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Detection of ventilation paths using high-resolution roughness parameter mapping in a large urban area

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Abstract

In this study, an urban roughness mapping method is presented on the example of a large study area in Szeged, Hungary, as an example. With this roughness mapping procedure, the potential ventilation paths of the city can be located. Our calculations of the roughness parameters are based on a 3D building database; however, this new approach using the lot area polygons provides more detailed results than other recent studies. The detected ventilation paths could play a significant role in the development of the urban heat island circulation and result in the reduction of air pollution in the central parts of the city. Based on our results, we can mark out the areas where the city government should keep the advantages of the ventilation paths considering the human comfort aspects of the urban climate, thus providing important input data for urban planning procedures.

Keywords: 3D building database; Frontal area; Roughness length; Displacement height; Porosity; Urban roughness mapping

1. Introduction

In urban areas, the surface geometry and characteristics have been changed compared to the original natural surfaces. In urban environments, the water and energy balances are modified which often results in higher urban temperature compared to the surroundings (urban heat island, UHI). The UHI has a marked diurnal variation: the largest urban–rural contrast appears at night, while during the daytime the temperature difference is moderate. The cities are about the roughest surfaces; the enhanced drag effect of the urban surface on the air flow is one of their most important features. Due to the larger roughness of the surface, the average wind speed is lower in the cities than in the surrounding rural areas [1]. The regional wind tends to hinder the formation of the UHI and modifies its spatial structure [2].

In direct analogy with the well-known land-sea breeze system, the city generates a local air flow, the so-called country breeze. Its driving force is based on the fact that a city is commonly warmer than the rural background. For the development of the country breeze, the regional winds need to be very weak, so anticyclonal weather conditions are ideal for this flow system. The horizontal temperature (and therefore pressure) gradient can be sufficient to induce low-level breezes across the urban–rural boundary, which converge in the center from all directions. There is uplift in the center of the city and also a counter-flow in the higher air layer (Fig. 1). The vertical thermal structure is as important as the urban–rural thermal differences, since the vertical instability also promotes this 3D circulation [1]. Unlike the land-sea breeze system, there is no diurnal reversal of flow because the city is usually warmer than the countryside. If the inflow is strong enough to penetrate the city by overcoming the frictional drag of the complex urban surface, the winds can be slightly stronger compared to the surrounding areas [1]. In short, this is the urban heat island (-induced) circulation (UHIC) [4].

During the day, the country breeze can be observed above the roof level (in the urban boundary layer), since the building roofs are the hottest parts of the cities due to the insolation. At that time, the instability of the air makes the vertical movement easier so the small horizontal thermal gradient (weak UHI) is sufficient to drive this

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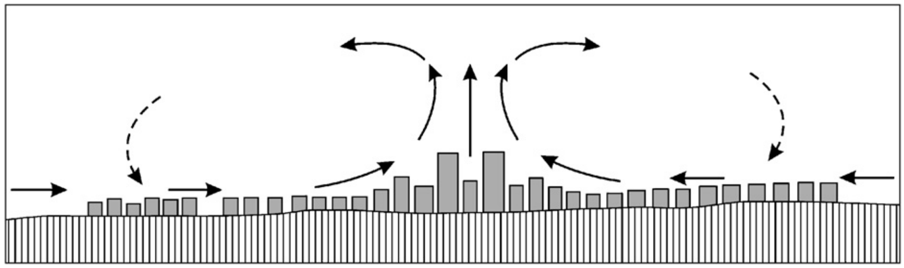

Fig. 1. Schematic shape of the urban heat island circulation (modified after [3]).

system. At night, the thermal difference is significant under the roof level among the buildings (in the urban canopy layer, UCL); therefore, the country breeze can be found here [5]. Owing to the high surface roughness of the city, the development of the nocturnal country breeze needs significant thermal difference between the urban and rural surface.

In reality, the UHIC is a relatively unstable and intermittent system with flow patterns rather than continuous mono-directional air movements [5]. The general effect of different factors such as meteorological conditions, existing buildings and other obstacles causes certain directions to be more prominent. As Haeger-Eugensson and Holmer [6] showed, at night the advective inflow by the UHIC plays a significant regulating role in the development and strength of the UHI, since the intrusion of the cool air into the city decreases the urban–rural temperature contrast, thus weakening its driving forces itself.

This meso-scale circulation could offer a potential for the improvement of the urban air quality [5,7]. The depth of the inflow in the UHIC system depends on the roughness of the surface. If the city has parts where the roughness is lower than in the other areas and these are interconnected the country breeze can reach the inner parts of the city and it can reduce the accumulated pollution. These are the so-called ventilation paths.

For describing the geometry or texture of the surface and as a consequence its roughness, several parameters are known. The roughness parameters describe how effective a surface area is in transforming the energy of the average wind, flowing over it, into turbulent motion in the boundary layer above Davenport et al. [8]. The most commonly used parameters are the zero-plane displacement height (z_d) and the aerodynamical roughness length (z_0) [9,10]. The connection between the wind and the drag force of buildings can be characterized by z_0. It is a key parameter for studying the urban atmosphere, as it can be utilized for example in pollutant dispersion modeling and in large-scale flow models to provide a momentum boundary condition for determining the wind patterns [2,11]. Further known parameters, which are partly necessary for the calculation of z_d and z_0, are the plan area ratio (λ_P), building plan area density referring to the height z ($\alpha_P(z)$), frontal area ratio (λ_F), complete aspect ratio (λ_C), height-to-width ratio (λ_S), average height weighted with frontal area (z_H), depth of the roughness sublayer (z_r) (e.g. [12–15]), roughness volume density ($\rho r(z)$) [16] and the effective height (h_{eff}) [17]. Burian et al. [18] gave a comprehensive review of the most common morphological parameters and their calculation for a sample area around the downtown of Los Angeles, CA. In their work, a 3D urban dataset, land use/cover information, a Digital Elevation Model (DEM) and roads were integrated and analyzed using a geographic information system (GIS). Mean parameter values were calculated for the entire area and for each land use type, and, in addition, in some cases on spatial grids and as a function of height a.g.l. This work was extended for a larger area around Houston, TX [18].

Grimmond and Oke [13] mentioned a coefficient p that was allowed for the porosity of trees. Some sort of porosity for the UCL can also be introduced that can be a useful tool for roughness mapping.

If we evaluate the roughness parameters in a large urban area, we have the opportunity to find the potential ventilation paths essential for enhancing the efficiency of the country breeze. Matzarakis and Mayer [17] and Mayer et al. [19] summarize the supposed requirements of the ventilation paths with the following points: (a) aerodynamic surface roughness length lower than 0.5 m, (b) negligible zero-plane displacement, (c) sufficiently great length in one direction, at least 1000 m, (d) sufficiently great width, minimum width is double to four times the height of the lateral obstacles, but at least 50 m, (e) the edges of paths should be comparatively smooth, (f) the width of the obstacles in a path should not be greater than 10% of the width of the path, (g) the height of the obstacle in a path should not be greater then 10 m, (h) obstacles within a path should be oriented so that their greatest width is parallel to the axis of the path, (i) single obstacles within a path should have a ratio of height to horizontal distance between two successive obstacles of 0.1 for buildings and 0.2 for trees.

Based on these requirements, there is an opportunity to give some advice for the local government on how to promote the intrusion of the cool and clean air and to decrease air pollution level in urban environments. The most important points suggested by Barlag and Kuttler [5] are the following:

(i) almost straight free paths must be kept to the center of the city;