Urban areas parameterisation for CFD simulation and cities air quality analysis.

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Abstract: The aim of this work is to highlight the importance of a site-specific characterization of urban areas needed for Computational Fluid Dynamics (CFD) simulations and urban air quality studies. As a case study, we consider Cagliari, an Italian town, whose heterogeneous urban texture can be representative of many European historical towns, quite different from large American cities that are generally analysed in literature. Basic steps needed to compute the main morphometric and fluid dynamics parameters from Digital Elevation Models (DEM) are reviewed and some possible caveats on using gridded DEM analysis are highlighted. Results show how site-specific analysis provides quite different parametrisations from those obtained by literature results, which cannot be transposed to other urban contexts. Morphometric site-specific analysis represents a key issue in urban numerical simulations, since the application of non-representative morphometric input data may dramatically affect their results.

Keywords: *Morphometric Parameters, Urban Aerodynamic Roughness, Urban Canopy Model.*

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Biographical notes:

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1 INTRODUCTION

An appropriate description of the interaction between the air flows and the built environment is essential when performing numerical simulations, no matter of the target application and the spatial scales involved. Actually, when running mesoscale models aimed at weather forecasting and air quality prediction on large areas, the parametrization of the average effect of the small-scale atmospheric processes is highly complex due to the nonlinear processes involved as well as to land heterogeneities, especially in urban context (Arnfield, 2003; Pelliccioni et al., 2016). This is a critical issue which can be further complex in case of unstable and convective boundary layers, where more complex spatial structures may arise also in case of flat terrain (Badas and Querzoli, 2011), and nonlocal mixing should be properly considered. Although been a nontrivial issue, the positive effect of their adequate characterization has been widely demonstrated (Salamanca et al., 2010; Chen et al., 2011).

Indeed, the characterisation of the urban areas is fundamental also for microscale models, which require more detailed descriptions of the urban morphology, rather than a parametrization representing its average effect on the complex physical processes, as required by mesoscale models.

Moreover, when numerical simulations are performed at neighbourhood or building scale, as in Computational Fluid Dynamics (CFD) models, the proper description of the urban surrounding is necessary for two purposes. It is needed to set the urban roughness length in the regions surrounding the target area, which are not explicitly modelled although included in the simulation domain, as well as to define appropriate approaching wind boundary condition (Blocken, 2015; Pelliccioni et al., 2015).

Urban canopy parameterization and fluid dynamic parameters, needed for the above reasons, are generally developed on the basis of simple urban configurations, which consider the urban canyon as the fundamental unit. Specifically, urban canopy models used in large scale numerical simulations can be broadly divided into single-layer (e.g., Masson, 2000) and multi-layer (e.g. Martilli et al., 2002) models. This is the reason why studies performed on simple configurations, including two-dimensional urban canyons are valuable (Badas et al., 2017; Ferrari et al., 2017; Garau et al., 2018).

In his pioneering work, Oke (1988) highlighted how canyon flow characteristics depend on the Canyon Aspect Ratio (AR_c), defined by the ratio between the canyon width (w_c) and the mean building height ($\overline{z_H}$) (Figure 1a).

$$AR_c = \frac{w_c}{\overline{z_H}} \tag{1}$$

Other authors, e.g. Hang and Li (2011), Chan et al. (2003) and (Garau et al., 2017), showed the influence of the Building Aspect Ratio (AR_b), i.e. the ratio between the building width (w_b) and the building height ($\overline{z_H}$):

$$AR_b = \frac{w_b}{\overline{z_H}} \tag{2}$$

As an example, Figure 2 shows how deeply canyon mean flow, in case of $AR_B = 1$, changes between $AR_c = 1$ (Figure 2a) and $AR_c = 0.5$ (Figure 2b). Data were obtained experimentally in a water flume, applying in-house two frame particle tracking velocimetry (Besalduch et al., 2014, 2013; Falchi et al., 2006). Higher order statistics, and the street canyon ventilation are also strongly affected by the canyon morphology (Badas et al., 2017; Bernardino et al., 2015; Garau et al., 2018b). These effects can also become more evident when thermal effects are considered in the street canyon (Nazarian and Kleissl, 2016) or when the urban morphology interacts with different atmospheric conditions, such as in case of a Convective Boundary Layer, a situation where more complex and localized spatial structures arise also in case of flat terrain (Badas and Querzoli, 2011).

Grimmond and Oke (1999) proposed a morphometric characterisation method to estimate aerodynamic parameters. They described building shapes and proportions schematically and defined the associated parameters empirically. Of course, an elementary unit must first be defined in order to fulfil a morphometric study. Fundamental measurements involved in the elementary unit description are sketched in Figure 1b. Apart from the yet cited $\overline{z_H}$, the other parameters are the building planar area A_P, the building frontal area, along a specific direction, A_F, and the total planar area of the element (considering the building pertinent area) A_T. Building projection area on a certain plane (A_F) varies with the direction that defines that plane, being its normal. Two morphometric parameters, namely Plan Area Index (λ_p) and Frontal Area Index (λ_f) can be defined:

$$\lambda_p = \frac{A_P}{A_T} \tag{3}$$

$$\lambda_f = \frac{A_F}{A_T} \tag{4}$$

When two-dimensional canyons are considered, the relationship between the two set of parameters becomes:

$$\lambda_p = \frac{w_b}{w_b + w_c} \ ; \quad \lambda_f = \frac{\overline{z_H}}{w_b + w_c} \tag{5}$$

Today, morphological analysis is greatly aided by geospatial data availability. Recently, the urban boundary layer parameterization project, NUDAPT (National Urban Database and Access Portal Tool), was created to provide accurate and homogeneous urban dataset on more than 40 American cities (Ching et al., 2009). Other initiatives have been developed in this field, however most studies are performed in American cities, whilst European and, in particular, Italian urban areas have received less attention.

Without a specific and accurate morphometric parameter dataset, input model parameters related to urban structure have to be derived from available datasets and reference values, not necessarily respondent to the specific condition. This may have not negligible effects on the simulation outcomes. Hence, it is fundamental to perform morphometric analysis of different sites in order to develop more accurate parameterizations, and also to configure laboratory set-ups to provide a database for validation with ad-hoc morphologies.

Moreover, another aspect deserves attention: generally morphometric studies are performed on gridded data on a regular grid (Burian et al., 2002; Ratti et al., 2002, 2006; Di Sabatino et al., 2010). Other approaches are performed on adaptive grids or irregular elements based on Voronoi polygons (Ketterer et al., 2017). Actually, results can be significantly affected by element selection, and the choice of the most appropriate methodology should be investigated.

The work presents a morphologic analysis of Cagliari, an Italian town, quite representative of many historical European towns, with the aim to present a GIS based methodology and to discuss the outcomes of a regular or irregular grid choice.

2 METHODS

Thanks to the availability of geospatial data, the analysis described above can be conveniently performed and automated. The procedure here implemented is based on a Digital Surface Model (DSM) and a Digital Terrain Model (DTM), both at 1 m resolution (WGS84/UTM32N-EPSG:32632 reference system). Moreover, we used building and street vectorised datasets. These datasets were retrieved for our case study, Cagliari (Figure 3a), from “Sardegna Geoportale” (http://www.sardegnageoportale.it/navigatori/sardegnamappe/). Data analysis was automated using QGIS and MATLAB® software, as better detailed in the following.

A GIS analysis is the first step of a general methodology, and it allows a simple data viewing, a pre-processing phase and data manipulation. The building heights dataset was obtained subtracting DSM from DTM; it is referred to the street topographic level and was used for the following analyses. Some morphometric parameters were computed from a GIS procedure; e.g. it is possible to calculate λ_p with simple logical operations on building data, once the adopted grid type is defined. Others, such as λ_f, were processed in MATLAB®, using the *Mapping Toolbox*. As an example, Figure 3b shows the rotation of irregular grid elements, necessary to define building projection on the wind direction and to compute corresponding λ_f. Street and building vector data were processed to determine direction, distances and other geometrical information, in addition to associating raster height data to building elements.

The computation of λ_p and λ_f parameters was also used to derive Zero Plane Displacement Length (z_d) and Roughness Length (z_0). These fluid dynamics parameters are used in CFD models to define the incident wind profile:

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z - z_d}{z_0}\right) \tag{6}$$

where u is the flow speed at height z, u_* is the friction velocity and k is the von Karman constant. This formulation is rather questionable in urban context (Fernando, 2010) because of the patterns high inhomogeneity, however the morphometric parameters are usually calculated under simplified conditions.

Several morphometric methods have been developed and tested in order to derive z_d and z_0 (Grimmond and Oke, 1999). A review of the different formulas and the choice of the most appropriate method goes beyond the scope of the present investigation. Different methods were tested for our case study, but apart from the obvious differences in numerical results, they all reflected the heterogeneous urban morphology in z_d and z_0 maps, as described in Section 3.

In the following, we present the results obtained applying the MacDonald method:

$$\frac{z_d}{z_H} = 1 + \alpha^{-\lambda_p}(\lambda_p - 1) \tag{7}$$

$$\frac{z_0}{z_H} = \left(1 - \frac{z_d}{z_H}\right) \exp\left\{-\left[0.5\beta \frac{C_D}{k^2}\left(1 - \frac{z_d}{z_H}\right)\lambda_f\right]^{-0.5}\right\} \tag{8}$$

where α and β are empirical coefficients and C_D is the drag coefficient. The authors suggested using $\alpha = 4.43$, $\beta = 1.0$, $C_D = 1.2$, and we adopted the same values. MacDonald formulas were obtained considering an urban building schematization, so we considered these as the most representative among proposed methods.

In order to compare the outcome of the analysis performed on regular square grids and irregular elements, assessments were carried out by means of three different settings: an irregular grid whose elements are defined on the street graph, hence following the shape of the building blocks (Figure 4a), a 50 m × 50 m gridded map (Figure 4b), a 100 m × 100 m gridded map (Figure 4c). Actually, different grid scales were employed for morphometric analyses (Ketterer et al., 2017; Ratti et al., 2002; Burian et al., 2002; Di Sabatino et al., 2010) and a consensus on defining a standard methodology has not been achieved by the scientific community yet (Fernando et al., 2010). Here, small scale grids were chosen to compare regular and irregular grid outcomes at similar resolutions as well as to investigate the town heterogeneity.

Indeed, the morphometric analysis was applied to Cagliari central neighbourhoods (Bonaria, Marina, Castello, Villanova, San Benedetto and Stampace – displayed in Figure 4d), which have a different historical development that is reflected in their urban texture and, therefore, into morphometric features. The obtained data were statistically analysed at each neighbourhood scale as well as considering the whole grids representing central Cagliari mean parameters.

3 RESULTS

Figure 4 shows colour maps of λ_p over the analysed urban area, computed on the three adopted grids. All the maps display a heterogeneous λ_p distribution, with notable difference from one neighbourhood to another one, whilst less variation is shown within each district. In order to quantitatively compare the results obtained with the three grids, Figure 5 shows λ_p and λ_f mean values with bars representing standard deviation for each neighbourhood and for the whole Cagliari urban area. Here, λ_f refers to the value averaged in every wind direction

(λ_f were computed at wind direction intervals of 10°). Apart from the variability among the neighbourhoods, it is apparent how irregular grid mean values, both for λ_p and λ_f, are closer to those obtained for the 100 *m* grid with respect to the 50 *m* ones. Actually, the frontal area index, λ_f, is highly dependent on grid resolution and it generally decreases with increasing grid size. In fact, when larger grids are considered, buildings that would contribute to the frontal area, A_F, in case of smaller grids are partially shaded by forward buildings, thus determining lower λ_f values.

We also analysed the λ_f directional value, in order to better evaluate anisotropies, due to the building layout preferential direction, when facing the incident wind. Results obtained for three of the analysed neighbourhoods are displayed, as an example, in polar plots of Figure 6. A remarkable difference is apparent: while regular grid data show maximum values on the diagonal direction irrespective of the district analysed, λ_f polar plots computed on irregular element grids are notably different one from the other. Actually, the behaviour observed for the regular grids is prevalently driven by a geometrical reason of the grid itself, more than being a result of the specific urban layout. In fact, when square elements are considered, the frontal area that can be occupied by buildings is largest for wind direction of 45°, and this inevitably distorts the λ_f result. The same outcome is apparent from the λ_f polar plots obtained for whole Cagliari area and displayed in Figure 7. Cagliari λ_f values for the regular grids resemble those obtained by Ratti et al., 2002) for other cities (London, Tolouse, Berlin) using regular 100 m grids: they all have maxima around 45° directions, with Cagliari 100 m grid data almost overlapping Toulouse ones. Conversely, Cagliari irregular block results display an isotropic λ_f distribution, since the effect of the anisotropies highlighted in some neighbourhoods (and discussed above) are lost when averaging data at larger scales. Actually, we compared mean morphometric values since it is a common practise to use them as a reference in this context (Pelliccioni et al., 2016). Nonetheless, it should be pointed out that, for non-Gaussian statistical distributions, the choice of the mean value as the representative one is rather questionable. Moreover, from the modelling point of view, the focus is not the correct representation of the morphometric parameters as such, but their bulk effect on the urban boundary layer, which is usually represented using formulas developed from the analysis of regular urban outlines. This issue deserves further investigations, which however goes beyond the scope of the present work.

The heterogeneous distribution of λ_p and λ_f values is reflected into the roughness length z_0 map, computed according to MacDonald formula and displayed in Figure 8. In absence of such detailed studies, when urban roughness length z_0 or zero displacement length z_d are needed, one might choose the appropriate values following the urban area classification by Grimmond and Oke (1999), whose reference values are displayed in Table 2. According to the description given by these authors, Cagliari should be classified as a C urban area (i.e. residential-closely spaced < six-story row and block buildings or major facilities like factories, university, etc., town centre). However, comparing Table 1 and 2, while z_d falls within the proposed range, z_0 from the morphometric analysis is quite different from those obtained by Grimmond and Oke (1999). Moreover, z_0 distribution is highly heterogeneous (Figure 8), hence its mean value may not be representative.

This confirms that using parameterizations obtained in other regions can be misleading, providing different mean parameters. Moreover, when simulating small portions of the city, in order to represent appropriate boundary conditions, aerodynamic parameters should be computed with reference to the upwind target area, possibly using directional morphometric data, instead of adopting averaged value, which may fail to well represent the specific urban context effect on the urban boundary layer.

4 CONCLUSIONS

Simulating air flows in urban contexts requires input parameters synthetically representing the complex interactions between the boundary layer and the built environment (Amicarelli et al., 2012). These parameterizations may have a great influence on the simulation results, both in case of air quality models (Di Bernardino et al., 2018) or in CFD context (Ferrari et al., 2016). From the analysis performed on Cagliari and here presented, we can draw some general conclusions. First of all, caution has to be considered when using literature data obtained in different urban contexts. Secondly, the complex town historical development is reflected into the heterogeneous distribution of morphometric parameters. Hence, their mean values computed over the whole town, may not be meaningful and, for some applications (such as a CFD study and pollutant dispersion modelling at a building or block scale, morphometric parameters should be first assessed at a homogeneous neighbourhood level, and then their bulk effect, averaged along the upwind fetch, should be estimated. Moreover, the comparison of λ_f computation for gridded dataset showed misleading results that can be conveniently overcome using irregular elements extracted from the street graph.

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FIGURES

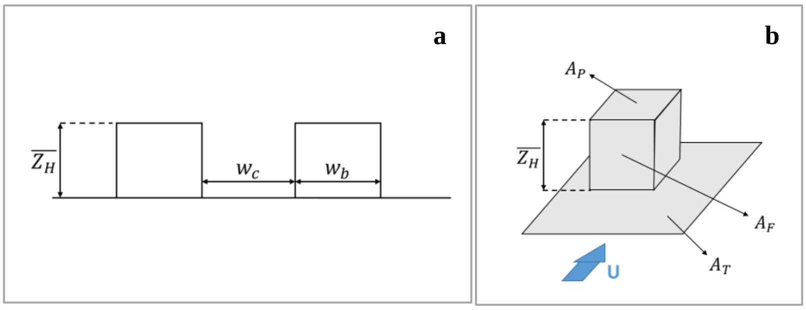

Figure 1. Basic parameters to define (a) urban canyon aspect ratios ($AR_c = W_C/\overline{z_H}$, $AR_b = W_b/\overline{z_H}$); (b) planar ($\lambda_P = A_P/A_T$) and frontal ($\lambda_F = A_F/A_T$) area indexes.

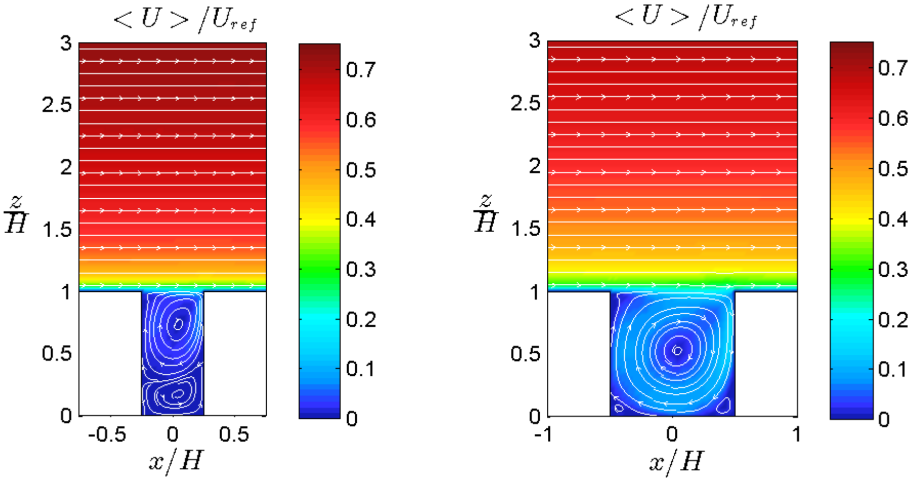

Figure 2: Non dimensional velocity field colormap, with superimposed streamlines in urban canyons with $AR_b = 1.0$ and $AR_c = 0.5$ (a) and $AR_c = 1$ (b). Velocity field is made non dimensional by the free stream velocity U_{ref} at the top of the domain z/H=9.

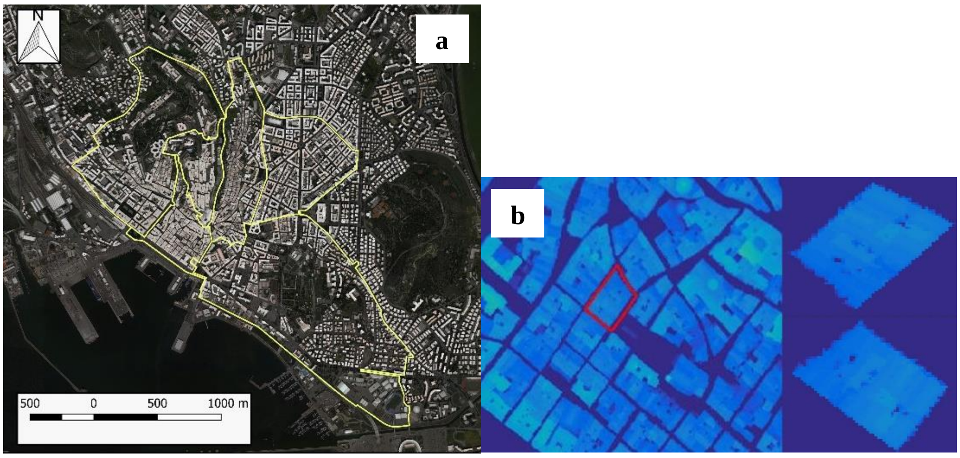

Figure 3. (a): Cagliari planimetric map, yellow lines highlight neighbourhood subdivision; (b) identification of an isolated building pertinent area and its rotation for λ_f calculation.

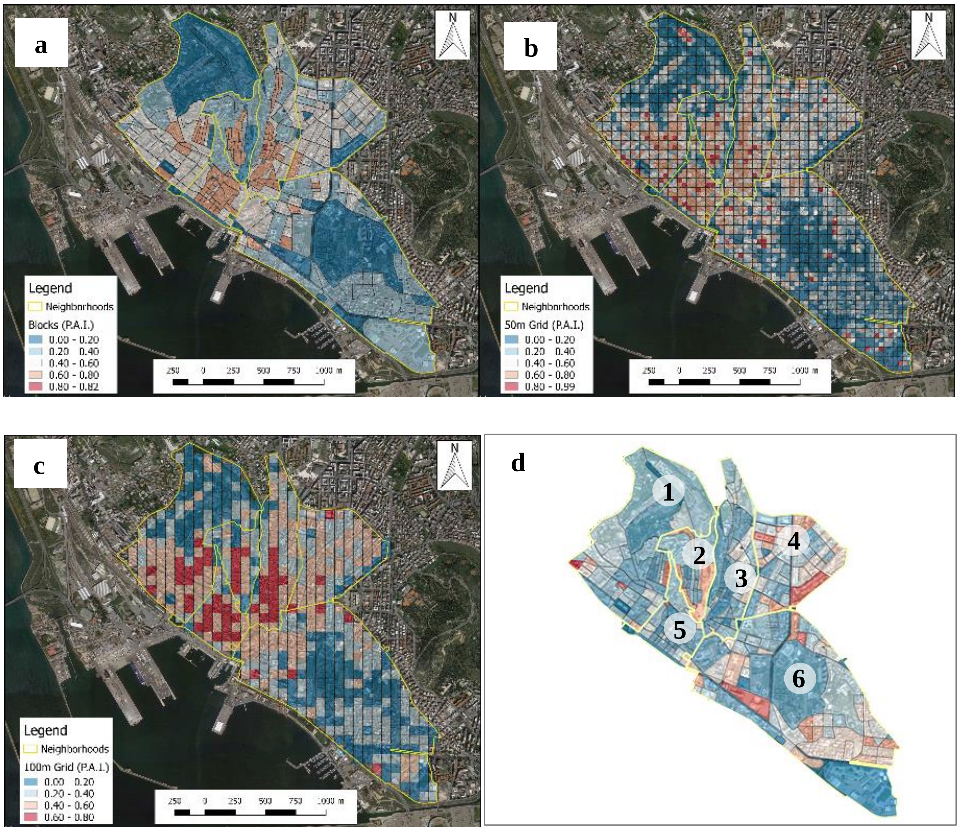

Figure 4. λ_p colormap distribution on Cagliari urban area computed from subdivision in irregular blocks (a), gridded elements at 50 m (b) and 100 m (c). Yellow lines highlight neighbourhood subdivision: Stampace (1), Castello (2), Villanova (3), San Benedetto (4), Marina (5), Bonaria (6), as displayed in plot (d).

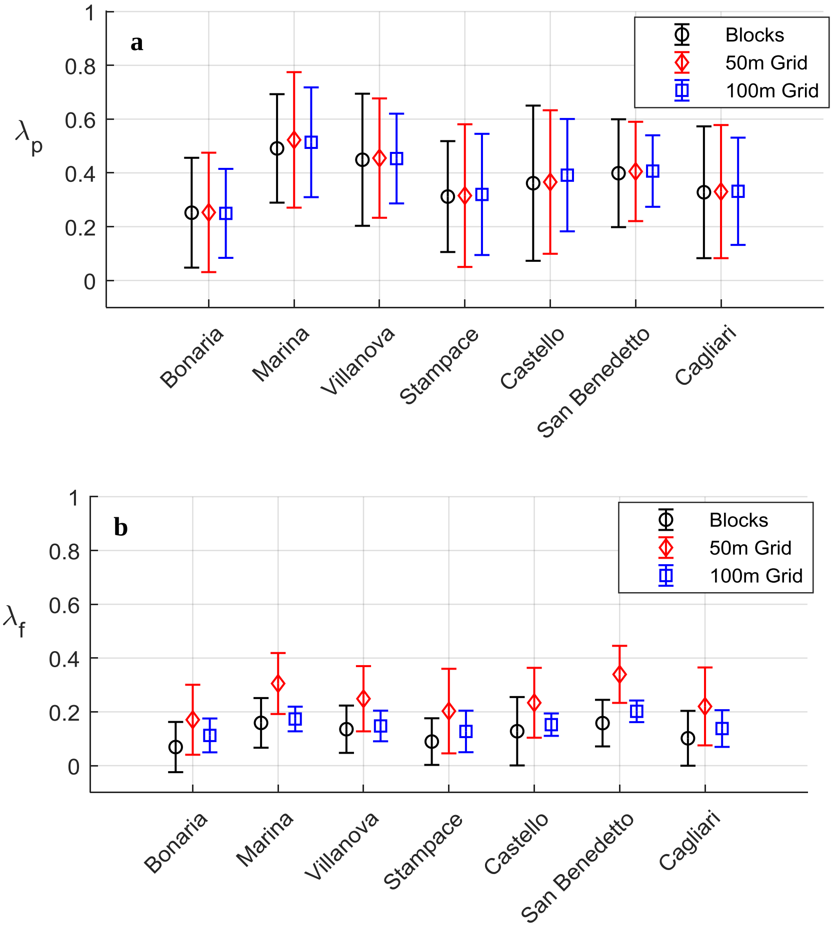

Figure 5. λ_p(a) and λ_f(b) mean values with standard deviation bars computed on each neighbourhood and the overall studied urban area, as obtained from subdivision in irregular blocks (black), gridded elements at 50 m (red) and 100 m (blue).

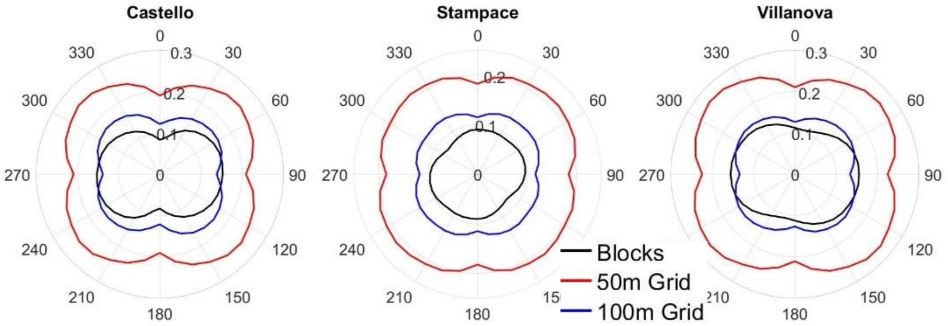

Figure 6. λ_f polar plots computed for the corresponding wind direction for three Cagliari neighbourhoods, using subdivision in irregular blocks (black line), regular gridded elements at 50 m (red line) and 100 m (blue line).

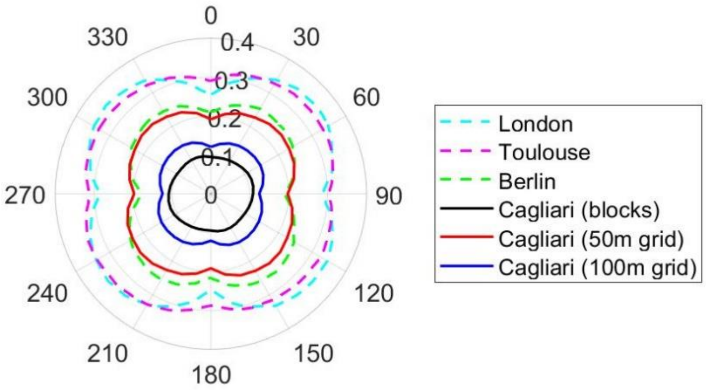

Figure 7. λ_f polar plots for the whole Cagliari area using subdivision in irregular blocks (black line), gridded elements at 50 m (red line) and 100 m (blue line) compared with other study cases performed on regular grids (dotted lines).

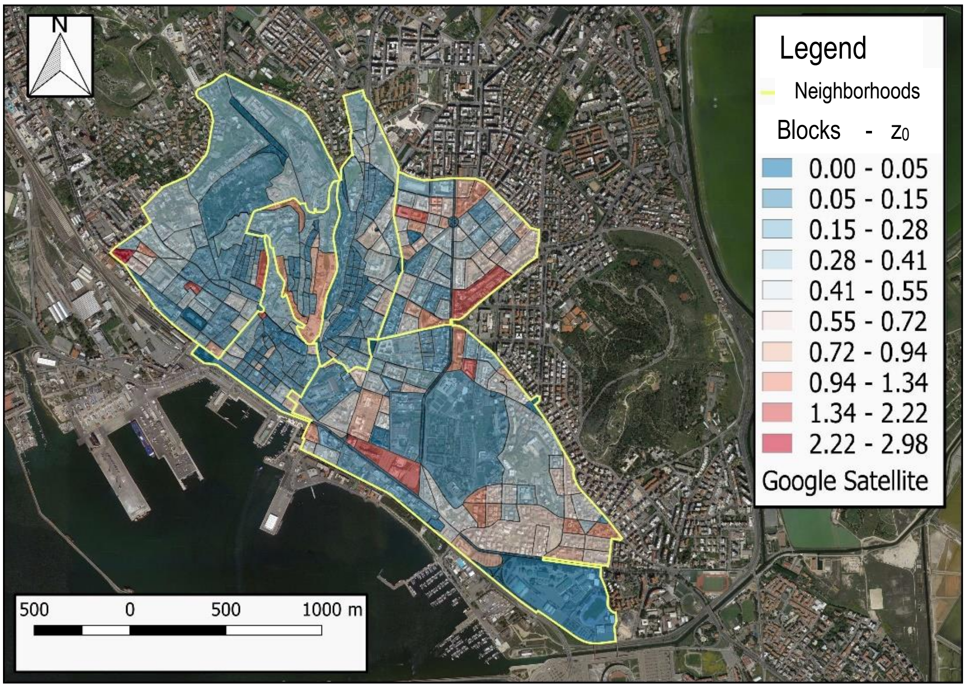

Figure 8. Urban roughness, z_0, colormap obtained by using irregular blocks on Cagliari

TABLES

Table 1: Comparison between aerodynamic properties obtained for Cagliari and available literature data for some other European cities.

Site	$z_H\ (m)$	$\lambda_p\ (-)$	$\lambda_f\ (-)$	$z_d\ (m)$	$z_0\ (m)$
Cagliari	21	0.33	0.10	10.7	0.47
Berlino	20	0.35	0.23	12.1	1.18
Tolosa	16	0.40	0.32	10.9	0.92
Londra	15	0.55	0.32	11.9	0.30

Table 2: Aerodynamic parameters for the four urban area classes defined by Grimmond and Oke, (1999), ordered by height and density.

Class	$z_H\ (m)$	$z_d\ (m)$	$z_0\ (m)$	**Urban Surface Form**
A	5-8	2-4	0.3-0.8	Low height and density
B	7-14	3.5-8	0.7-1.5	Medium height and density

C	11-20	7-15	0.8-1.5	Tall and height density
D	>20	>12	>2.0	High-rise