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Urban texture analysis with image processing techniques: winds and dispersion

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With 15 Figures

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Summary

The focus is the analysis of urban Digital Elevation Models (DEMs) with image processing techniques. A brief review of existing methods to derive sky view factors, building energy consumption and space syntax shows how well established parameters that relate to airflow and dispersion (such as the height-to-width of urban canyons and the aerodynamic roughness length) can be calculated. Other measures of urban directionality and periodicity, inspired by traditional image processing, are also introduced, such as the Radon, Hough and Fourier transforms and the variance plot. Analyses of three case study sites in London, Toulouse and Berlin are compared, showing considerable variation in the chosen parameters. Results suggest that the DEM format is an extremely versatile tool to investigate the urban intermediate scale, allowing analyses that would be very difficult or impossible to carry out using traditional vectorial models.

1. Introduction

Air pollution is an increasing concern in many cities all over the world. Despite the achievements in the reduction of emissions such as SO_2, NO_x and large particulates, most European cities still exceed the short-term air quality guidelines of the World Health Organization. This situation is dramatically exacerbated in developing countries, such as India and China, which are currently undergoing an accelerated urbanization process. A paper by the World Watch Institute reports:

> *"Researchers estimate that air pollution in 36 large Indian cities killed some 52000 people in 1995, a 28 percent increase from the early 1990s. China reported at least 3 million deaths from urban air pollution between 1994 and 1996. And a recent examination of 204 cities by the World Resources Institute ranked Mexico City, Beijing, Shanghai, Tehran, and Calcutta as the five worst in terms of exposing children to sulphur dioxide, nitrogen oxide, and particulates. Just by breathing the air in their homes and streets, these children inhale the equivalent of two packs of cigarettes per day"* (O'Meara, 1999).

Urban geometry or texture[1] – in particular the width of streets, their orientation, spacing,

[1] Urban texture is a commonly accepted, although loosely defined, expression in the architecture disciplines. Here we will use it as a substitute for 'urban geometry', when the level of detail implied is that of the intermediate scale (which is defined here as that of a group of buildings or a few city blocks, say up to the order of 10^3 meters).

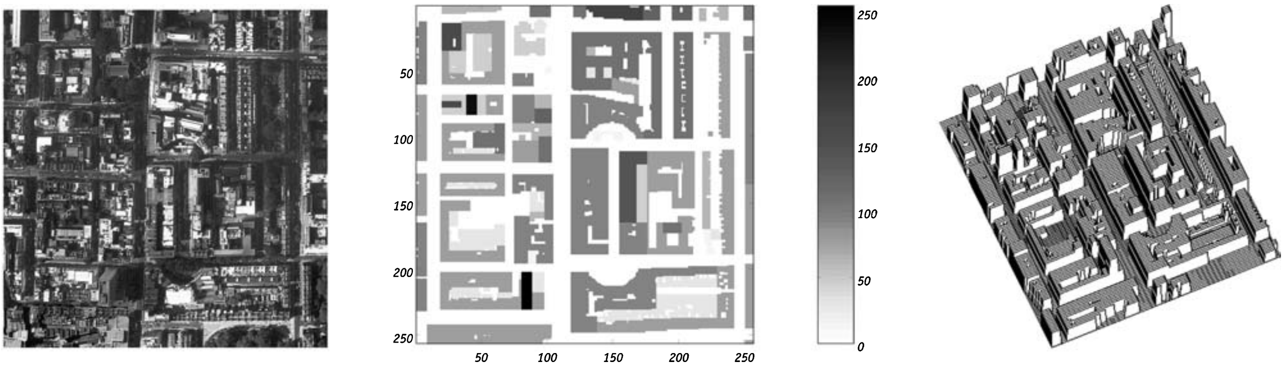

Fig. 1. Case study site in central London as an aerial image (left), as Digital Elevation Model DEM (centre) and as an axonometric view (right). Both the DEM image and the axonometric view contain the same amount of geometric information. The colorbar next to the DEM represents an 8-bit 0–255 scale, which converts to building heights based on the ratio 1 grey level = 0.156 meters. The two horizontal and vertical scales next to the DEM image represent pixel numbers, which convert to meters following the ratio 1 pixel = 1.560 m. In other terms the case study site measures 400×400 m in plan and has a maximum height of 40 m. This will apply to all the images in this paper unless otherwise stated

intersection, and so on – is a major determinant of pollution dispersion, or the lack of it. Tall buildings tend to produce turbulence and vertical mixing in the atmosphere, while height-to-width ratios of urban canyons affect street ventilation. More generally, buildings modify the urban wind field, influencing air exchanges and the dispersion of pollutants – be they emissions from transport, housing, industry or toxic agents deliberately introduced into the atmosphere.

Besides air pollution, the modification of the urban wind field produced by buildings has further effects on the city environment. Shelter at street level affects comfort of pedestrians, with a favorable effect in cold climates and vice-versa in hot ones. Pressure variations on building façades determine the potential for natural indoor ventilation. Simple air movement tends to oppose the formation of the urban heat island, thereby modifying the distribution of temperatures in the city; conversely, the urban heat island creates a temperature gradient between the city and the surrounding countryside and gives rise to local winds, which may have a beneficial pollution dilution effect. Munn (1970) and Melaragno (1982) review a number of other interactions.

Due to its multi-faceted impact on the city environment, wind is a key element in urban studies. It is no surprise that Givoni (1998) states: "*Of all the climatic elements the wind conditions are modified to the greatest extent by urbanization*". And more cogently: *"From the viewpoint of modifying the urban climate and urban comfort by urban design, modifying the urban wind conditions offers the greatest potential"*.

Studies on winds in urban areas, however, have mostly focused on two main spatial scales: the scale of the isolated building and the urban scale, which extends conventionally many tens of kilometers. The intermediate scale, sometimes called the 'neighborhood' scale – which is defined here as that of a group of buildings or a few city blocks, say up to the order of 10^3 meters, and which would be the most promising for the architect and urban designer – is relatively unexplored (see, for example, Di Sabatino, 2000). This lack can be partially attributed to the difficulty of modeling the geometry of the city and estimating its influence on the physics controlling flow and dispersion.

This paper discusses how a number of image processing algorithms could be used to analyze very simple raster models of the urban geometry (the so-called Digital Elevation Model or DEM, described below) and extract information relevant to flow and other transfer processes at the intermediate scale. The DEM, an example of which is shown in Fig. 1, is a compact way of storing urban 3D information using a 2D matrix of elevation values; each pixel represents building height and can be displayed in shades of grey as a digital image. It is becoming an increasingly available support to describe cities, due to recent advances in sensing technologies such as lidar. DEMs for three case study sites in central

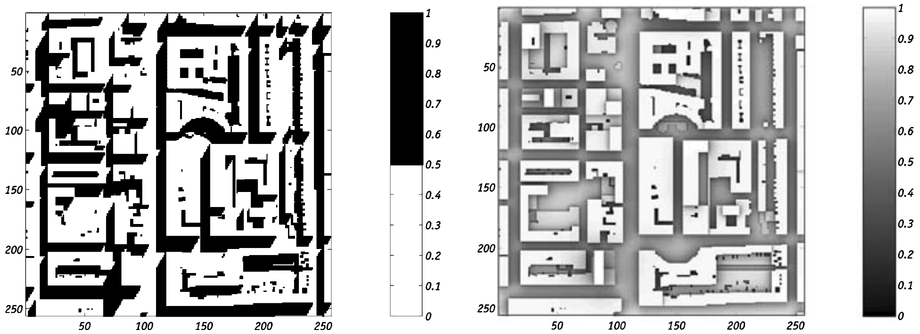

Fig. 2. An example of parameters that can be obtained by applying image processing techniques to a DEM: shadow casting with sun position azimuth = 30°, altitude = 30° (black = shadow, white = sun); sky view factors on the urban surface (dimensionless values 0–1)

London, Toulouse and Berlin will be shown in Fig. 8.

Its analysis with image processing techniques in the urban context has proven to be very conducive to the calculation of a number of urban parameters. Shadow casting and sky view factors can be easily obtained (Fig. 2; Ratti and Richens, 2004). Energy consumption in buildings can be simulated, based on the coupling of image processing techniques with the LT model (Fig. 3; Ratti et al., 2000; Ratti, 2002). Space syntax measures of urban connectivity and various analyses of the city as a network of streets can be derived (Fig. 4; Ratti, 2004).

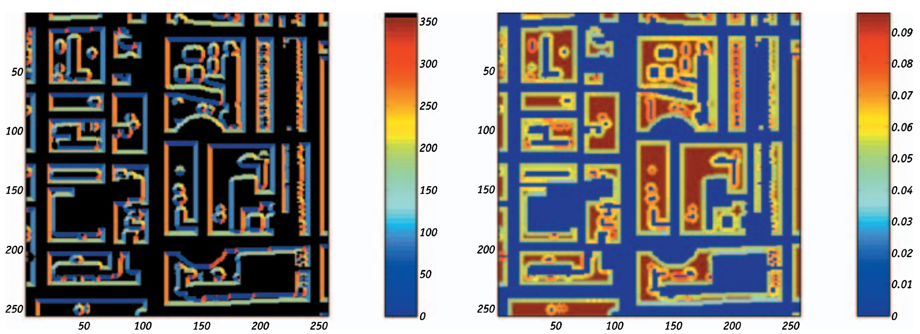

Fig. 3. Calculation of building energy consumption parameters in the London case study using the LT Method (Baker and Steemers, 2000): passive zones, i.e. building zones within 6 m from a façade, classified according to their orientation (values in degrees 0–360); energy consumption simulation based on a 50% glazing ratio and using all other non-morphological parameters in the LT Model as default (values in kWhm^{-2} year^{-1})

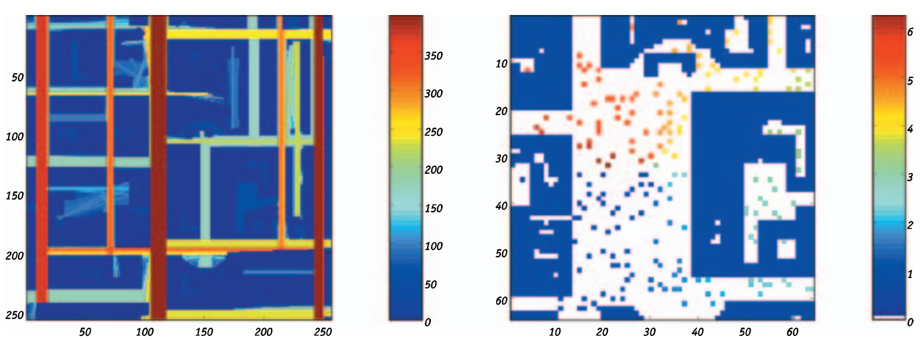

Fig. 4. Maximum of the sum of the length of the lines of sight in two opposite directions (values in degrees 0–360); cellular automata simulation, based on Batty et al. (1998), to model pedestrian movement on a portion of the on the London case study (values simply shows the quadrant they belong to)

With air quality becoming an increasing concern in many cities all over the world, could the analysis of urban DEMs contribute to the study of the urban atmosphere, such as the winds, and thereby provide estimates of input parameters for dispersion models?

2. The urban wind field: background

"The urban wind field is rarely simple" (Landsberg, 1981). This section reviews some key parameters commonly found in the urban climatology literature, which will be the basis of the analyses presented in the subsequent part of the paper.

In general, wind measurements in urban areas show a reduction of the average speed and an increase in turbulence when compared to open areas (Landsberg, 1981). Take a single building: the separation of the flow above and behind it produces a pressure difference across, and hence a drag force on, the building and increased turbulence near and downwind of it.

The features that appear in the flow around a single obstacle are also present in the case of a group of buildings, though in general the latter would interfere with each other. Different kinds of interference exist, based on the spacing of buildings as described in Oke (1988). At wide spacing the building wakes do not interfere (*isolated obstacle flow*); at closer spacing the wakes from upstream buildings affect the flow around downstream buildings (*wake interference flow*); at even closer spacing the bulk of the flow no longer enters the zone between the buildings (canyon), where a vortex develops (*skimming flow*). The occurrence of any of these regimes is a function of urban geometry. For simplified building layouts (arrays of parallel slabs), it can be predicted based on the height-to-width (also called aspect or H/W) and the length to width ratios of the canyons (L/W).

The mutual sheltering between buildings – in other words how the perturbation due to each single obstacle adds up – can also be tackled from another perspective by focusing on the connection between the wind and the drag force on buildings. This connection can be characterized by the aerodynamic *roughness length*, z_0. z_0 is a key parameter in studying the urban atmosphere, as it affects the wind over the city; large scale flow models utilize the roughness length (and its spatial variation) as a momentum-related boundary condition.

A number of methods have been suggested to determine the value of the roughness length. Historically, the classical way has been based on measuring wind profiles from tall masts (see for instance Davenport et al., 2000). This type of measure, however, is difficult to obtain in urban areas because it requires observations from anemometers exposed at a level well above the average height of the buildings. A number of empirical formulas have therefore been suggested to calculate the roughness length directly, without wind measurements, when the geometry of the obstacles is known. Until recently these methods were limited to simple arrays of buildings, but the growing availability of large 3-D databases and computational capabilities is starting to allow unprecedented possibilities for roughness length determination (Ratti et al., 2002). These rely on algorithms based on the drag force on individual buildings and the interference between the flows around the buildings. An extensive review of the technique is contained in Grimmond and Oke (1999), who use DEM analysis in urban areas to calculate the aerodynamic roughness in the framework of raster Geographical Information Systems. A number of other methods to estimate the urban aerodynamic roughness exist in the literature. In general, it is possible to take advantage of increasing computational capabilities and use generic CFD calculations to develop algorithms for z_0. Basly et al. (1999) attempt to extract urban morphological features – and therefore classes of aerodynamic roughness – from satellite images, while Menenti et al. (1996) suggest the use of airborne laser altimetry.

While the aerodynamic roughness length is essential to the knowledge of the winds above the urban canopy, the problem of describing winds within the canopy has been tackled in different ways. Amongst them are Computational Fluid Dynamics (CFD) simulations (Ní Riain et al., 1996; Nørstrud et al., 2000), testing of scale models in wind and water tunnels (Kastner-Klein and Plate, 1999; Pavageau and Schatzmann, 1999) and empirical rules of thumb (Bottema, 1999). When considering the flow and pollution dispersion at the scale of individual streets, the height-to-width ratio of the canyon is again the main geometrical input required for dynamic models designed to provide the flow field and the concentrations in streets of traffic generated pollutants, such as NO_x, CO, ozone, benzene and others (Nakamura and Oke, 1988; McHugh et al., 1997). Levels are calculated from traffic emissions within individual streets, with a contribution from the background pollution above the urban canopy.

Finally, there are a number of methods that are aimed at defining and deriving simplified morphological parameters that can then be related to the urban winds. For instance, Steemers et al. (1996) use the concept of urban porosity and a number of geometrical quantities to assess the wind response to texture. In a similar way (although originally in the context of solar radiation) Compagnon and Raydan (2000) define a measure of urban directionality. Grosso et al. (2000) use simple ratios of ground occupation and building density to assess the potential of natural ventilation in buildings (and compared them with CFD results). Croxford et al. (1995) test methods of analysis of street configuration such as Space Syntax to evaluate the migration of pollution in the street networks.

The sections below will show how the parameters reviewed above can be calculated by analyzing urban DEMs with image processing techniques, thus informing the knowledge of urban winds.

3. The canyon height-to-width ratio

As discussed above, a key parameter at the individual street scale is the *height-to-width* ratio of the street canyons (also called *aspect* or H/W). How could it be calculated over an extensive urban area? The first issue to tackle is its definition: this is trivial when dealing with canyons of uniform height, such as those commonly found in the literature, but becomes trickier in real cities, which often present irregular building arrangements. In some cases, the very notion of 'canyon' blurs: in squares, for instance, a number of height-to-width values can be defined, according to the selected orientation. Problems also arise in the case of street junctions or loose, sprawling urban textures.

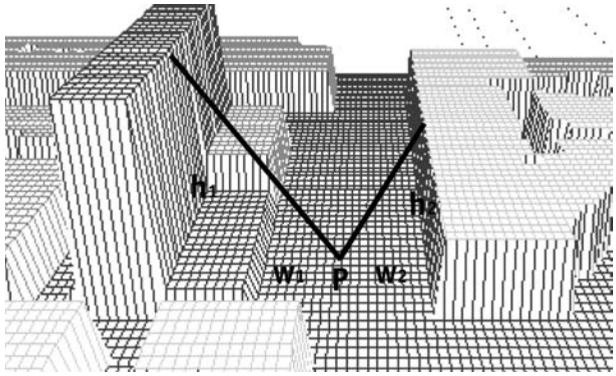

Fig. 5. While the definition of the height-to-width or aspect ratio is trivial in canyons of uniform height, it becomes more complicated in real cities with irregular building patterns. The figure above shows a possible way to calculate it based on the obstruction angles in opposite directions: $(\mathrm{H/W})_{P_i} = \frac{h_{i,1}+h_{i,2}}{2(w_{i,1}+w_{i,2})}$

As a general case, it can be considered that the height-to-width is a function of the orientation α. The definition that has been adopted here relies on assigning to each pixel a value of height-to-width based on the two obstruction angles in the directions α and $\alpha + 180$. Expressed as a formula:

$$(\mathrm{H/W})_{P_i} = \frac{h_{i,1} + h_{i,2}}{2(w_{i,1} + w_{i,2})}.$$

Notations refer to Fig. 5, where $(\mathrm{H/W})_{P_i}$ represents the value of the height-to-width ratio at point P_i, h_i represent the height of the obstructing buildings in two opposite directions and w_i the horizontal distance of those buildings from point P_i. The application of an *ad-hoc* written morphometric algorithm produces the results shown in Fig. 6, which refers to the London case study.

Height-to-width statistics may be used to highlight urban areas with poor ventilation and pollution dispersal (large height-to-width) or little shelter (low height-to-width). Alternatively, the height-to-width ratio averaged over an area of the city could be used as a more concise measure. If plotted against orientation, it can give a polar graph or a polar histogram, showing the distribution of canyon height-to-width ratios. One application is an alternative version of Oke's formula to relate the urban heat island to street configuration and is based on the canyon aspect ratio height-to-width (Oke, 1981). The latter can therefore be used as a substitute for the average view factor from the urban canyon to the sky.

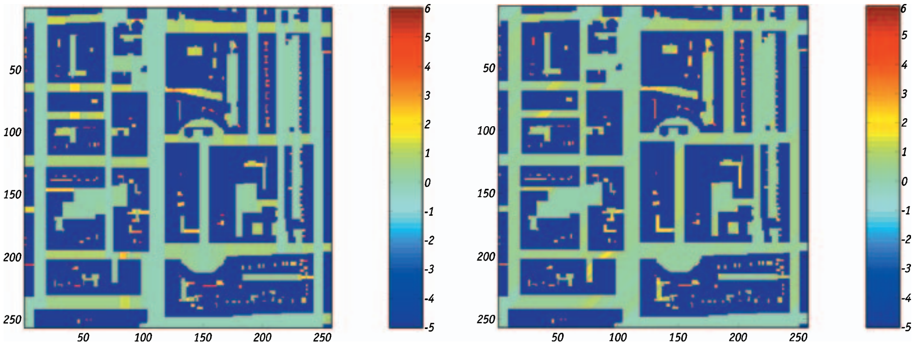

Fig. 6. Height-to-width ratios on the London case study at directions 0° and 45° (dimensionless values based on the formula in Fig. 5; building have been assigned an arbitrary value −5 in order to differentiate their color from that of the canyons)

4. Aerodynamic roughness and its calculation on a DEM

Another fundamental parameter for studying the winds in urban areas is the aerodynamic roughness length z_0. How can it be calculated from a DEM?

Many expressions for the roughness length z_0 are found in the literature (Grimmond and Oke, 1999) and these commonly use the averaged height of the buildings (weighted by frontal area) z_H, the plan area ratio λ_P and the frontal area ratio λ_F (see for example Macdonald et al., 1998):

$$z_H = \frac{\text{total of [height of the building} * \text{frontal area]}}{\text{total frontal area}} = \frac{\sum HA_F}{\sum A_F}$$

$$\lambda_P = \frac{\text{total plan area of the buildings}}{\text{total site area}} = \frac{\sum A_P}{\sum A_T}$$

$$\lambda_F(\theta) = \frac{\text{total frontal area of the buildings } (\theta)}{\text{total site area}} = \frac{\sum A_F(\theta)}{\sum A_T}.$$

The three ratios can be derived from the analysis of DEMs. λ_P is straightforward: it is enough to count built and un-built pixels on the image. The frontal area is a little more complicated, as it is a function of orientation, i.e. $\lambda_F = \lambda_F(\theta)$. Using standard image processing algorithms it is possible to derive the unit vector perpendicular to the DEM surface on each pixel. The dot product between this vector and a horizontal unit vector in the direction θ gives the projection of the building surface along that direction. Summing the results over all negative pixels (we are interested in the frontal area in a given wind direction, which means a negative dot product) gives $\lambda_F = \lambda_F(\theta)$. In a similar way it is possible to obtain z_H, which is simply an average of the building height weighted using the frontal area.

By using these ratios in the formulas found in the literature, a roughness rose can be calculated. Results for three case study sites in London, Toulouse and Berlin are given in Table 1 and Fig. 8 (the respective DEMs can be seen in Fig. 7). The three cities are represented on the same graph, as in this case the inter-comparison of results is more important than their directional variation. Although the frontal area in London is large, the city has a comparatively small roughness. This is due to the tight spacing of buildings, which leads to a predominantly skimming flow (as if the wind were not ‘seeing’ the obstacles). Due to the smaller built density, Berlin has the maximum aerodynamic roughness, while having smaller frontal area. This agrees

Table 1. Values of geometrical parameters in London, Toulouse and Berlin

	London	Toulouse	Berlin
λ_P, built to total area ratio [ ]	0.55	0.40	0.35
z_H, average of the heights weighted with frontal area (also averaged all azimuth) [m]	14.8	16.1	19.9
λ_F, frontal area density (average all azimuth) [ ]	0.32	0.32	0.23
z_0, roughness length (average all azimuth) [m]	0.30	0.92	1.18

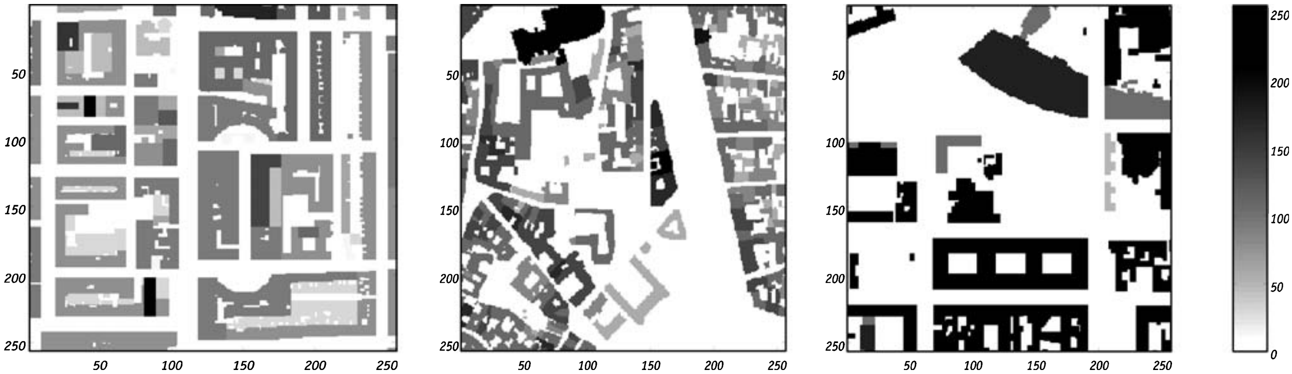

Fig. 7. Case study sites in central London, Toulouse and Berlin (from left to right); they all measures 400 × 400 m in plan, as explained in Fig. 1

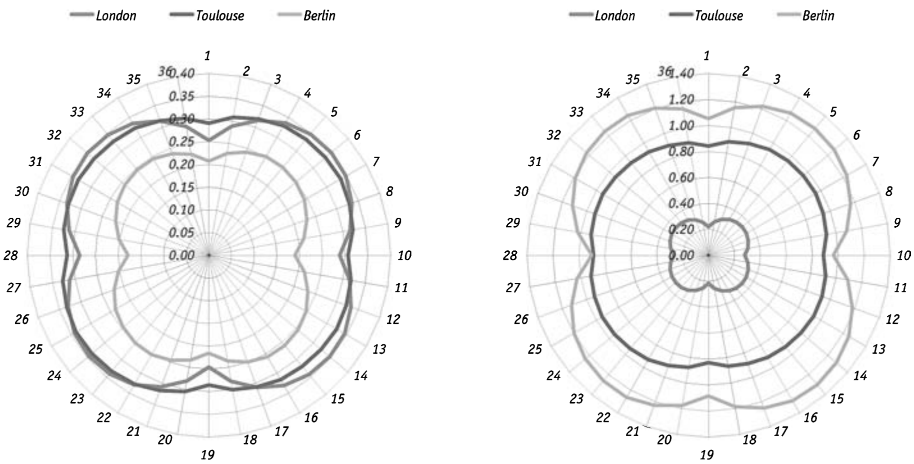

Fig. 8. Polar diagram showing the variation of λ_F (left, dimensionless values) and z_0 (right, values in m) with orientation, in London, Toulouse and Berlin

with Oke (1988), who reports that the peak roughness for building-like elements scattered on a plane appears at densities of about 0.25.

Incidentally, the rose-shaped pattern that is noted in the λ_F plot of London and Berlin comes from the fact that most buildings in these two cities are parallelepipeds aligned with the x–y axes and their windward-area increases to a maximum in the diagonal direction.

In general, the size of these case study sites (400 × 400 m) would not be enough to perform a roughness calculation; however, this can be accepted here as the sites may be considered representative of larger urban areas with similar textural features. If that was not the case and there was a spatial variation of roughness, a possible difficulty would arise. One approach to overcome it, however, would be to consider 'neighborhoods' each with a definable urban texture.

At this point it is well to remember that the surface roughness length is not of great interest *per se*. The surface roughness length is really a surrogate for the connection between the surface stress and the wind speed at some height above the urban canopy (that is, the local surface drag coefficient). Although the development of a logarithmic velocity profile (of a vertical extent sufficient to deduce z_0 from field or laboratory experiments) requires a considerable fetch, the flow close to the surface will come in to local equilibrium far sooner, thereby allowing the use of 'neighborhoods' of different local surface roughness. In a sense it could be said that the roughness length characterizes the 'wall function' required by an (atmospheric) computational fluid dynamics model.

The parameters z_H, λ_P and λ_F, determined from DEMs or otherwise have been used recently for obtaining other wind-related variables such as the advective velocity within the urban canopy, the exchange velocity for transfer between the in- and above-canopy flow and the characteristic turbulence levels within the urban canopy (see, for example, Bentham and Britter, 2003; Hanna and

Britter, 2002; Britter and Hanna, 2003). However, using these parameters or focusing too strongly on determining the surface roughness length (or the roughness displacement length) may have distracted attention away from deciding how best to characterize the flow, and the related heat, mass, moisture and pollutant transfer processes through and over an urban area and what statistical parameters are best suited to describing those processes. As a specific example, the spatial variability of pollutant levels is of considerable interest. What statistical measure of the urban texture could be developed to reflect the contribution of the urban texture to that spatial variability? If a good statistical measure can be developed, then its calculation via DEMs is straightforward. This is still to be done in a comprehensive, rational, pragmatic and widely agreed upon way.

It will be shown below how the image processing of urban DEMs could provide other insights into urban winds. The techniques of analysis come from the image processing literature, although to our knowledge they have not been applied to the urban context yet. They might therefore throw a different light on established climatology issues in cities.

5. Urban texture directionality: the Fourier, Hough and Radon transforms

At a basic level, the essential information about the urban wind is its direction. Therefore the first parameter to identify is the one that characterizes the directionality of the urban texture as this will strongly influence the winds near to and within the urban canopy. This approach has traditionally been taken by designers, aiming at defining rules of thumb for the layout and orientation of streets (in a way not dissimilar to that presented by Bottema, 1999).

A number of ways of extracting information on directionality are available from traditional image processing, such as the Fourier, Hough and Radon transforms.

The prime tool for studying directionality and periodicity in images is the 2-D *Fourier transform*. This is a standard function and can be applied to urban DEMs. Results for the three study areas of London, Toulouse and Berlin are shown in Fig. 9. The Fourier transform is not new in urban climatology, as it is sometimes used for data analysis or as a mathematical tool to solve the equation of motion in complex terrain (for instance, in linearized perturbation models). However, as a tool to describe the directionality of the urban texture, the Fourier transform might not be the most effective one; although the primary orientations are distinguished in the plots of Fig. 9, they are still hard to interpret.

Another way to analyze the directionality of images is the *Hough transform*, a tool that isolates features of a particular shape within an image. The basic idea of this technique is to detect curves that can be parameterized – like straight lines, polynomials, circles, etc. – in a suitable parameter space. Due to our interest in directionality, we will limit ourselves to straight lines.

The typical image processing use of the Hough transform is the following: take a black and white image, detect edges on it and apply the transform. Results highlight the predominant lines and constitute valuable information, for instance, when needing to reconstitute an image with holes

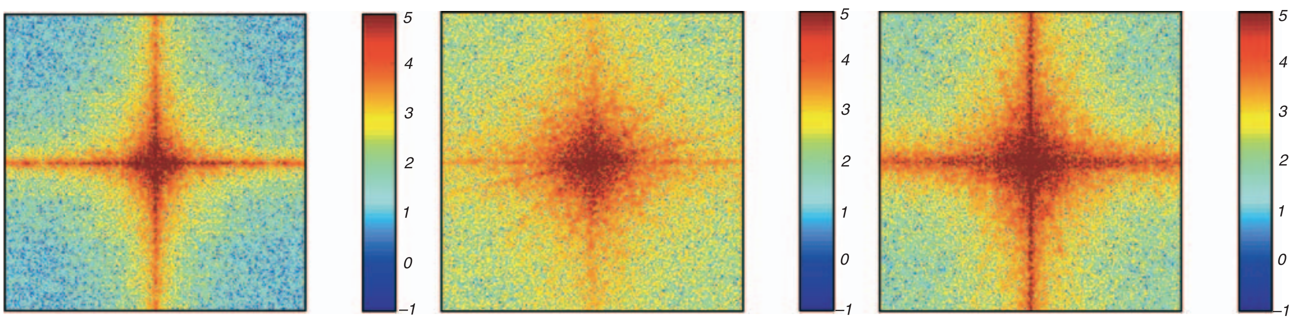

Fig. 9. Fourier Transform (a standard Matlab function) for London, Toulouse and Berlin (from left to right; values show the sum of the squares of the real and imaginary parts of the Fourier transform using a color-scale)

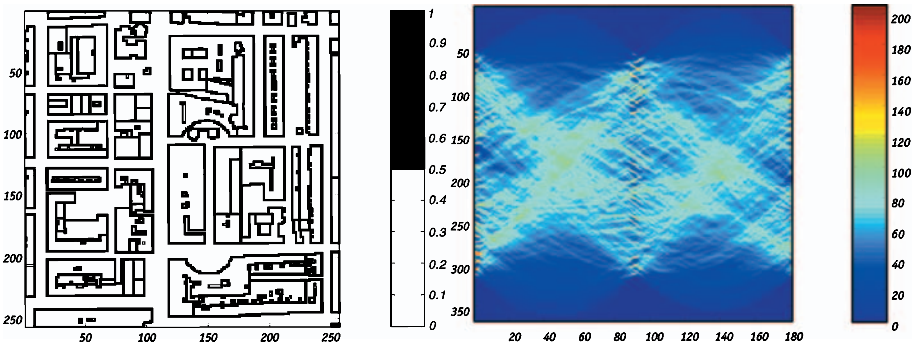

Fig. 10. Edge detection on the London DEM using a 'Sobel' filter (left, black = edge pixels), Hough transform (right, values in pixel counts)

or noisy patterns. This whole sequence of operations is presented in Fig. 10 for the London DEM, after it has been converted to black and white. Peak values can be noted on the x axis at $\theta = 90$ and $\theta = 180$; they correspond to the horizontal and vertical direction of façade alignment.

An extension of the Hough is the so-called *Radon transform*, which does not deal with black and white images but with grey-scale ones. Therefore it counts not only the number of black cells lining up, but adds up the value of all non-zero pixels. In other words, the Radon transform is the projection of the image intensity along a radial line oriented at a specific angle. An easily interpretable form of the Radon transform, which is surprisingly rare in the scientific literature, is

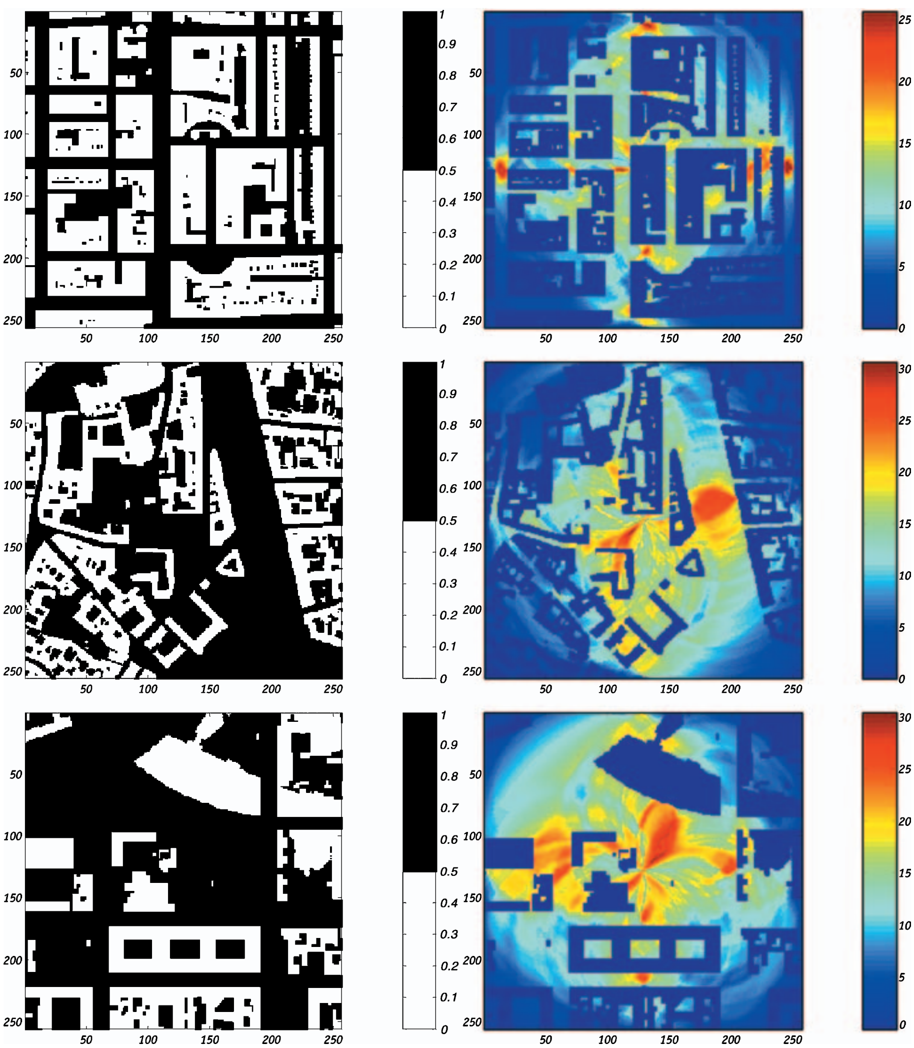

Fig. 11. Black and white images of London, Toulouse, Berlin (left, black = built pixels), Radon transforms (right, values in pixel counts). Note the precise fit of red spots in the street network: they appear in each urban canyon at the point of minimum distance from the centre of the image (as can be understood from the mathematical definition of the Radon transform). Therefore, from the position of these spots it is possible to have an idea of the directionality of the urban texture. For instance the large red spot that appears on the Toulouse Radon transform at an orientation of approximately 15° (in a polar co-ordinate system placed at the centre of the image) is produced by the main boulevard that crosses the city at approximately 105° (=15° + 90°)

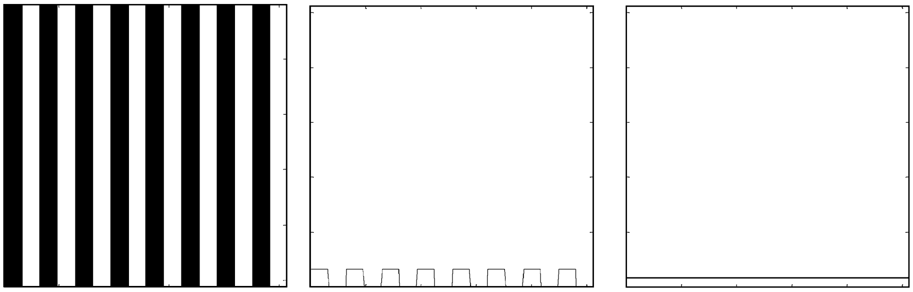

Fig. 12. Explaining the functioning of the variance plot: the average East–West and North–South profile (centre and right) of a simplified zebra texture (left)

the polar one, which was produced here by writing an *ad-hoc* conversion algorithm. All the coefficients of the transform remain the same, although they are now plotted according to a polar co-ordinate system centered in the middle of the image. Results for the case study sites in London, Toulouse and Berlin are presented in Fig. 11. Note how red spots fit exactly into the street network and appear in each canyon at the point of minimum distance from the centre of the image. Therefore, by examining their position, it is possible to gain insight into the directionality of the urban texture. For instance, the large red spot that appears on the Toulouse Radon transform at an orientation of approximately 15° (in a polar co-ordinate system placed at the centre of the image) represents the main boulevard, which crosses the city at approximately 105° (=15°+90°).

The main problem with the Hough and Radon transforms is that they detect the lining up of pixels but not their contiguity (incidentally, this is considered an advantage in image processing, as it means that the transforms are tolerant of gaps and relatively unaffected by noise). A continuous and a broken line would return the same answer, provided that they have the same total length and totalize the same number of entries in the accumulator array. On the DEM this means that for a given direction θ, one long continuous canyon and a number of shorter courtyards that are lined up but separated by other buildings or streets would be indistinguishable on the transforms – while clearly behaving differently in terms of response to wind.

6. The variance plot

Despite their theoretical interest, the Fourier, Hough and Radon transforms of DEMs are not easy to interpret. An alternative approach to study the directionality of a given urban texture, taking inspiration from the flow in porous media, is based on a simplified estimate of the blocking effect of buildings at different angles[2]. It leads to the construction of a polar graph, which we have named *variance plot*.

The principle is best explained with an example. Take for instance the vertical black and white strips of Fig. 12, which can be interpreted as a DEM of regularly spaced rows of buildings – which we will call North/South. Now take a number of equally spaced East/West sections through the texture and calculate their average: the resulting profile is a wavy one, like that shown in Fig. 12. Now repeat the process in the vertical North/South direction; this time the profile is flat. If the procedure is applied to another direction, the resulting profile will be a slightly wavy one, in-between the two described above. In other words the 'waviness' of the profile is a measure of how close to the direction of the main axes of the DEM we are.

More generally, on irregular urban DEMs, if the direction of scan is parallel to the street pattern, the profile will show strong troughs where the streets occur; while if the direction is oblique to the street pattern, a much smoother curve will appear. Hence the introduction of the variance (or square mean value: the sum of the squared differences between the profile and its mean value) as an estimate to quantify the smoothness or waviness of a profile. This is plotted against the azimuth in the polar graphs of Fig. 13 for London, Toulouse and Berlin.

The analysis of the variance plots presented in Fig. 13 underlines some features that can also be detected by sight, such as the prevailing North/South and East/West orientations in central

[2] This approach was first suggested by Dr. Nick Baker at the Martin Centre, University of Cambridge.

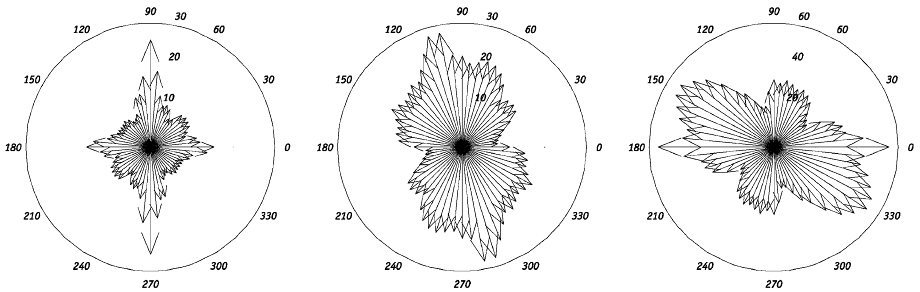

Fig. 13. Polar diagram showing the variance of the average urban profile in different directions; the case study sites in London, Toulouse and Berlin are shown from left to right (values in m)

London. A closer inspection, however, also shows details which are not immediately evident on the DEM and illuminates properties which are not otherwise apparent: for instance, the difference in magnitude between the North/South and East/West axes in London, which is due to the fact that most East/West streets are interrupted by Tottenham Court Road and do not line up across the site.

To discriminate between these many measures of urban directionality and choose the one that best represents the wind response to urban texture would require extensive experimental data arising possibly from field studies but more likely from physical modeling in a wind tunnel or from generic CFD studies. Steemers et al. (1996) report on a significant correlation between the variance plot and model measurements in a wind tunnel, but more work would be needed to fully validate their conjecture.

7. Implications for urban design at the intermediate scale

The primary reason for focusing on the urban intermediate scale – as set forth in the introduction of this paper – was to inform design problems. So far the processing of DEMs seems a good way to analyze cities at that scale; but what could be its relevance to the architect and urban planner?

Let's take for instance the aerodynamic roughness. It is widely accepted that there are two major targets in urban design, when dealing with the modification of the wind environment:

- maximizing the dispersion of pollutants;
- controlling wind speed and turbulence at street level.

For example, the dispersion of pollutants from traffic in urban areas requires a maximum turbulence and vertical transport – and therefore high values of aerodynamic roughness. As a general rule, the roughness increases when buildings are added to a surface. The taller the elements and the greater their number, the higher the roughness – until a certain density beyond which the roughness starts decreasing (this can be explained by the appearance of a skimming flow, which means that the wind does not 'feel' the lower buildings anymore).

In order to increase the roughness, it is therefore good to introduce a number of tall buildings scattered within the urban texture. Oke (1988) and Givoni (1998) suggest this, among others.

The second urban design target, that of controlling wind speed and turbulence at street level, is more delicate than pollution dispersion. An unquestionable threshold concerns the safety of pedestrians. To this end, Bottema (1999) introduces a danger threshold for balancing in gusts. Below this threshold, however, desired wind conditions at street level vary with climate. A breeze is beneficial in hot regions, where it increases heat loss and contributes to the thermal comfort of pedestrians; it is detrimental in cold or mid-latitude climates – like that of London and most northern European cities.

Because of the effect of roughness in creating turbulence, in these climates there are conflicting exigencies: on the one hand the need to enhance street ventilation and pollution dispersion (high roughness values) and on the other the necessity to provide wind shelter (low roughness value, among others). The solution must be a compromise: for certain values of height-to-width both requirements can be satisfied. According to Bottema (1999) this happens when the height-to-width ratio is between 1/2 and 1/10, while Oke (1988) suggests an ideal height-to-width ≈ 0.65. In the presence of tall buildings it is nonetheless necessary to examine at closer

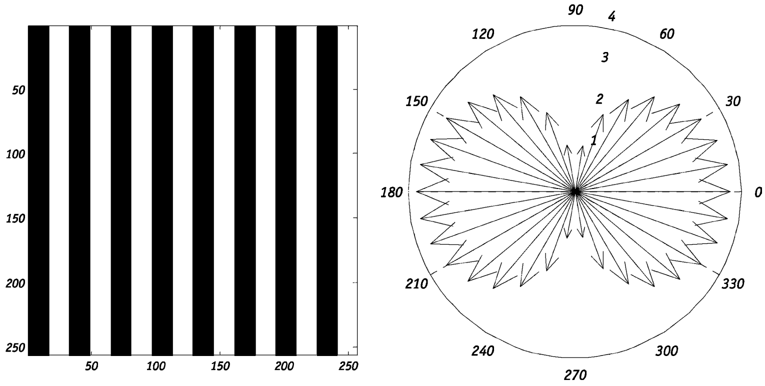

Fig. 14. Roughness rose (right, values in m) of a simplified texture (left, black = built pixels) made of building rows

detail local effects – which in some cases may produce an increase in wind speed up to 300% (Givoni, 1998).

It is now possible to address a simple problem in urban design: given a number of parallel rows of buildings, is it better to have them parallel or orthogonal to the prevailing winds?

Figure 14 shows the roughness length rose for this configuration. The minimum roughness – and therefore minimum pollution dispersion – is found when the axis of the texture is parallel to the wind. Despite its low roughness, it is clear that this configuration also provides poor shelter and should be avoided in colder climates. This is also noted by Bottema (1999): *"A configuration with long buildings aligned with the wind (a 'flow channeling configuration') yields not only little shelter but also poor street ventilation: the flow channeling may yield reduced vertical mixing . . . as well as unexpected lateral transport . . ."*. Against design intuition and common sense, it is therefore best to orientate buildings orthogonal to the prevailing wind.

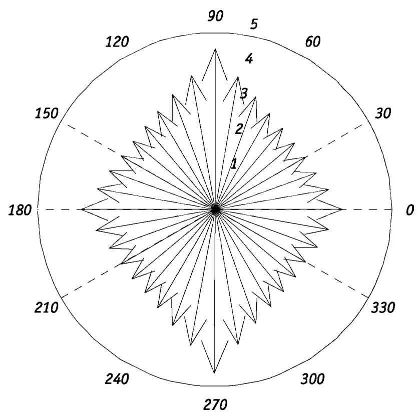

Fig. 15. London case study: polar plot representing $1/z_0$ (values in m^{-1}); note the good accordance with the variance plot of Fig. 13

Finally, something should be said about the relationship between the roughness rose and the variance plot. Maximum variance means channeling the air in the street canyons and having little vertical mixing. It therefore means minimum roughness. Thus, something like an inverse proportionality should hold between the two parameters. This can be seen for instance in Fig. 15, which plots $1/z_0$ in London and is reassuringly similar to the variance plot of Fig. 13.

8. Conclusions

This paper opens with a question: could the analysis of urban DEMs be of any use to characterize urban winds and to estimate input data for pollution dispersion models?

We conclude in the affirmative. Urban DEMs prove very effective in the calculation of parameters that can be used to model winds within and near the urban canopy. For instance, they can be used to calculate the height-to-width distribution of canyons, or to estimate the aerodynamic roughness length which, when interpreted as a local drag coefficient, can be utilized in large scale flow models to provide a momentum boundary condition for determining the wind field. The compact representation of 3D urban geometry using the 2D support of a DEM is extremely versatile at the urban neighborhood scale and allows analyses that would be very difficult or impossible to carry out using traditional vectorial models.

In some instances, image processing techniques can suggest new types of analyses or interpretations that are currently not incorporated in urban climatology. For instance, tools such as the Fourier transform (inspired from traditional image processing) or the variance plot might, if corroborated by experimental evidence, offer new insights in the study of urban winds. It is up to users to assess the new potential offered by the technique and to learn to interrogate the DEM creatively, based on our understanding of the underlying environmental processes.

Some of these algorithms have been applied to different case study DEMs, including portions of central London, Toulose and Berlin and simplified urban texture patterns. Results show considerable variation in wind related parameters with urban morphology. This is evident both between different directions in one city, as shown by the variance plot and the roughness rose, and between one city and another. For instance, the difference in roughness between London and Berlin is more than 300%, suggesting a significant difference in, say, dispersion properties. This evidence, as extracted from the analysis of urban DEMs, could lead to effective design guidelines and have substantial impact on several urban disciplines.

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