direction, it is also important to have correct values of maximum and minimum temperatures, humidity, and the roughness coefficient of the terrain. The research area is a rectangle 980 m by 1190 m. The spatial resolution used was 7 m by 7 m by 5 m (height). The roughness of the terrain was set to 0.2 (roughly corresponding to a sparsely built medium-high buildings). The maximum temperature was set to 26°C, and the minimum temperature was set to 14°C. The humidity varied between 25% and 98%. The wind directions were changed by 5°, while the other values remained the same.
Table 1. Results of stability tests.

| Input flow direction, ° | 245  | 235  | 240  | 250  | 255  |
|-------------------------|------|------|------|------|------|
| Maximum wind speed, m/s | 32.88| 32.25| 32.18| 33.44| 33.75|
| Minimum wind speed, m/s | 0.06 | 0.14 | 0.26 | 0.15 | 0.14 |
| Average value, m/s      | 19.13| 18.90| 19.03| 19.32| 19.53|
| Dispersion              | 57.62| 58.87| 58.30| 57.25| 56.68|
| Mode                    | 27.05| 27.00| 27.03| 27.07| 27.09|

Number of cells with V>30 m/s

|                      | 20/0.08% | 56/0.23% | 26/0.11% | 14/0.06% | 11/0.05% |
|----------------------|----------|----------|----------|----------|----------|

Number of cells with V>25 m/s

|                      | 6873/28.7 | 6564/27.4 | 6743/28.2 | 7160/29.9 | 7482/31.3 |
|----------------------|-----------|-----------|-----------|-----------|-----------|

Number of cells with V<10 m/s

|                      | 4010/16.8 | 4372/18.3 | 4110/17.2 | 3839/16%  | 3642/15.2 |
|----------------------|-----------|-----------|-----------|-----------|-----------|

Spatial differences

|                      |          |          |          |          |          |
|----------------------|----------|----------|----------|----------|----------|

In order to define whether the spatial distribution of the wind speeds was, in fact, similar across all simulations, the results which were mapped in ENVI-met were overlaid. If the wind speed in the area is similar across the simulations, it will have the same color on the map. Therefore, when the maps are overlaid, the color will remain the same, as for each layer the color does not change.

However, if the spatial distribution of the wind speed varies significantly, the contours of the areas with similar wind speeds will not overlay the same area anymore, which will result in intersecting borders between the areas with different wind speeds, therefore, it can be easily seen. To conclude, if the result of the overlay shows little to no overlapping and color mixing, the spatial distribution of the wind speed does not vary significantly across the simulations.

After overlaying the results of simulations for 5 different inflow directions which were gradually varied by 5° in each direction to reach the difference of 10° from the studied direction, the map below was made. It can be clearly seen that for the most part the contours of the wind speed areas are similar, however in the open area to the east of the buildings the contours start to overlap. This can be explained by a significant role of buildings in the definition of the wind direction in urban areas (wind
tunneling), but in the open plains changes to the input direction cause the wind direction to shift accordingly. The average wind speed values differ by less than 1 m/s, which indicates a great level of stability of the model if there are errors in the inputs of the wind directions.

![Figure 3. Stability test results as overlaid maps.](image)

Because of stability of the results if the wind directions are varied, it is possible to define dangerous areas in the MSU campus, where the wind speeds have reached or exceeded hurricane wind speeds. Primarily these areas tend to be grouped around the corners of the buildings. However, it should be noted that wind speeds of over 25 m/s take more than a quarter of the area, while the areas with wind speeds of 30 m/s or more take less than a percent. With an input speed of 28.3 m/s it can be concluded that the wind speeds are usually lower in the urban areas, however in some areas the wind speed increase drastically to hurricane speeds or higher.

3. Results
One of the main advantages of the ENVI-met is a user-friendly interface with a variety of possibilities, which allows no other specific apps or programs to be used in order to map and interpret simulation results. Therefore, the results of the simulations in ENVI-met are maps of the studied parameters. Since the main goal of this work is to define dangerous areas and the wind speed distribution showed little variability in the direction changed up to 20°, it is reasonable to assume that there is a need to model just the distributions with 4 primary wind direction inputs - 0°, 90°, 180°, and 270°.

One further detail in defining which parameters should be studied is the areas where the wind affects the people and infrastructure. The levels of 1.5 m and 12.5 m were chosen, since they reflect the main possible hazards from an increase in wind speed. The 1.5 m level reflects the human experience in the wind. Where will a person encounter the strongest winds and in which direction they will be blowing? The answers to these questions may also evoke a picture of debris flows, which can also cause damage to humans.
Figure 4. Results of modelling as maps of wind speeds at heights of 1.5 m and 12.5 m.

As a result of the analysis of the wind speed distribution at 1.5 m, there are several conclusions to be outlined. First, the wind speed is significantly decreased in the areas with trees or in the yards of buildings. It is reasonable to assume that not only the buildings are a significant obstacle for the wind, but also the trees may be seen as an obstacle that can be used to decrease the observed wind speeds. The observed wind speeds in the areas mentioned above are less than 10 m/s, which is considered reasonably comfortable for humans. Second, the maximum observed wind speeds at the same height can reach up to 37 m/s. A hazardous area that can be seen, the simulation with the inflow direction of 270°, is the corner of the Faculty of Physics, where the air flows around the building, instead of stopping on it, which creates an increase in the wind speed. Another area of increased wind speeds, this time for the 0° and 180° directions, is the southeastern corner of the MSU main building.

The areas with wind speeds of more than 25 m/s vary significantly between the simulations. For example, for a wind direction of 180° these areas make up 0.22% of the territory, whereas for the 90° inflow the same wind speeds cover 14.4%. This incidence may be explained by the configuration of the buildings.

To conclude, the main dangerous areas for the pedestrian height are open areas and corners of buildings.

Table 2. Results of simulations with different input directions.

| Input flow direction, ° | 0       | 90      | 180     | 270     |
|------------------------|---------|---------|---------|---------|
| Maximum value, m/s     | 35.88   | 31.69   | 37.20   | 31.30   |
| Minimum value, m/s     | 0.14    | 0.07    | 0.09    | 0.005   |
Average value, m/s

|       |        |        |        |        |
|-------|--------|--------|--------|--------|
|       | 16.30  | 16.53  | 15.40  | 16.44  |

Dispersion

|       |        |        |        |        |
|-------|--------|--------|--------|--------|
|       | 56.27  | 64.49  | 40.29  | 55.44  |

Mode

|       |        |        |        |        |
|-------|--------|--------|--------|--------|
|       | 18.95  | 18.85  | 18.85  | 18.88  |

Number of cells

|       |        |        |        |        |
|-------|--------|--------|--------|--------|
|       | 33/0.14%| 191/0.8%| 4/0.02%| 1/0.004%|

It is possible to assume from the above results that the areas with trees are the safest in case of a rapid increase in the wind speed. It must be noted, however, that most damage and casualties come from falling trees or debris. This happens because, as it was shown earlier, trees are, in fact, quite similar to walls in their effects and, therefore, they experience significant forces from the wind pressure. Therefore, it is important to explore the wind speed distribution at the typical tree height. As the height of a typical tree (note that the median of the height was chosen to represent the largest area), 12.5 m was chosen.

The wind speeds at this level are higher than at the pedestrian level. The highest wind speeds tend to be grouped around the corners of buildings. This can be explained by both the air moving around the corner and the air moving upwards from the lower levels.

It can be also noted that because of roughness and friction, low buildings can still influence, even to a small degree, higher levels of the area.

The overall distribution of the wind speed is otherwise similar to the one seen at the pedestrian level.

4. Conclusions

The ENVI-met model can be considered as a reliable source of model information for different approaches in urban engineering. The results of the above modelling show high stability if the input data contain errors in wind directions. Therefore, it is possible in the future to estimate human comfort levels taking into consideration wind speeds. This work can be used as an example of such modelling.

There is also a possibility to use ENVI-met for modelling extreme weather events to reveal the potentially dangerous areas. In the case of the MSU campus, the areas with the highest wind speeds are the ones without trees or corners of large buildings. In these areas there is a possibility of damage by flying objects.

However, the true danger is in the areas where the wind speeds can be drastically decreased by trees, so that the trees experience forces large enough to bring their branches or the whole tree down.

This work and software can be used in the future to create a wind safety system that could encompass the whole Moscow agglomeration.

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References

[1] World Urbanization Prospects. The 2009 Revision Report 2009 (New York: United Nations, Department of Economic and Social AffairsPopulation Division) 47 p

[2] Li H, Meier F, Lee X, Chakraborty T, Liu J, Schaap M and Sodoudi S 2018 Interaction between urban heat island and urban pollution island during summer in Berlin Sci. Total Environ. 636 818–28
[3] Kuksova N E and Toropov P A 2019 Mechanisms of squall formation in the Moscow region on May 29, 2017 International Youth School and Conference on Computational Information Technologies for Environmental Sciences CITES 2019 278–80

[4] Kislov A V and Konstantinov P I 2011 Detailed spatial modeling of temperature in Moscow Russ. MeteorolHydrol 5 25-32

[5] Varentsov M I, Konstantinov P I and Samsonov T E 2017 Mesoscale modelling of the summer climate response of Moscow metropolitan area to urban expansion IOP Conference Series: Earth and Environmental Science 96 1-13

[6] Varentsov M I, Samsonov T E, Kislov A V and Konstantinov P I 2017 Simulations of Moscow agglomeration heat island within framework of regional climate model COSMO-CLM [in Russian] Moscow University Vestnik 5 Geography 6 25-37

[7] Varentsov M, Wouters H, Platonov V and Konstantinov P 2018 Megacity-induced mesoclimatic effects in the lower atmosphere: A modeling study for multiple summers over Moscow, Russia Atmosphere 9 50

[8] Konstantinov P I, Varentsov M I and Malinina E P 2014 Modeling of thermal comfort conditions inside the urban boundary layer during Moscow’s 2010 summer heat wave (case-study) Urban Climate 10 563-72

[9] Bogatkin O G and Enikeeva V D 1992 Analysis and Forecast of Weather for Aviation (St. Petersburg: Gidrometeoizdat) p 72

[10] Lokoshchenko M A et al 2018 Ecological and Climatic Characteristics of the Atmosphere of Moscow in 2017 According to the Data of the Meteorological Observatory of Lomonosov Moscow State University ed. M.A.Lokoshchenko (Moscow: MAKS Press)

[11] Kuksova N E 2019 Synoptic Mechanisms of Dangerous Weather Phenomena in the Warm Half of the Year in the Moscow Region of Moscow State University (Moscow: Moscow State University)

[12] https://www.envi-met.com/

[13] Huttner S 2012 Further Development and Application of the 3D Microclimate Simulation ENVI-met (Mainz:University of Mainz)

[14] Dubinsky S I and Doroshenko A V 2011 Effect of planting tree on the structure of surface air flow inside the city building Vestnik MGSU 4 45-9

[15] Ozkeresteci I, Crewe K, Brazel AJ and Bruse M 2003 Use and evaluation of the ENVI-Met model for environmental design and planning: an experiment of linear parks Proceedings of the 21st International Cartographic Conference Durban, South Africa 10-16