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Object-oriented approach to urban canyon analysis and its applications in meteorological modeling

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ABSTRACT

The study applies object-oriented analysis to the extraction of urban canyons and introduces the concept of directed urban canyon which is then being experimentally applied in urban meteorological modeling. Summary of current approaches for describing urban canyon geometry is provided. Then a new theoretical approach to canyon delineation and three-level hierarchical classification is presented. The study discloses an original methodology based on triangular irregular network (TIN) designed to allow extraction of directed and undirected urban canyons from cartographic data and estimation of their geometric characteristics. Obtained geometric properties of canyons are coupled with land cover data into the database, which is then applied in micro-to-local scale temperature and wind modeling. Using URB_MOS model and the derived database we refined COSMO_RU modeling results which facilitated the decrease of the mean root square error of temperature forecast from 4.0 to 2.1 degrees. Estimation of possible wind accelerations along canyons using the derived database is also presented. Results and future perspectives are summarized in the concluding part.

1. Introduction

A theory of urban canyons has been originally developed by Oke (Nunez and Oke, 1977; Oke, 1987) in the second part of XX century. According to this theory, an urban canyon is a three-dimensional space between buildings with two boards (building walls) and a bottom (the road). The main canyon parameters are its height H and width W, which together define height/width ratio that is being widely used in urban climate modeling. In some cases, canyon length L of the canyon and its azimuthal direction (orientation) θ are also being used. Fig. 1 illustrates these characteristics.

Short-term dependencies between the meteorological regime of urban canyons and their characteristics are significantly less investigated than their climatic properties. Almost all the existing models of the urban boundary layer consider canyons as one of the numerous land cover types, like parks or water bodies (Kusaka et al., 2001; Martilli et al., 2002). Dynamic models such as WRF (Shamarock et al., 2008) include urban block that can assimilate one fixed direction of an urban canyon (Kusaka et al., 2001). However, this approach is suitable for the cities with regular built-up layout and one prevailing canyon direction only. Masson (2000) developed a reductive scheme of thermal balance calculation for urban areas with more chaotic structure by integrating all possible canyon directions. This scheme was implemented as urban block in COSMO_CLM

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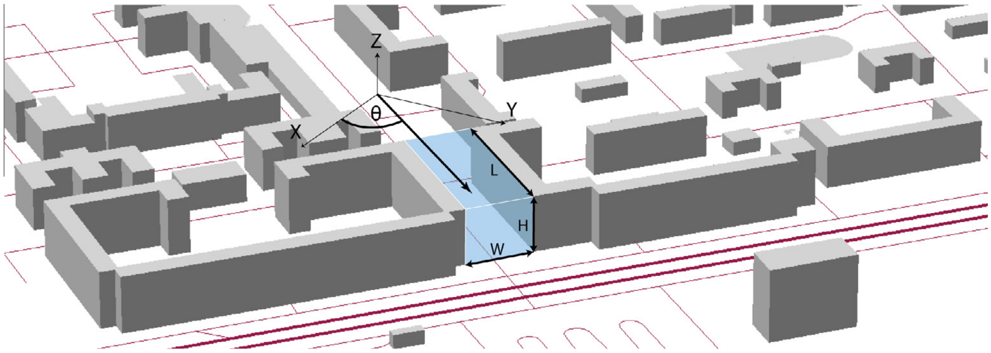

Fig. 1. Urban canyon and its parameters. *W* – width, *H* – height, *L* – length, *θ* – direction.

meteorological model (Trusilova et al., 2013). Inclusion of specialized urban module results in more detailed urban weather and climate forecasts. However, for some large cities like Moscow, Russia with radial-circular street layout prevailing, or Tokyo with its irregular street network, coarse canyon descriptions are correct for modeling average daily characteristics only and, consequently, for climatic predictions (Kislov and Konstantinov, 2011).

Short-term prediction of diurnal variation of meteorological parameters needs detailed description of urban environment. This description can be effectively derived from spatial data such as spatial databases (Lindberg, 2007; Gál and Unger, 2014) and remote sensing imagery (Moran, 2010; Peeters and Etzion, 2010; Pu et al., 2011). During the last two decades, significant progress has been achieved in development of supporting methods based on Geographical Information Systems (GIS). A wide array of urban geometric characteristics (Burian et al., 2002) can be derived and used in various tasks including meteorological modeling (Gál et al., 2008), architecture planning (Kropf, 1996) and even robots' navigation (Hrabar et al., 2005).

The main investigated geometric characteristics of an urban environment include canyon height/width ratio, sky view factor (percentage of visible sky from the point, abbreviated as SVF, see (Johnson and Watson, 1984)) and frontal area index (the ratio between area of the walls visible from a particular direction, to the area of the cell on which these buildings are located, see (Raupach, 1992)). Various algorithms are designed for calculation of these parameters, and results are used for urban climate investigations. Ratti et al. (2006) proposed a raster algorithm to estimate canyon height/width ratio. Unger (2009) revealed the connection between urban heat island and sky view factor using 3D Urban Database. Wong et al. (2011) calculated a frontal index and estimated urban ventilation from cartographic databases in various azimuthal directions. Chen and Ng (2011) used cartographic databases for SVF and frontal area density calculation, classified them to derive thermal load map and wind dynamic map respectively, and finally produced climatic map classes.

Urban geometry characteristics are usually calculated for *one point*, thus characterizing a particular location in urban space. A raster-based approach often helps to solve such tasks. If urban *digital elevation model* (DEM) is used for calculation, then height/width ratio or sky view factor are calculated for each raster cell using focal analysis (Ratti et al., 2006; Gál and Unger, 2014). The frontal area index, which is an integral value over some area, is also calculated by regular grid tessellation of the city (Wong et al., 2011).

At the same time, a large demand in characterization of an urban environment coming from architects, planners and meteorologists has lead to the emergence of such an interdisciplinary field as *urban morphology* (Moudon, 1997), which suggests the city to be described in terms of its physical form. In urban morphology approach the city is decomposed into three major elements: buildings, plots and streets, while four levels of detail are possible in investigation: building/plot, street level, city and regional levels. Various classifications are developed to decompose city structure (Kropf, 1996; Osmond, 2010; Oliveira, 2013). Kropf (1996) developed the concepts of specificity level, resolution level and outline/external form in urban morphology analysis. Böhm (1998) introduced the urban structural unit idea, which was lately evolved by Osmond (2010), who, in turn, introduced the hierarchy of inbuilt spaces such as parks. Recently Oliveira (2013) proposed the *morpho* approach to assess the urban form. His methodology considers only physical properties of an urban form and includes a limited number of characteristics that are used to estimate the degree of *urbanity*. It included estimation of accessibility, density and divergence of urban elements. One of the major parts of this study was related to the calculation of parameters of street networks and centerlines based on works of Hillier et al. (2010) and Turner (2007).

From this summary we can differentiate between two alternative approaches to investigation of urban environment. Urban climate researchers are interested in local or continuously distributed characteristics. Urban morphologists study the city as a structure of discrete geometric objects, each having its functional properties. The intersection of both approaches leads us naturally to the definition of urban canyon. This also gives raise to the urban canyon investigation from a new point of view, which is in between local point-wise calculations, and those averaged over some abstract area, representing the level of analysis of the canyon itself. Such investigations require a methodological framework to the definition, extraction and description of canyons as geometric elements of urban environment with the focus on meteorological applications. By using this integrated approach we will be able to make assumptions like "this particular canyon has high h/w

ratio and this one has low value". Or "this chain of canyons is long and stable in direction and is subject to wind acceleration". Because each canyon is analyzed as a separate object, we should call this approach *object-oriented*.

In this paper we present main theoretical principles and some methods that can be applied for object-oriented urban canyon analysis in terms of meteorological applications. We offer a classification of canyons in two types: directed and undirected, and also the following classification scheme for buildings in terms of canyon type they form based on topological relationships. A three-level hierarchy of the canyons based on their spatial extent and relationship with road network is introduced. Canyons are geometrically delineated using vector database whereas their geometric properties are calculated using triangulation. These properties can then be averaged across individual canyons or over some area (i.e. model cell). Statistical method for main and secondary canyon directions recognition is also developed. Results obtained for Moscow city are then statistically assessed and analyzed. Using this methodology a multi-scale database containing combined information on general urban canyon characteristics and land cover distribution has been developed. Main characteristics are then fed into URB_MOS meteorological model which refines the forecast made by standard COSMO_RU model. Results of the temperature and wind modeling are then derived and analyzed.

2. Theory

Object-oriented analysis of canyons is based on the assumption that canyons are physical spaces that can be extracted as geometric volumes with particular shape. Local geometry of an urban canyon is mainly defined by the distance between buildings and their height. Canyon azimuthal orientation (direction) also plays an important role. It influences diffusion, advection and wind velocity. In classic theory, a canyon describes the relationship between each pair of buildings. Every new pair composes a new canyon. However, when neighboring canyons have common longitudinal axis, it can result in the wind acceleration or blocking effects.

This leads us to the natural conjecture that such canyons can be chained into one lengthy volume called **directed canyon**. We can say that the length L of a directed canyon is much larger than its width $W: L \gg W$. It also should have constant or gradually changing direction. In most cases directed canyons are formed by street network, thus the edges of a street network can be considered as the axes of directed canyons. All other spaces between buildings, which are not crossed by street network are formally considered to be **undirected canyons** in our theory.

We offer the following classification of canyon levels that can be used for modeling of land–atmosphere interactions at different scales. It has strong connections with standard scales of urban climatology:

1. *Micro-canyons*. The basic level, at which limits of each canyon are defined by each pair of buildings (a "pure" classic canyon). Micro canyon extraction does not differentiate between directed and undirected canyons. This level of canyon is atomic and should be used for *microclimate* tasks such as investigation of canyon energy balance, building energy use or estimation of thermal comfort conditions. Information about micro-canyons will be useful (as usual) in detailed TEB-models. Architects can find micro-level useful for finding an optimal placement and geometric parameters of individual buildings in the surrounding context. The typical linear scale of micro-canyons is tens of meters.
2. *Meso-canyons*. Intermediate level which is defined as the chain of micro-canyons between two crossroads. Long meso-canyons can be subdivided into sections having homogeneous built-up (the same construction materials, number of floors, etc.). This level is atomic to the city's directed canyons network and should be used for modeling *local and meso-scale* atmospheric processes. Possible applications include urban weather forecasts and estimation of the urban energy balance (UEB). In general, now it is clear that urban meteorological modeling is developing in direction of scale enlargement and information about directed canyons is essential for validation and usage of these models as boundary conditions for horizontal advection equation. The typical linear scale of meso-canyons is hundreds of meters.
3. *Macro-canyons*. Global level, at which canyons are identified by road network strokes. The concept of strokes has been developed by Thomson and Richardson (1999) for street network generalization and is based on the "good continuation" principle. This principle means that network edges that join at one point with small deviation angle, can be merged into one lengthy stroke. This stroke corresponds to the chain of meso-canyons called macro-canyon. Macro canyon level can be used for some specific tasks such as analysis of main city ventilation corridors. Obtaining detailed information about macro-canyons can be useful also for extreme wind events prediction in city. Because this type of meteorological forecasts is quite important for urban infrastructure, specialized meso-scale wind models can be developed in the future. The same holds for meso-canyons. Typical size of macro-canyons in large cities varies from hundreds of meters to kilometres.

The list of spatial data needed for canyon extraction includes:

1. Geometry of individual building footprints.
2. Heights of buildings.
3. Linear street network (for derivation of directed canyons).
4. Land cover polygons (for exclusion of spaces that cannot be attributed to canyons, e.g. forest areas).

In cases when canyons should be extracted with true bottom surface city DEM is also required. In turn, a true 3D description would also demand for full 3D geometry of buildings. We will describe 2D case where the bottom of every canyon is considered flat and every building is virtually extruded to its height and is considered to be a prism. All calculations are based on these assumptions.

3. Materials and methods

Our methodology of object-oriented canyon analysis consists of the following stages:

1. Extract canyons and classify them into directed and undirected. Classify buildings according to their topological relationships with the two types of canyons stated above.
2. Extract canyons' hierarchy for canyon-based analysis.
3. Estimate canyon local and average height, width and their ratio.
4. Estimate modal directions of directed canyons.

When describing stages (3) and (4) we will show how extracted canyon characteristics can be calculated and averaged over some regular grid tessellation (which is needed for modeling applications).

In this section we will also present the derived database that includes calculated characteristics. Materials used in experimental work are presented in concluding paragraph at the end of this section.

3.1. Canyon extraction and buildings' classification

The canyon is a space between buildings (Oke, 1987). Our approach follows this statement straightforwardly. To cover the space between neighboring buildings we need to connect their corners and walls by some space tessellation. In 2D case, where each building is represented by its polygonal footprint, this task can be simply solved by constructing a TIN (de Berg et al., 2008) which includes the vertices and polygon edges as its elements. Only triangles outside of the buildings should be considered. We also assume that canyon can be formed not only by a pair of buildings, but by a pair of one building and tall vegetation polygon too.

Based on this approach, the following GIS-based methodology for extraction and classification of urban canyons has been developed:

1. Triangulate the vertices and edges of building polygons and polygons of tall vegetation (forests), which can also form canyons with buildings. Constrained Delaunay triangulation allows preserving existing edges.
2. Use spatial query to reject the triangles inside the buildings and forested areas.
3. Select triangles that have at least one vertex belonging to the building (two others can belong to the forest). Attribute them as being canyons.
4. Select canyon triangles intersected by street network. Attribute them as the elements of **directed canyons**.
5. Invert canyon triangles selection and attribute resulting triangles as the elements of **undirected canyons**.

If needed, forested areas can be simply omitted from canyon extraction by excluding triangles that connect buildings and forest polygons.

As canyons are produced by the building environment, all buildings can be classified in terms of the type of the canyon they form. Four cases are possible based on topological relationship *touches* (Egenhofer and Franzosa, 1991).

- directed (*touches* directed canyons & *not touches* undirected canyons);
- undirected (*touches* undirected canyons & *not touches* directed canyons);
- directed and undirected (*touches* both types of canyons);
- no canyon (*not touched* by any canyon).

An example of canyon areas extraction and building classification is presented in Fig. 2. Note that this classification does not include the "classic" individual canyons which are defined by 1:1 relationship between each pair of buildings, but rather *the spaces occupied by canyons*. Next, the hierarchy of canyon objects can be extracted.

3.2. Extraction of canyon objects hierarchy

Object-oriented analysis of canyon characteristics may deserve averaging them *per each canyon* and not per each modeling cell. This can be important not only for micro-scale meteorological modeling but also for urban morphology studies and their social and economic applications, such as thermal comfort conditions estimation (Konstantinov et al., 2014).

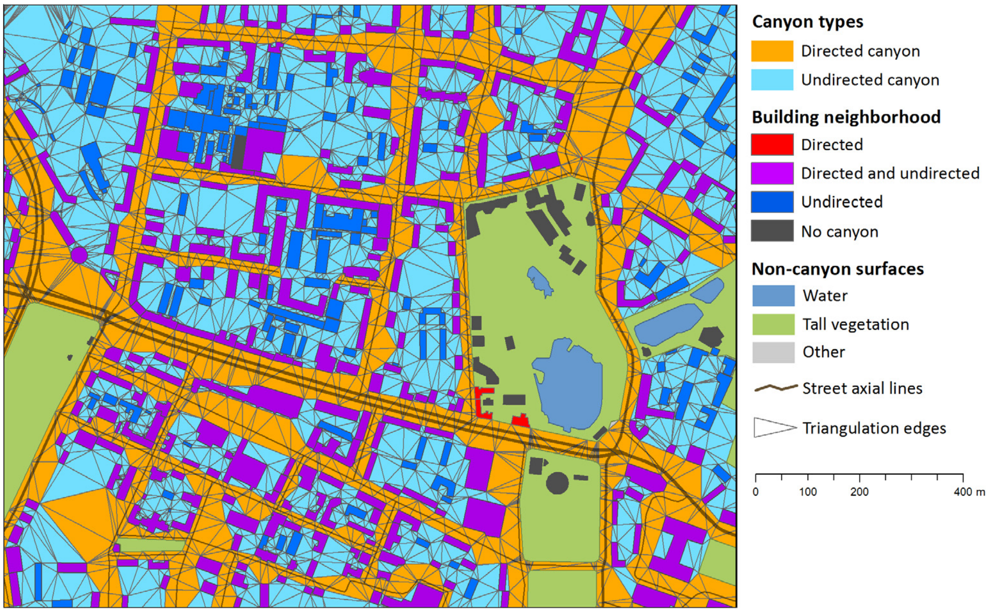

Fig. 2. Types of canyons and canyon-producing buildings.

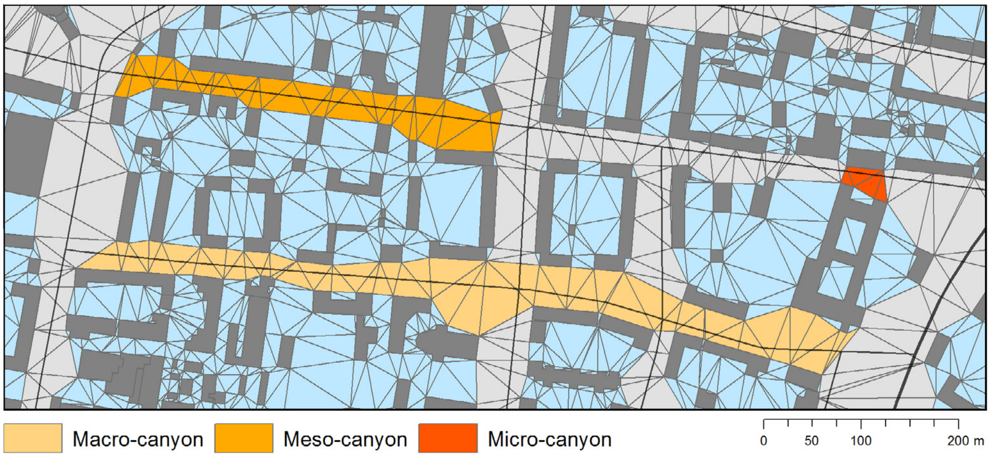

Fig. 3. Hierarchy of directed canyons.

Extraction of canyon objects hierarchy introduced in the previous Theory section is illustrated in (Fig. 3). At *micro* level every canyon is defined by the union of the triangles between each pair of the buildings. If we want to extract the *directed* canyon formed by current building, an algorithm should look for a building pair across the street network edge.

Spatial join operation should be applied to extract meso- and macro-canyons. First, every triangle is attributed with the identifier of network edge or stroke it belongs to (here we consider that every street is represented by one edge). Generally each triangle receives several identifiers, which would be true for triangles covering crossroads point. Crossroads triangles are excluded from meso-canyons. First and last crossroads triangles are also excluded from the macro-canyon. Finally the triangles with the common street identifiers are merged in order to get the area occupied by each particular canyon. Looking at Fig. 3 one would infer that meso-canyon is limited by one street between crossroads, and macro canyon is formed by the chain of meso-canyons connected at crossroads.

The length L of directed canyon is then simply derived as the total length of the street network elements it covers. For micro level the corresponding part of the network edge should be used instead.

In the next paragraph we will show how canyon geometry can be assessed locally and then averaged by each canyon or over some area, i.e. model cell. While the mean value is representative for height/width ratio, the direction is better characterized by modal values. For urban street network bi-modal distribution of directions is typical.

3.3. Estimation of height/width ratio

Given TIN-based canyons, **canyon width** calculation can be localized for each triangle. The width can be approximated by triangle altitude that is perpendicular to the triangle side not intersected by street axial line (see Fig. 4). Triangle altitude can is calculated as:

$$w_i = \frac{2S_i}{a_i}, \tag{1}$$

where S_i is the area of ith triangle and a_i is the length of the triangle side perpendicular to the height.

If the triangle is located at crossroads or belongs to the undirected canyon its width can be estimated by putting a triangle altitude perpendicular to its shortest side:

$$w_i^* = \frac{2S_i}{\min(a_i, b_i, c_i)}, \tag{2}$$

where S_i – area of ith triangle and $a_i,\ b_i,\ c_i$ – its sides.

After that the **mean weighted canyon width** inside the jth canyon or jth modeling cell can be found as:

$$W_j = \frac{\sum_{i=1}^{n} S_i w_i}{\sum_{i=1}^{n} S_i}, \tag{3}$$

where n is the number of triangles inside the canyon or cell. When analysis is performed for directed and undirected canyons separately, triangles can be divided into two corresponding parts and then processed in the same way.

The **mean weighted canyon height** can be found by the following weighted average:

$$H_j = \frac{\sum_{i=1}^{n} P_i h_i}{\sum_{i=1}^{n} P_i}, \tag{4}$$

where n is the number of buildings inside the jth cell or adjacent to jth canyon and P_i is the perimeter of ith building. Similarly to the width estimation, when canyons are investigated separately, only the sides of the buildings that are adjacent to canyons should be used in perimeter calculation. The area of the building can also be used as the weight, however, for directed canyons the perimeter segment facing to the street is much more representative due to the fact that a large part of the building is hidden inside a city block.

Finally, the mean canyon proportions (averaged, directed or undirected) inside jth canyon or jth cell can be described by **height/width ratio** R_j:

$$R_j = \frac{H_j}{W_j}. \tag{5}$$

The next paragraph demonstrates how directed canyons can be characterized by their prevailing directions in some area.

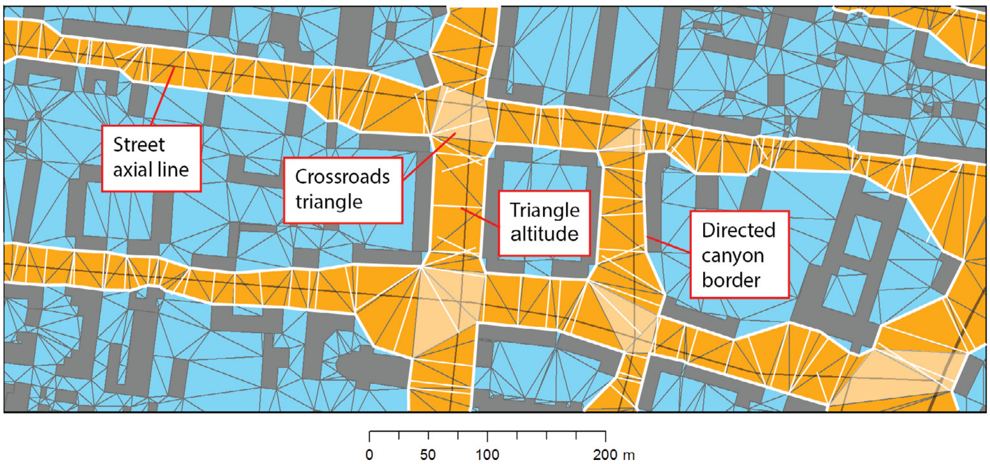

Fig. 4. Canyon width estimation using triangle altitudes.

3.4. Estimation of modal directions

The most typical city built-up induces two main directed canyon orientations in some local neighborhood, which are usually perpendicular to each other. These orientations correspond to the first and second mode in the distribution of street directions inside the model cell. The ratio of their frequencies reflects predominance of one direction over another. This idea is illustrated in Fig. 5.

The following histogram-based algorithm has been applied for estimation of modal directions:

1. Dice street network into the fragments using the model grid to limit the analysis by the boundaries of every cell.
2. Split the street lines at their vertices into two-point segments.
3. Calculate the direction of each segment using coordinates of its endpoints. Direction intervals $[0, \pi)$ and $[\pi, 2\pi)$ are equivalent and all directions should be mapped to $[0, \pi)$.
4. Establish the number of histogram bins N and corresponding bin width $h = \pi/N$.
5. For each ith bin calculate the sum of length of the segments, which azimuthal directions fall into corresponding azimuth interval $[\theta_i, \theta_{i+1})$:

$$S_i = \sum_{j=1}^{n} l_j : \theta_j \in [\theta_i, \theta_{i+1}), \cup[\theta_i, \theta_{i+1}) = [0, \pi). \quad (6)$$

6. Find bin number $i = m$, in which S_i has a maximum value; set the number of the first mode class $m_1 = m$.
7. Find bin number $i = r > m1$, that generates highest peak S_i right to the m_1.
8. Find bin number $i = l > m1$, that generates highest peak S_i left to the m_1.
9. Set the second mode bin number $m_2 = r$ if $S_r > S_l$ and $m_2 = l$ otherwise.
10. Calculate the modal values for the primary and secondary directions as:

$$\Theta_{m_1} = \theta_{m_1} + h\frac{S_{m_1} - S_{m_1-1}}{2S_{m_1} - S_{m_1-1} - S_{m_1+1}}; \quad \Theta_{m_2} = \theta_{m_2} + h\frac{S_{m_2} - S_{m_2-1}}{2S_{m_2} - S_{m_2-1} - S_{m_2+1}}. \quad (7)$$

11. Calculate the ratio of modal values as $f_\Theta = \frac{S_{m_1}}{S_{m_2}}$.

If the histogram has only one peak, the second mode is not calculated. The situation when the cell does not contain any road segments is also possible. In this case the histogram will be empty and no modal directions would be determined.

As calculated modes depend on the width of histogram bin, it is worth to perform steps (4)–(10) using different values of h. In our experimental work (see next paragraph) we used three values, in which semicircle was subdivided into $N = 6, 7, 8$ sectors that correspond to bin widths equal to $h = 30, 25.7, 22.5$ degrees respectively. An averaged value of calculated modes can then be used for modeling.

A pattern of modal directions calculated in that way is presented in Fig. 6. For this illustration we used two-color coding with large orange arrow indicating main direction and smaller blue arrow corresponding to the secondary modal direction.

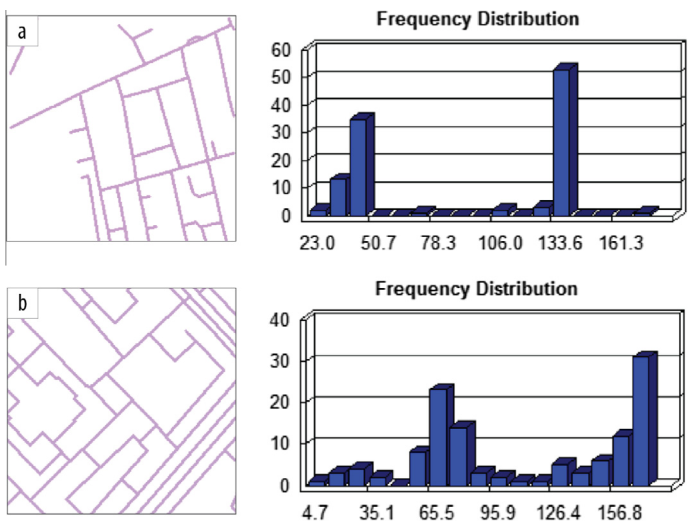

Fig. 5. Modal directions of the canyons (a and b – two examples).

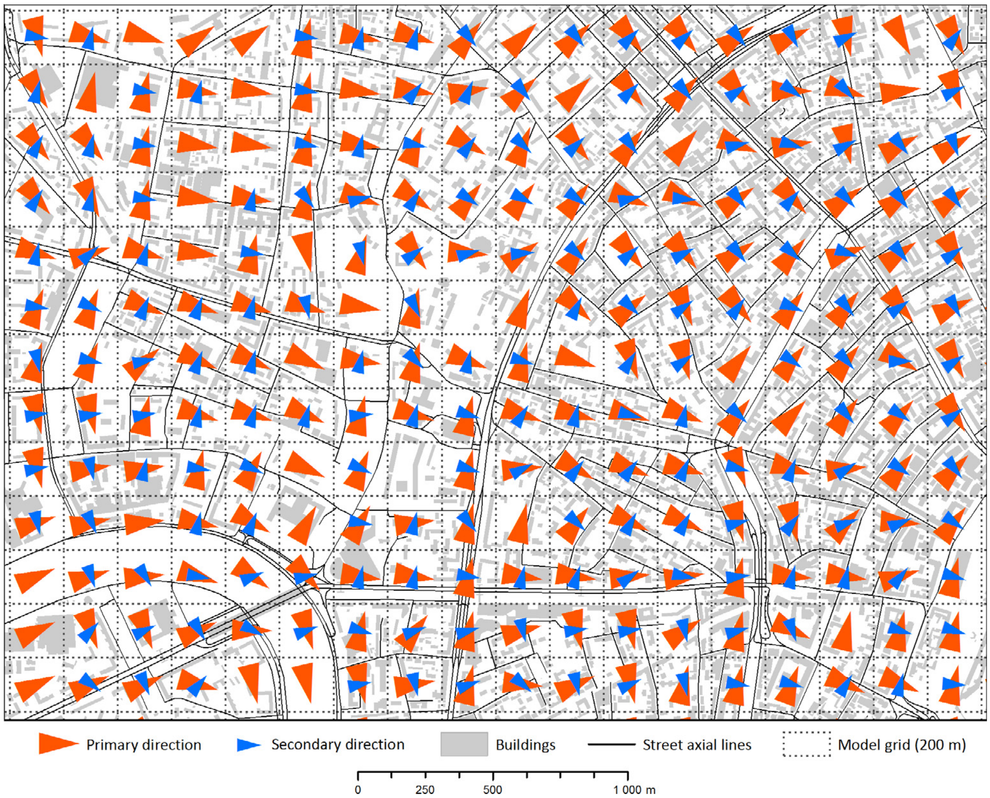

Fig. 6. Modal directions of directed canyons.

As can be noted, in some cases there is only one mode, and several cells contain no street network and therefore have no modal canyon direction.

3.5. Database of urban canyon and land cover characteristics

Described characteristics of canyons were calculated and included into the database that describes urban environment in Moscow, Russia for meteorological modeling purposes. The most convenient way to describe the urban environment is to calculate its various average, modal and ratio parameters using the same grid as used in particular meteorological model. The list of characteristics depends on the requirements of the input data for model. In our case data was prepared for URB_MOS model (Konstantinov et al., 2014).

Derived table structure is presented in Table A.1 (Appendix A). Cell ID is stored in the field Number 1. The characteristics 2–13 describe land cover, 14–44 are intended to reflect urban canyon geometry. Table A.2 stores 6 supplementary characteristics. The database contains some geometric characteristics that were not discussed in our paper, such as SVF and frontal area index. They were derived using well-known algorithms (Gál et al., 2008; Chen and Ng, 2011).

Simple land cover classification used in the database includes the categories that can be easily extracted from the vector cartographic data: (a) buildings, (b) roads, (c) green spaces, (d) water, (e) industrial, (f) other. This classification scheme differs from traditional schemes like those used in (Grimmond and Souch, 1994; Lemonsu et al., 2008) in a way that it does not include pervious/impervious surfaces and tall vegetation as types of land cover. It is more topographically than physically oriented. This is because cartographic data does not always include information about building and road materials, ground type in open spaces, and also is not sufficiently detailed in description of green spaces that could be mixture of forest, bushes and open grass. Better differentiation can be achieved by using remote sensing imagery. However, the scope of the current research is strictly limited to capabilities of cartographic data.

We derived three tables for $R = 1000$, 500 and 200 m to allow sequential downscaling of the modeling process. The database is maintained in ArcGIS for Desktop 10.1 software. The structure of the database table is similar for every resolution.

3.6. Materials

Data sources supporting this work include GIS Region Prof topographic Moscow database by Geocentre Consulting Ltd. SRTM90 and ASTER GDEM digital elevation models were also used at modeling stage. Land cover classification was performed in Esri ArcGIS for Desktop 10.1 software. Customised software for canyon extraction and description has been developed using Java programming language. Statistical assessment of geometric parameters was performed in R software. Temperature and wind was modeled using URB_MOS model (Konstantinov et al., 2014).

Note on data requirements and other data sources. Our methodology relies on the availability of vector urban database that includes individual building footprints. Building attributes must include either height or number of levels to assess H/W ratio, SVF, frontal area index and other factors that rely on height information. Extraction of canyons and estimation of their directions does not require height or level information. Any multipart polygons existing in the database should be broken up into singlepart features.

Samsonov and Konstantinov (2014) assessed OpenStreetMap database for possibility of extraction of urban environment parameters required by climate modeling. They revealed that OSM map features classification can be easily mapped into simpler that then can be used in parameterization of urban climate models. Using population/number of buildings ratio (B-ratio) and number of buildings/number of buildings with level data ratio (L-ratio) they showed that OSM building coverage is not satisfactory in all largest world urban areas.

In many cases information about urban environment is extracted from satellite imagery. Building mask is usually derived as a binary raster. It should be vectorized to be used as data source in our methodology. The notes about height information and multipart features remain the same as for vector databases.

4. Results and discussion

4.1. Statistical assessment of canyon geometry parameters

The proposed TIN-based methodology allows to obtain mean canyon width, height and h/w ratio for the individual canyons and to average them by grid cells. Thus we can calculate the "true" average canyon parameters and then look at their behavior when they are averaged over the grid tessellation.

For analysis purposes we excluded the triangles that have zero building height (these can be triangles touching unattributed objects). Then the whole selection of triangles was used for estimation of the mean values. The mean width of directed and undirected canyons over Moscow City equals to 45 and 38 m respectively. At the same time mean height appeared to be 19.5 and 13 m respectively. The smaller height of the latter is mostly influenced by the presence of the small infrastructural buildings like kindergartens, transformer vaults and local stores. Finally, average h/w ratios for directed and undirected canyons in Moscow city are 0.43 and 0.34 respectively.

The spatial distribution of directed canyon h/w ratio for 500 m resolution is presented in Fig. 7. Statistical distribution of the values for 200, 500 and 1000 m resolutions is shown in Fig. 8. In these figures we cut long tails containing outliers for better representation, and set maximum value to 1.5. It can be seen that smaller grid sizes produce values that are statistically closer to the reference values obtained by averaging TIN triangles. H/w ratio histogram has uni-modal distribution with single mode close to the mean value. Also it is clear that *h/w ratio is sensitive to grid resolution*. As grid resolution increases, the kurtosis becomes more significant and the frequencies of low values decrease. If h/w ratio is included as one of the model parameters, the distribution of the values is more reliable when the data is averaged using fine grid resolution.

4.2. Modeling the spatial pattern of wind acceleration probability

One of the applications of directed canyon concept is that it can be used in simple and quick categorical estimations of wind acceleration probability. Extreme wind blasts often occur in directed canyons when direction of the wind corresponds to the direction of the canyon. For modeling of this phenomenon the information about modal canyon direction is necessary.

Using the modal directions from our database (parameters 36–44) we were able to reconstruct spatial patterns of wind acceleration probability for four dominating directions: south (S), south-west (SW), west-south-west (WSW) and west (W). We used numerical score with 5 gradations. Let Θ_1 be the first modal canyon direction within the cell, D is given wind direction and $\alpha = |\Theta_1 - D|$ is the angle at which the wind approaches the canyon. Then the score S is calculated using the following rules:

$$\begin{cases} S = 1, \alpha \in [0, 5]; \\ S = 2, \alpha \in (5, 27.5]; \\ S = 3, \alpha \in (27.5, 50]; \\ S = 4, \alpha \in (50, 72.5]; \\ S = 5, \alpha \in (72.5, 90]. \end{cases} \tag{8}$$

Resulting picture for 200 m resolution grid is shown in Fig. 9. This score is calculated for quick revealing and mapping of the areas with high potential of wind acceleration. The main corridors of wind acceleration can be extracted from this raster. After the areas with high probability of wind acceleration are revealed, more realistic wind acceleration estimation could be performed through analytic solving of wind velocity equation in surface boundary layer.

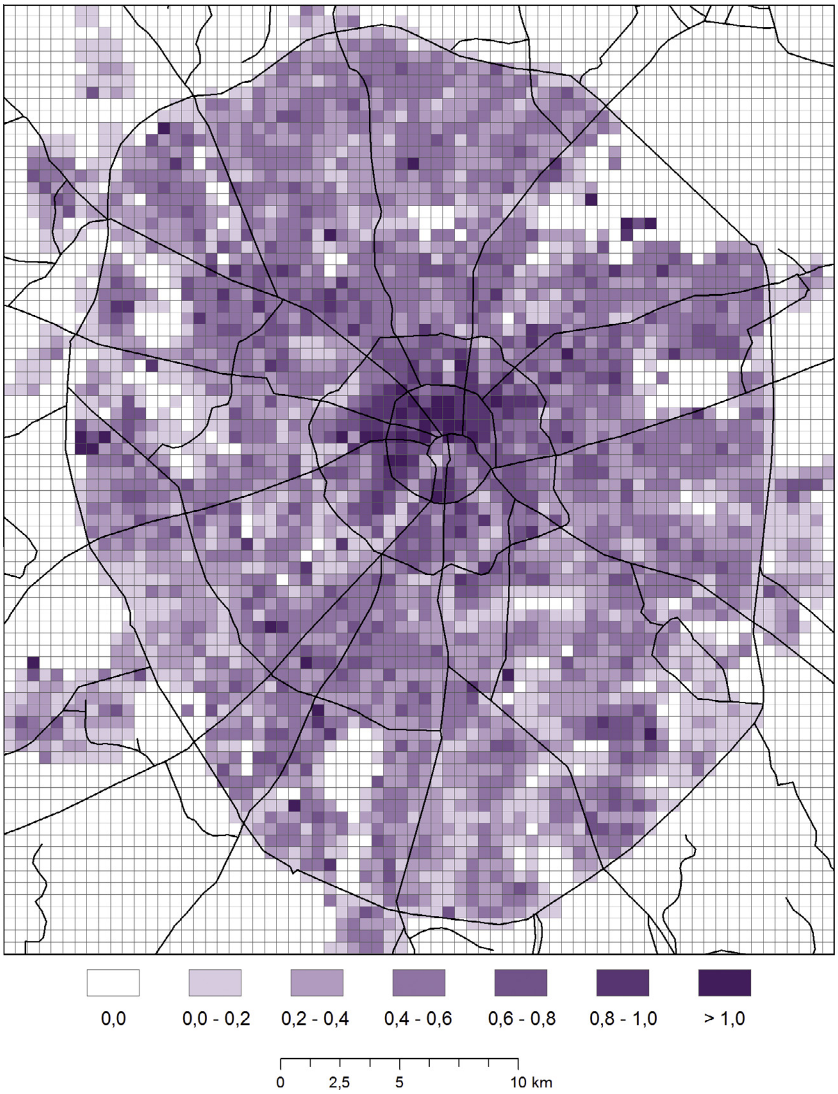

Fig. 7. Directed canyon h/w ratio. Cell size = 500 m.

4.3. Temperature and wind modeling using URB_MOS model

To apply the derived urban canyon and land cover parameters in meteorological modeling we used experimental URB_MOS model briefly described in (Konstantinov et al., 2014). This urban canopy model is based on urban canyon concept and was elaborated in 2013 at Department of Meteorology and Climatology of Moscow State University. Main parameterisations of turbulence in URB_MOS were verified by UrbEx-2011. This experiment involved a wide spectrum of observations, including the surfaces and air temperature measurement at different parts of the canyon and the sensible heat flux measurement by the acoustic anemometer was lead in April 2011.

URB_MOS is based on the TEB-Scheme by Masson (2000) and some parameterisations from Martilli scheme (Martilli et al., 2002). The canyon is represented by four surfaces (roof, road and two walls), which are divided into several segments (with the exception of roof). For each of the segments heat and radiation balance are calculated separately, with processes of shadowing, re-reflection and re-emission taking into account and sky-view factor computed for the central points of each segment. Generally speaking, URB_MOS is the post-processing module for regional models (COSMO_RU in our case). Parameters obtained from COSMO_RU in our experimental set-up are listed in Fig. 10a. They are coupled with information from our database and several additional parameters (also listed in Fig. 10a). All input fields for URB_MOS model that are used as initial and boundary conditions are summarized in Table 1.

Derived modal canyon directions in URB_MOS are used in diffusion and advection module for different transparency options in different directions in urban canopy layer (Fig. 10b). This model does not (currently) use the information on

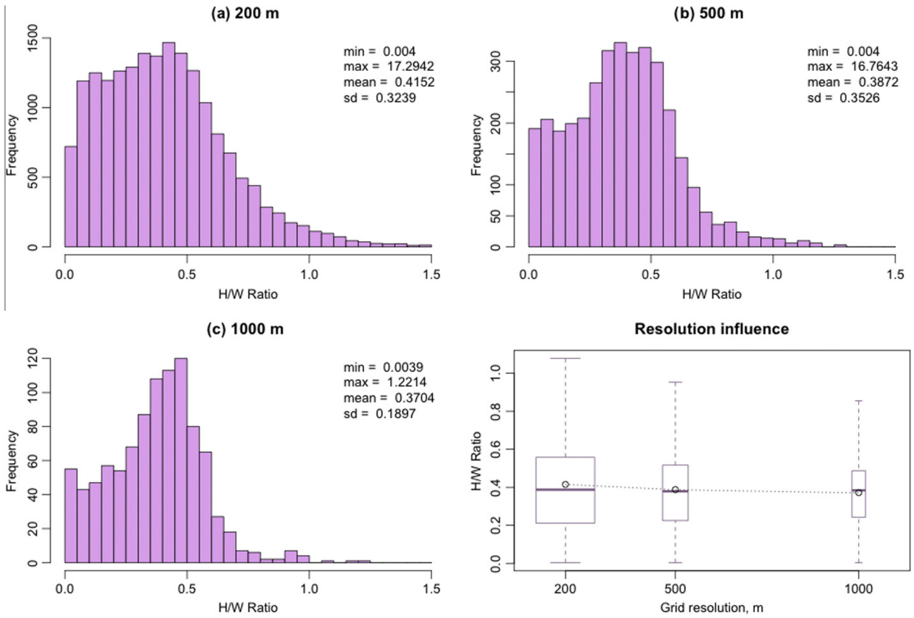

Fig. 8. Histograms of directed canyon h/w ratio for different grid resolutions.

the secondary street direction. The main feature of the model is multicell grid in which land cover and canyon information is represented (Fig. 10c). Term «multicell» means that in each cell the ratio between areas of every land cover type is taken into account instead of one dedicated land cover value. This ratio is used for modeling energy fluxes inside the cell.

Land cover classes from our database are interpreted by URB_MOS model using the following rules:

- Roads and buildings are considered to be impervious surfaces.
- Industrial territories are divided in proportion of 1:1 between pervious and impervious surfaces, as they may contain both mentioned types.
- Green spaces are considered to be tall vegetation spaces.
- Other territories are considered to be pervious surfaces, such as open ground and grass.

Preliminary experiments showed how URB_MOS reproduces local wind and temperature distributions. We compared the results of the modeling with the standard version (without urban block) of regional model COSMO_RU that is used in Russian Hydrometeorological Centre (Hydrometcentre) and validated them via observations from Balchug weather station in the center of Moscow city. Balchug (Fig. 11) is the standard WMO station located at 55.745°N, 37.63°E and 124 m altitude above the sea level (in Baltic height system BHS-1977). Balchug data archives are available from September 20, 1946. Station metadata are presented in Table 2 and the meteorological data available for simulated periods are summarized in Tables 3 and 4.

The comparison showed that results refined in URB_MOS by inclusion of detailed canyon and land cover parameters, are closer to observations than initial COSMO_RU's forecast (Fig. 12). Mean root square error of temperature forecast decreased from 4.0 to 2.1 degrees.

Figs. 13 and 14 illustrate how URB_MOS model reproduces characteristic features of urban heat island. We chose 26–28 April 2011 dates due to availability of a good data from UrbEx-2011 experiment (Konstantinov et al., 2014) and August 2011 due to expecting thermal differences between different Moscow parts. Among the main found features there are:

- more intensive heat island during the night period;
- temperature anomalies on water bodies (see Moscow river that flows from NW to SE);
- lower temperatures inside green areas;
- heat tail from leeward side of the city;

Similar cartographic estimation concerning wind reproduction by URB_MOS is shown in Fig. 15. It reflects how the built-up influences wind in various directions of the canyons. In case of west wind the velocity is more intensive in latitudinal canyons, and for south wind the velocity is higher in meridional canyons.

It should be mentioned that the calculations were based on several assumptions. The first concerns the ratio of the pervious and impervious surfaces for industrial areas, which was set to 1/1. The second is related to the parameterisation of territories with tall vegetation which is rather conditional and can be significantly improved using remote sensing data.

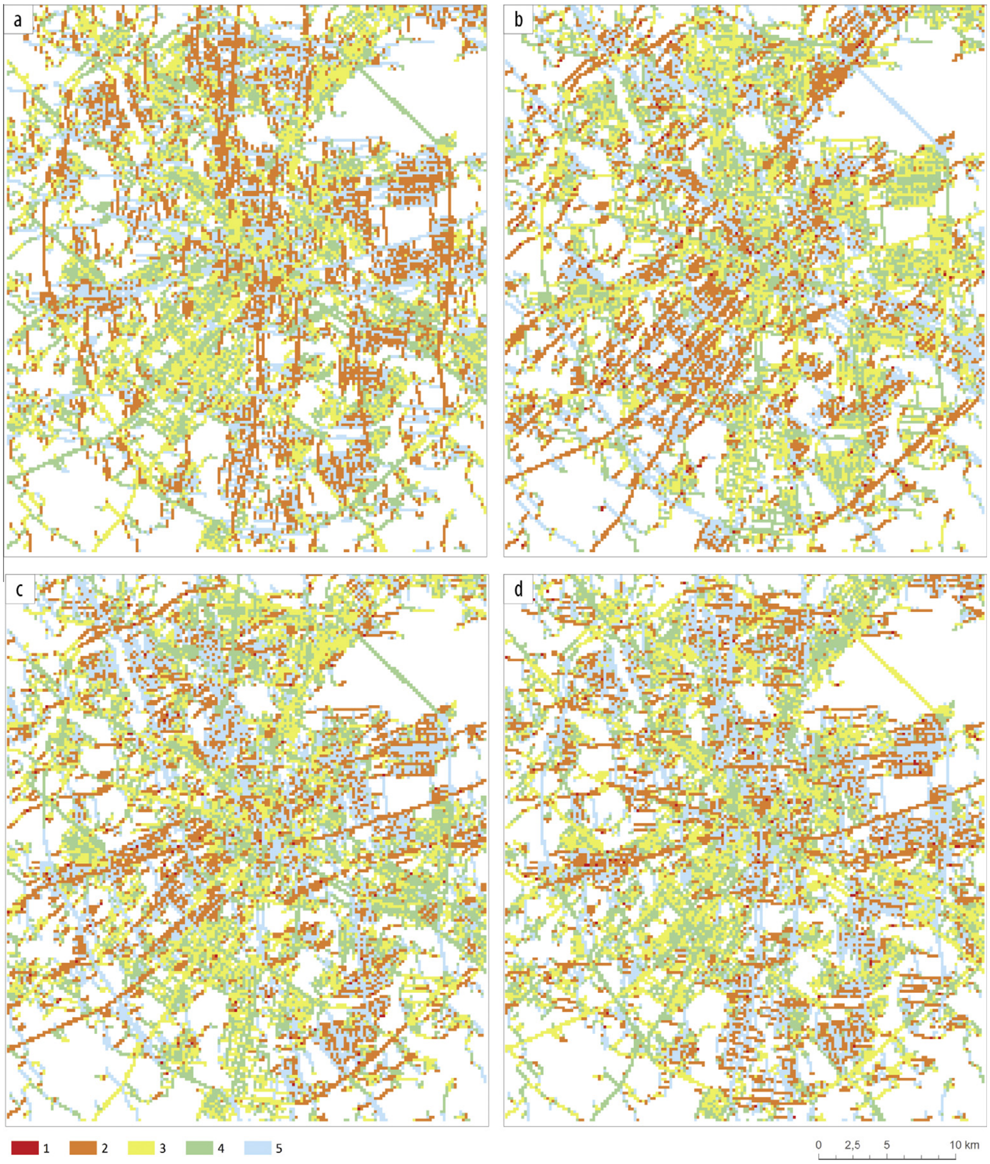

Fig. 9. Probability classes of wind acceleration. Azimuth: (a) S; (b) SW; (c) WSW; (d) W.

Despite the many shortcomings of URB_MOS model including coarse description of water and vegetation cells and simple computational schemes, its results appeared to be promising. This is tied to more accurate accounting of physical properties of underlying surface (albedo, heat capacity) and progressive method of thermal advection and diffusion modeling, that became possible with detailed description of urban canyon geometry and land cover acquired from our database.

5. Conclusion

This paper introduces object-oriented canyon analysis approach into urban climate studies. Using spatial analysis in GIS it is possible to extract canyons from vector databases and then analyze their local and averaged characteristics. Presented approach fills the methodological gap between local point-wise calculation of canyon characteristics and their averaged estimations over the area. Established hierarchy of canyon types allows sequential upscaling of the level of investigation from limited spaces between neighboring buildings (urban canyons as they are usually defined) to lengthy avenues. This result can be seen as a theoretical and methodological contribution both to urban climate and urban morphology research domains.

The main results presented in this paper can be summarized in following points:

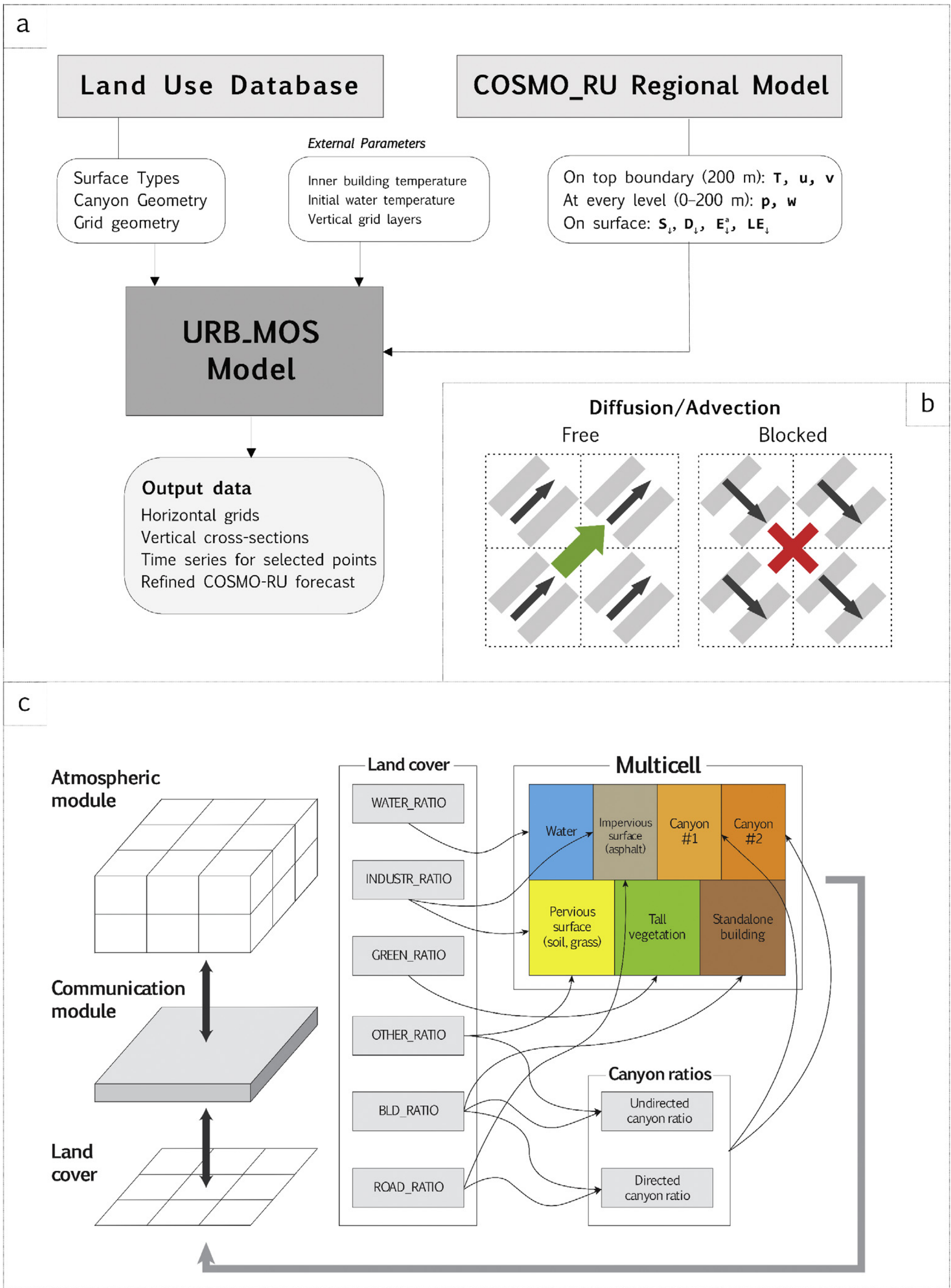

Fig. 10. URB_MOS meteorological model. (a) Input and output data for URB_MOS model; (b) using canyon directions in modeling diffusion and advection; (c) URB_ structure.

1. Theoretical concept of object-oriented urban canyon extraction and analysis that allows differentiation between directed and undirected canyons, introduction of canyon hierarchy and canyon-based analysis.
2. TIN-based methods of canyons extraction and estimation of their geometric parameters. Basic parameters include height, width and height/width ratio.
3. Network-based method of extraction of individual canyons and estimation of their length based on network edges (meso-level) and network strokes (macro-level).
4. Statistical approach to detection of primary and secondary canyon directions and their ratio.
5. A simple method of categorical estimation of wind acceleration probability along directed canyons from modal directions.

Table 1
Input URB_MOS fields (for initial and boundary conditions).

	Variable	Field
1	T	Air temperature
2	T_v	Virtual air temperature
3	θ	Potential air temperature
4	q	Specific air humidity
5	u	Wind u-component
6	v	Wind v-component
7	w	Vertical wind component
8	p	Air pressure
9	ρ	Air density
10	$S_\downarrow$	Downward direct solar radiation
11	$D_\downarrow$	Downward diffuse solar radiation
12	$S^a_\downarrow$	Downward longwave radiation
13	$LE_\uparrow$	Latent heat flux

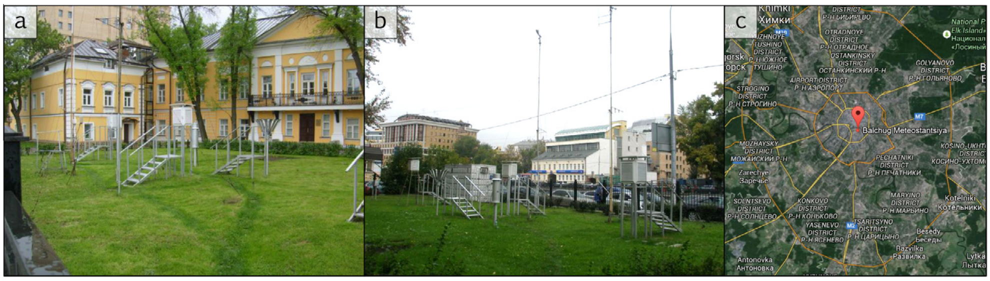

Fig. 11. Balchug weather station. (a) View from the street; (b) view towards the street; (c) location in Moscow city.

Table 2
Balchug weather station metadata.

	Parameter	Measurement method	Accuracy
1	Air temperature	Mercury thermometer 2 m AGL, every 3 h (WMO)	±0.1 °C
2	Relative humidity	Wet-bulb and dry-bulb mercury thermometers 2 m AGL, every 3 h (WMO)	±1%
3	Wind speed (10 m)	Anemorumbometer M-63M-1 10 m AGL, every 3 h (WMO)	±0.1 m/s
4	Ground level pressure	Mercury barometer 2 m AGL, every 3 h (WMO)	±0.1 mmHg
5	Precipitation	Tretyakov precipitation gage 2 m AGL, 2 times per day (WMO)	±0.2 mm

Table 3
Meteorological conditions during April 26–28 2011 on Balchug station.

	Parameter	Average	Range
1	Air temperature, °C	15.7	9.5–21.6
2	Relative humidity, %	36	23–60
3	Wind speed (10 m), m/s	1	0–2
4	Sea level pressure, mmHg	766.8	761.2–770.5
5	Precipitation Σ, mm	0	0

Table 4
Meteorological conditions during April and August 2011 simulation dates on Balchug station.

	Parameter	April 17, 6 a.m.	August 3, 3 p.m.	August 4, 6 a.m.
1	Air temperature, °C	20.0	13.8	4.4
2	Relative humidity, %	37	69	56
3	Wind speed (10 m), m/s	2	1	1
4	Sea level pressure, mmHg	764.4	764.1	759.1
5	Precipitation Σ, mm	–	–	–

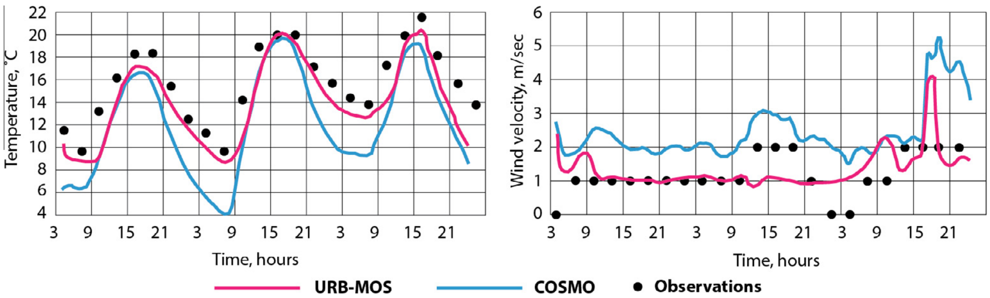

Fig. 12. Results of temperature modeling for Balchug weather station (26–28 April 2011).

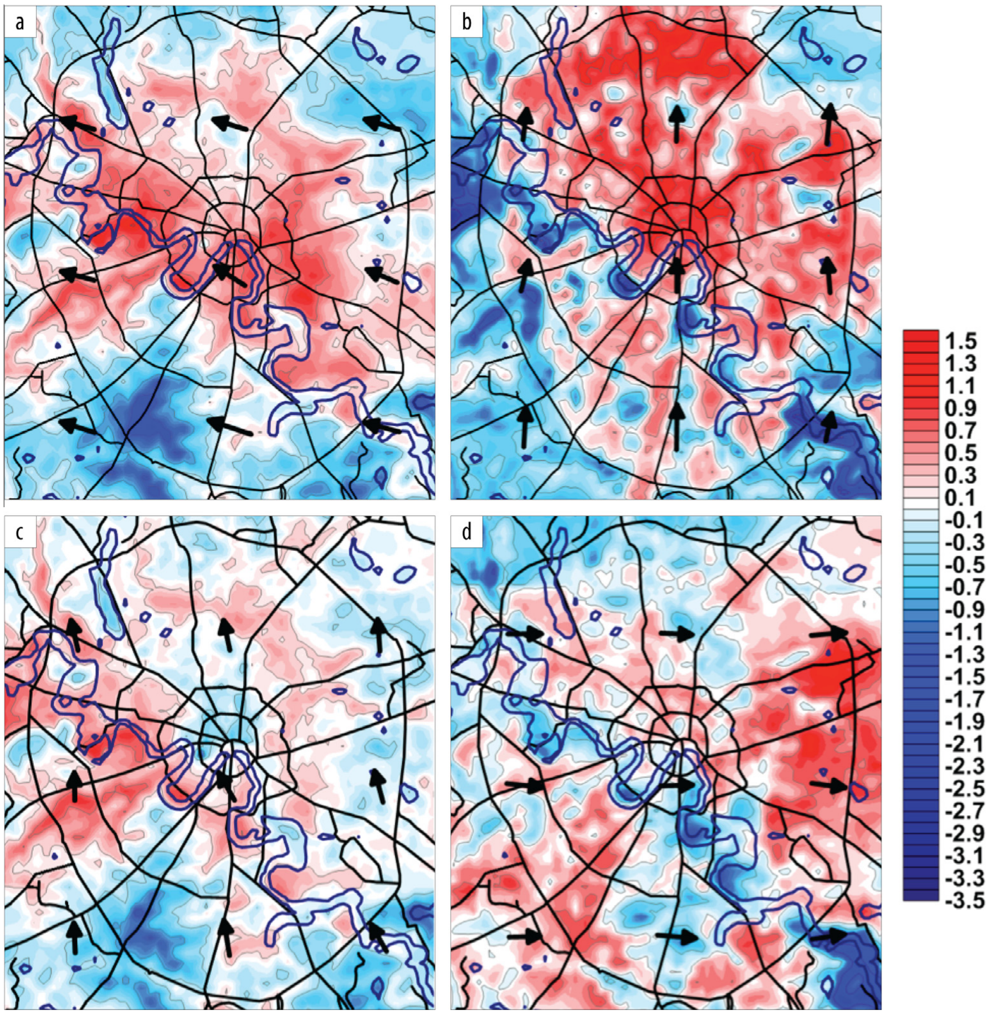

Fig. 13. Spring 2011 temperature anomalies from the mean field value (Celsius degrees) by URB_MOS model. (a) 4 p.m. 26 April (day); (b) 6 a.m. 27 April (night); (c) 4 p.m. 27 April (day); (d) 6 a.m. 28 April (night).

6. Temperature and wind modeling results obtained by using URB_MOS model using the derived canyon characteristics that showed the improvement of temperature and wind forecast comparing to standard version of COSMO_RU model.

Extraction and analysis of directed canyons highly depends on the presence of linear street network. Thus, in the absence of this GIS layer, it should be reconstructed from other data sources. Another aspect that has not been investigated in the paper is the stability of canyon direction. For now every canyon that is intersected by street network is considered to be

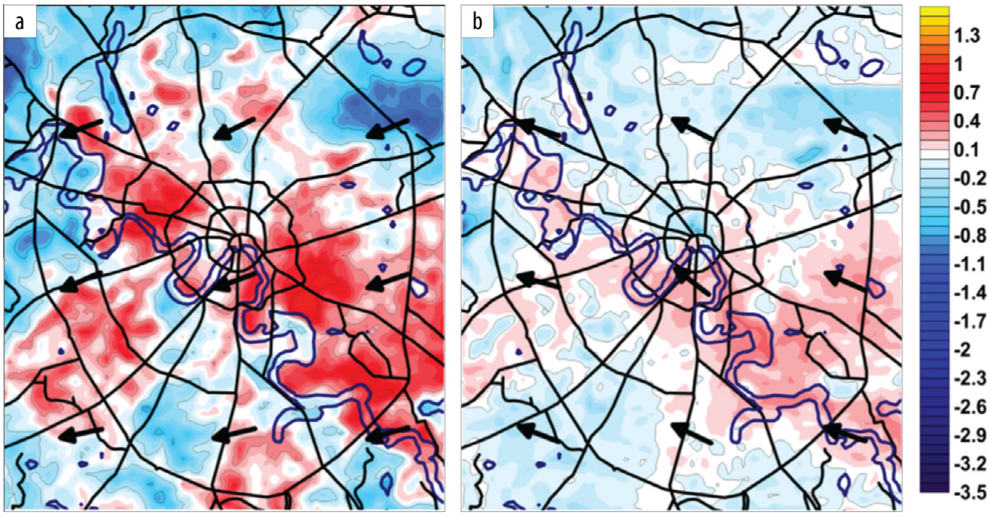

Fig. 14. Summer 2011 temperature anomalies from the mean field value (Celsius degrees) by URB_MOS model. (a) 4 p.m. 3 August (day); (b) 6 a.m. 4 August (night).

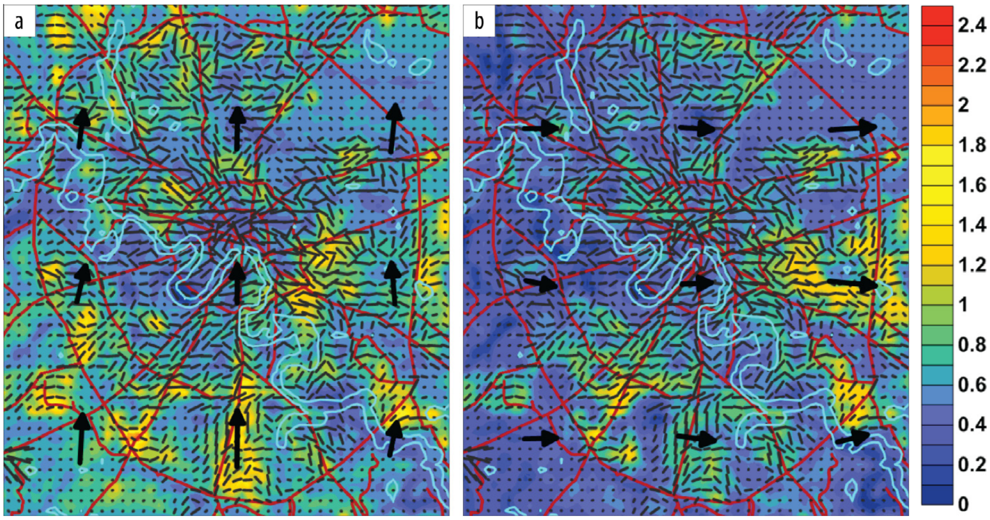

Fig. 15. Wind speeds (m/s) by URB_MOS model. (a) South wind, 6 a.m. 17 April 2011; (b) west wind, 6 a.m. 28 April 2011.

directed. However the sinuosity of the street may produce completely different physical conditions. The future studies should give us an answer to the question, where the limits of directed canyons are and how they can be classified further in terms of the street longitudinal shape. For now all computations are performed in separate scripts and programs. We plan to develop comprehensive automation of described methods of urban canyon description in a specialized software. Another important issue that should be investigated further is the performance of the proposed algorithms (especially TIN-based that could be computationally intensive over large territories).

The most perspective extension of proposed methodology seems to be canyon-based analysis which is truly object-oriented. Various geometric properties of micro-, meso- and macro-scale canyons should be investigated and their applicability in urban climate modeling should be assessed. Object-oriented canyon analysis can also be applied in architectural studies, urban morphology, planning and various physical and social aspects that are being human concerned within the urban space.

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Table A.1
Database table scheme.

N	Field name	Type	Domain	Units	Description
1	OBJECTID	Long integer	$[0, +\infty)$	–	Identifier
2	BLDAREA	Double	$(0, +\infty)$	m^2	Area of the buildings
3	BLDRATIO	Double	$[0, 1]$	–	Buildings ratio
4	GREENAREA	Double	$[0, +\infty)$	m^2	Tall vegetation area
5	GREENRATIO	Double	$[0, 1]$	–	Tall vegetation ratio
6	INDUSTRAREA	Double	$[0, +\infty)$	m^2	Industrial areas area
7	INDUSTRRATIO	Double	$[0, 1]$	–	Industrial areas ratio
8	ROADAREA	Double	$[0, +\infty)$	m^2	Roads area
9	ROADRATIO	Double	$[0, 1]$	–	Roads ratio
10	WATERAREA	Double	$[0, +\infty)$	m^2	Hydro area
11	WATERRATIO	Double	$[0, 1]$	–	Hydro ratio
12	OTHERAREA	Double	$[0, +\infty)$	m^2	Other area
13	OTHERRATIO	Double	$[0, 1]$	–	Other ratio
14	SVFMEAN	Double	$[0, 1]$	–	Mean SVF on surface
15	SVFNOBLDMEAN	Double	$[0, 1]$	–	Mean SVF with building roofs excluded
16	BLDMEANHEIGHT	Double	$[0, +\infty)$	m	Weighted mean building height
17	MDCWIDTH	Double	$[0, +\infty)$	m	Mean directed canyon width
18	MDCAREA	Double	$[0, +\infty)$	m^2	Mean directed canyon area
19	MDCRATIO	Double	$[0, 1]$	–	Directed canyon ratio
20	MDCHWRATIO	Double	$[0, +\infty)$	–	Mean directed canyon proportions (Height/Width ratio)
21	MUCWIDTH	Double	$[0, +\infty)$	m	Mean undirected canyon width
22	MUCAREA	Double	$[0, +\infty)$	m^2	Mean undirected canyon area
23	MUCRATIO	Double	$[0, 1]$	–	Mean undirected canyon ratio
24	MDCHWRATIO	Double	$[0, +\infty)$	–	Mean undirected canyon proportions (Height/Width ratio)
25	BLDCRATIO	Double	$[0, 1]$	–	The ratio of directed canyon buildings
26	BLDUCRATIO	Double	$[0, 1]$	–	The ratio of the directed and undirected canyon buildings
27	BLUCRATIO	Double	$[0, 1]$	–	The ratio of the undirected canyon buildings
28	FRONTINDEXN	Double	$[0, 1]$	–	Frontal index for 0° azimuth (N)
29	FRONTINDEXNNE	Double	$[0, 1]$	–	Frontal index for 22.5° azimuth (NNE)
30	FRONTINDEXNE	Double	$[0, 1]$	–	Frontal index for 45° azimuth (NE)
31	FRONTINDEXENE	Double	$[0, 1]$	–	Frontal index for 67.5° azimuth (ENE)
32	FRONTINDEXE	Double	$[0, 1]$	–	Frontal index for 90° azimuth (E)
33	FRONTINDEXESE	Double	$[0, 1]$	–	Frontal index for 112.5° azimuth (ESE)
34	FRONTINDEXSE	Double	$[0, 1]$	–	Frontal index for 135° azimuth (SSE)
35	FRONTINDEXSSE	Double	$[0, 1]$	–	Frontal index for 167.5° azimuth
36	DIR16	Double	$[0, 180)$	°	Primary canyon direction by 6 sectors (30°)
37	DIR26	Double	$[0, 180)$	°	Secondary canyon direction by 6 sectors (30°)
38	DIRRATIO6	Double	$[1, +\infty)$	–	Frequency ratio (primary/secondary) by 6 sectors (30°)
39	DIR17	Double	$[0, 180)$	°	Primary canyon direction by 7 sectors (25.7°)
40	DIR27	Double	$[0, 180)$	°	Secondary canyon direction by 7 sectors (25.7°)
41	DIRRATIO7	Double	$[1, +\infty)$	–	Frequency ratio (primary/secondary) by 7 sectors (25.7°)
42	DIR18	Double	$[0, 180)$	°	Primary canyon direction by 8 sectors (22.5°)
43	DIR28	Double	$[0, 180)$	°	Secondary canyon direction by 8 sectors (22.5°)
44	DIRRATIO8	Double	$[1, +\infty)$	–	Frequency ratio (primary/secondary) by 8 sectors (22.5°)

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Appendix A

See Tables A.1 and A.2.

Table A.2
Database table scheme (additional parameters).

N	Field name	Type	Domain	Units	Description
1	X	Double	$(-\infty, +\infty)$	m	Cell center Easting in UTM map projection
2	Y	Double	$(-\infty, +\infty)$	m	Cell center Northing in UTM map projection
3	LAT	Double	$[-90, +90]$	°	Cell center geodetic latitude (WGS84)
4	LONG	Double	$[-90, +90]$	°	Cell center geodetic longitude (WGS84)
5	ZMEAN	Double	$(-\infty, +\infty)$	m	Mean cell hypsometric height
6	AREA	Double	$(0, +\infty)$	m^2	Cell area

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