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Describing the urban form: morphometric indexes

Describiendo la forma urbana: índices morfométricos

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- Aerodynamic parameters can be related to the morphometry of urban shape.
- Morphometric indexes are an appropriate tool to relate urban morphometry and aerodynamic parameters.

Characterizing the urban form of cities from an aerodynamic point of view is essential to forecast pollutant dispersion, to implement and understand natural ventilation strategies or to enhance outdoor thermal comfort and pedestrian wind environment, to name a few. Nonetheless, accurate results make use, normally, of Computational Fluid Dynamic (CFD) simulations, wind tunnel experiments and/or field measurements. However, these methodologies are expensive, time consuming and sometimes impossible to carry out. Therefore, simplified ways of characterizing a city aerodynamically must be put forward to bridge this gap. Two of the most common aerodynamic parameters, namely z_0 (roughness length) and z_d (zero displacement length), can be related to the morphometry of the urban shape through simple morphometric indexes. This paper explores and analyses these indexes, and suggests an alternative and improved definition that might achieve more accurate results.

Morphometric indexes; Aerodynamic parameters; City; Urban form

- Los parámetros aerodinámicos pueden relacionarse con la morfometría de la forma urbana.
- Los índices morfométricos son una herramienta adecuada para relacionar la morfometría urbana con los parámetros aerodinámicos.

Caracterizar la forma urbana de las ciudades desde un punto de vista aerodinámico es esencial para poder prever la dispersión de contaminantes, para implementar y comprender las estrategias de ventilación natural o para mejorar el control térmico en exteriores o el ambiente de viento peatonal, por citar sólo algunos casos. Para cualquiera de estos análisis, si se desea disponer de valores de cierta precisión es habitual emplear simulaciones mediante dinámica de fluidos computacional (CFD), experimentos en túnel de viento y/o tomas de datos de campo. Estos métodos, sin embargo, implican una inversión económica y temporal que en ocasiones no es posible realizar. El empleo de métodos simplificados para caracterizar la ciudad desde un punto de vista aerodinámico puede ayudar a hacer más sencillos estos procesos. Dos de los parámetros aerodinámicos más habituales, z_0 (rugosidad superficial) y z_d (longitud desplazamiento cero) pueden ponerse en relación con la morfometría de la forma urbana a través de índices morfométricos simples. Esta comunicación explora y analiza estos índices, y sugiere una definición alternativa y mejorada que puede posibilitar resultados más ajustados.

Índices morfométricos; Parámetros aerodinámicos; Ciudad; Forma urbana

Abbreviations: Computational Fluid Dynamics (CFD), Urban Heat Island (UHI) Urban Canopy Layer (UCL), Urban Boundary layer (UBL), Monin-Obukhov Similarity (MOS), surface roughness length (z_0) and surface displacement length (z_d)

1. INTRODUCCIÓN

The need to quantify and understand momentum transfer close to and above roughness elements, such as buildings within a city, and the mixing and transport within these areas is important for a number of reasons. It can provide an enhanced understanding of the Urban Heat Island (UHI) effect, passive natural ventilation strategies for outdoor thermal comfort, dispersion of pollutants and pedestrian wind environment, to name a few.

In many cities, air quality has become an issue of increasing importance. Understanding how the buildings affect the airflow is very important to forecast pollutant dispersion.

The mixing and transport of pollutants in urban areas is governed by processes that occur at the street level, through the neighbourhood scale, up to the city scale and beyond [1]. The vertical exchanges between the Urban Canopy Layer (UCL) and the Urban Boundary layer (UBL) above the city play a crucial role, where advection from other parts of the city directly affects the UBL structure and pollutant levels [2].

A large number of investigations have been carried out to gain more understanding on the atmospheric circulation in an urban canopy by means of numerical simulations [3-7] wind-tunnel experiments [8-12] and field measurements [13].

2. THE MONIN-OBUKHOV SIMILARITY THEORY

The Monin-Obukhov Similarity (MOS) theory allows describing mean flow and temperature in the atmospheric surface layer as a function of a dimensionless height parameter. It is a special case of the similarity theory, an empirical method widely used in boundary layer meteorology.

The MOS theory generalizes the mixing length theory by using functions of dimensionless heights to characterize the vertical distributions of mean flow and temperature.

Even though the MOS theory is still questioned, it is however applicable to model the mean flow and turbulence properties above the urban canopy layer [1].

The two key scaling factors are the friction velocity , u_x, and the Obukhov length, L.

The latter accounts for the effects of atmospheric stability and buoyancy on turbulent flows. It characterizes the relative contributions of shear production and buoyant production to the turbulent kinetic energy and is defined as:

$$L = -\frac{u_*^3 / k}{g H_s / C_p \rho T} \tag{1}$$

where g is the acceleration due to gravity, C_p is the specific heat of air at constant pressure, ρ and T are the air density and temperature, respectively, and k is von Karman's constant taken to be 0.4. H_s is the sensible heat flux from the ground surface and thus this parameter is positive during day and negative at night.

The mean wind-speed profile follows the Monin-Obukhov similarity theory when two scaling lengths are included, z_0 (surface roughness length) and z_d (surface zero displacement height):

$$u(z) = \frac{u_*}{k}\left[ln\left(\frac{z - z_d}{z_0}\right) + \psi\left(\frac{z}{L}\right)\right] \tag{2}$$

where the universal dimensionless stability term, $\psi(z/L)$, equals to zero in neutral or adiabatic conditions; that is when $L \to \infty$ or $z/L \to 0$. The surface zero displacement height, or zero-plane displacement height, is the height above the ground at which the wind speed is equal to zero as a result of large obstacles; the surface roughness length accounts for the effect of the roughness of a surface on the wind flow and represents the height at which the wind speed becomes zero theoretically; and z is the height above the ground.

Our model makes use of neutral atmospheric conditions, for which the Monin-Obukhov similarity theory equation simplifies to:

$$u(z) = \frac{u_*}{k}\ln\left(\frac{z - z_d}{z_0}\right) \tag{3}$$

A number of methods have been proposed to estimate the values of the scaling lengths z_d and z_0. Grimmond and Oke [14] refer to two types of approaches that are most commonly used: morphometric methods and anemometric methods.

The latter uses data from field observations to solve the aerodynamic parameters, while the former relates aerodynamic parameters to measures of surface morphology.

Although wind-based methods have the advantage that the characteristics of the surface do not need to be specified, it is difficult to find a satisfactory measurement site in a developed city to collect high-quality data [15].

Furthermore, full-scale measurements are highly influenced by unsteady and uncontrollable meteorological conditions [16-18], and do not provide a complete image of the flow field, due to the low number of measuring locations.

Nevertheless, they provide essential data with which to verify mathematical models.

3. DISCUSSION. MORPHOMETRIC INDEXES

Precise understanding of the aerodynamic characteristics of cities is vital to describe, model, and forecast the behaviour of urban winds and turbulence at all scales [14].

These aerodynamic parameters, namely z_d and z_0, can be related to the morphometry of the urban shape through simple morphometric indexes.

Grimmond and Oke [14] conclude that the relationship between aerodynamic and morphometric parameters proposed by Bottema [19], Macdonald, et al. [20] and Raupach [21] are probably the best that are currently available. Nonetheless, this is out of the scope of this paper.

Two of the most common parameters that describe the morphology of groups of buildings are the plan area index (λp) and frontal area index (λf), defined as the ratio of the cross-section to the total plot area and the frontal area to the plot area, respectively.

The plan area-weighted height of buildings, $\overline{z_H}$ – commonly designated as $\overline{z_P}$ –, is also often used across the literature to describe the morphology of urban areas:

$$\lambda_p = \frac{\overline{A_P}}{\overline{A_T}} \qquad (4)$$

$$\lambda_f = \frac{\overline{A_F}}{\overline{A_T}} \qquad (5)$$

$$\overline{z_P} = \frac{\sum A_{P,i}\, h_i}{\sum A_{P,i}} \qquad (6)$$

where h_i and $A_{P,i}$ are the height and plan area of building *i*, respectively. Figure 1 illustrates the definitions of the main geometric dimensions of a simple, idealized obstacle array.

The plan area index provides a measure of the density of buildings, as buildings that are further apart have λ_p values close to zero.

The frontal area index, λ_f, provides a measure of the area of building face exposed to the wind; it represents the surface that the incoming wind flow can see. Therefore, a single building may have different frontal areas, depending on the wind direction, as shown in Figure 2.

Nonetheless, these definitions – Equations (4), (5) and (6) – are unable to account for a set of buildings of irregular heights and shapes. Therefore, it makes sense to introduce height-dependent geometric indexes to better understand and characterize the morphometry of the domain.

The improved plan area index is simply defined as:

$$\lambda_P(\mathrm{z}) = \frac{A_P(z)}{A_T} \qquad (7)$$

where $A_P(z) = \sum A_{Pi}(z)$ is the cross-sectional plan area of all buildings at height z, and is the cross-sectional plan area of building i at height z. Note that at $z=0$, we arrive to the same result as Equation (4). In other words, Equation (4) is a special case of Equation (7), where we evaluate the morphometric indexes only at ground level.

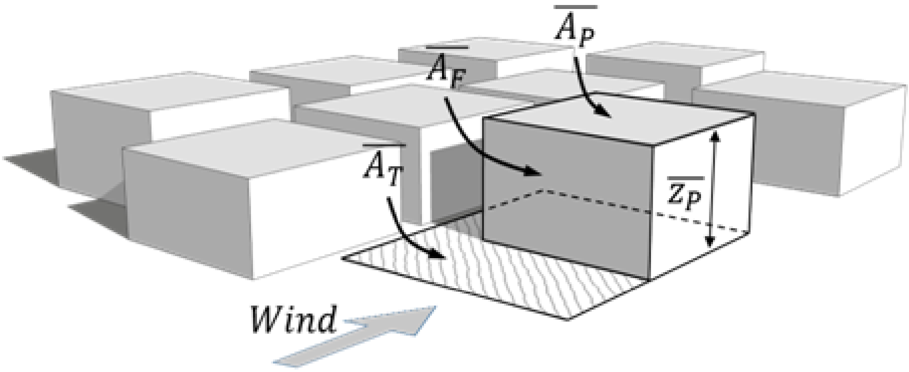

Figure 1: Definition of surface dimensions used in morphometric analysis.

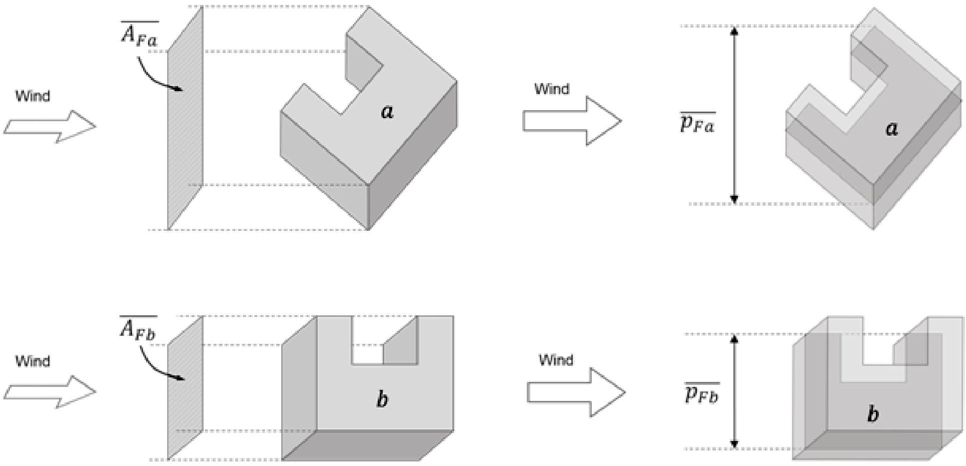

Figure 2: Representation of frontal area (left) and frontal perimeter (right).

Similarly, we define the frontal area index as:

$$\lambda_F(\mathrm{z}) = \frac{h_F P_F(z)}{A_T} \tag{8}$$

where $P_F(z) = \sum P_{Fi}(z)$ is the sum of projections, at height z, of the perimeters of all buildings onto the plane perpendicular to the flow direction and $P_{Fi}(z)$ is the projected perimeter of building i at height z, as seen in Figure 2.

Finally, the frontal area weighted average height of buildings, h_F, is defined as:

$$h_F = \frac{\sum h_i P_{Fi}\,(0) h_F}{\sum P_{Fi}(0)\, h_F} = \frac{\sum h_i P_{Fi}\,(0)}{\sum P_{Fi}(0)} \tag{9}$$

Once more, it can be stated that at $z=0$ Equations (8) and (5) are equivalent.

4. CONCLUSIONS

Some simple morphometric indexes that characterize urban shape can be related to the aerodynamic parameters z_d and z_0. The improved definitions of the plan area density ratio and the frontal area density ratio stated above might help to correctly characterize the morphology of buildings or sets of buildings which vary their cross-section with height and thus provide better estimates of z_d and z_0 through morphometric methods.

These improvements can be used to provide an enhanced understanding of how buildings affect the airflow, enabling a more accurate forecast of pollutant dispersion, providing a tool to prevent the Urban Heat Island effect and allowing intelligent design of passive natural ventilation strategies.

5. REFERENCIAS

[1] R. E. Britter and S. R. Hanna, "Flow and dispersion in urban areas," Annual Review of Fluid Mechanics, vol. 35, pp. 469-496, 2003.

[2] A. Martilli and J. L. Santiago, "CFD simulation of airflow over a regular array of cubes. Part II: analysis of spatial average properties," Boundary-Layer Meteorology, vol. 122, pp. 635-654, 2007.

[3] J. L. Santiago, A. Martilli, and F. Martín, "CFD simulation of airflow over a regular array of cubes. Part I: Three-dimensional simulation of the flow and validation with wind-tunnel measurements," Boundary-Layer Meteorology, vol. 122, pp. 609-634, 2007.

[4] O. Coceal, T. G. Thomas, I. P. Castro, and S. E. Belcher, "Mean flow and turbulence statistics over groups of urban-like cubical obstacles," Boundary-Layer Meteorology, vol. 121, pp. 491-519, 2006.

[5] Z. T. Xie, O. Coceal, and I. P. Castro, "Large-Eddy simulation of flows over random urban-like obstacles," Boundary-Layer Meteorology, vol. 129, pp. 1-23, 2008.

[6] R. Ramponi, B. Blocken, L. B. de Coo, and W. D. Janssen, "CFD simulation of outdoor ventilation of generic urban configurations with different urban densities and equal and unequal street widths," Building and Environment, vol. 92, pp. 152-166, 2015.

[7] Y. Cheng, F. S. Lien, E. Yee, and R. Sinclair, "A comparison of large Eddy simulations with a standard k-ε Reynolds-averaged Navier-Stokes model for the prediction of a fully developed turbulent flow over a matrix of cubes," Journal of Wind Engineering and Industrial Aerodynamics, vol. 91, pp. 1301-1328, 2003.

[8] R. N. Meroney, M. Pavageau, S. Rafailidis, and M. Schatzmann, "Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons," Journal of Wind Engineering and Industrial Aerodynamics, vol. 62, pp. 37-56, 1996.

[9] P. Kastner-Klein and E. J. Plate, "Wind-tunnel study of concentration fields in street canyons," Atmospheric Environment, vol. 33, pp. 3973-3979, 1999.

[10] F. Pascheke, B. Leitl, and M. Schatzmann, "Dispersion of traffic pollutants in street canyons - Systematic wind tunnel study to evaluate a field tracer experiment," 5th International Conference on Urban Air Quality, p. 4, 2005.

[11] H. Cheng and I. P. Castro, "Near-wall flow development after a step change in surface roughness," Boundary-Layer Meteorology, vol. 105, pp. 411-432, 2002.

[12] H. Cheng and I. P. Castro, "Near wall flow over urban-like roughness," Boundary-Layer Meteorology, vol. 104, pp. 229-259, 2002.

[13] G. Vachon, P. Louka, J. M. Rosant, P. Mestayer, and J. F. Sini, "Measurements of traffic-induced turbulence within a street canyon during the Nantes '99 experiment," Third International Conference on Urban Air Quality, 2001.

[14] C. S. B. Grimmond and T. R. Oke, "Aerodynamic properties of urban areas derived from analysis of surface form," Journal of Applied Meteorology, vol. 38, pp. 1262-1292, 1999.

[15] G. Liu, J. Sun, and W. Jiang, "Observational verification of urban surface roughness parameters derived from morphological models," vol. 16, pp. 205-213, 2009.

[16] M. Schatzmann and B. Leitl, "Issues with validation of urban flow and dispersion CFD models," Journal of Wind Engineering and Industrial Aerodynamics, vol. 99, pp. 169-186, 2011.

[17] M. Schatzmann, S. Rafailidis, and M. Pavageau, "Some remarks on the validation of small-scale dispersion models with field and laboratory data," Journal of Wind Engineering and Industrial Aerodynamics, vol. 67, pp. 885-893, 1997.

[18] T. van Hooff and B. Blocken, "Full-scale measurements of indoor environmental conditions and natural ventilation in a large semi-enclosed stadium: Possibilities and limitations for CFD validation," Journal of Wind Engineering and Industrial Aerodynamics, vol. 104, pp. 330-341, 2012.

[19] M. Bottema, "A method for optimisation of wind discomfort criteria," vol. 35, pp. 1-18, 2000.

[20] [20] R. W. Macdonald, R. F. Griffiths, and D. J. Hall, "An improved method for the estimation of surface roughness of obstacle arrays," Atmospheric Environment, vol. 32, pp. 1857-1864, 1998.

[21] M. R. Raupach, "Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index," Boundary-Layer Meteorology, vol. 71, pp. 211-216, 1994.

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