Carlo Ratti
Silvana Di Sabatino
Rex Britter

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ANALYSIS OF 3-D URBAN DATABASES WITH RESPECT TO POLLUTION DISPERSION FOR A NUMBER OF EUROPEAN AND AMERICAN CITIES

C. RATTI[1], S. DI SABATINO[2,4]*, R. BRITTER[2], M. BROWN[3], F. CATON[5] and
S. BURIAN[6]
[1] *University of Cambridge, Department of Architecture, Martin Centre for Architectural and Urban Studies, Cambridge, U.K.;* [2] *University of Cambridge, Department of Engineering, Cambridge, U.K.;* [3] *Los Alamos National Laboratory, Energy and Environmental Analysis Group TSA-4, Los Alamos, U.S.A.;* [4] *Cambridge Environmental Research Consultants Ltd, Cambridge, U.K.;*
[5] *Laboratorie d'Energétique et de Mécanique Théorique et Appliquée CNRS UMR 7563, Vandoeuvre Cedex, France;* [6] *University of Arkansas, Department of Civil Engineering, 4190 Bell Engineering Center, Fayetteville, AR, U.S.A.*
(author for correspondence, e-mail: silvana@cerc.co.uk, fax: +44 (0) 1223 357 492)*

Abstract. Dispersion models require as input various geometrical parameters to calculate the flow field and dispersion characteristics in the urban environment. As a result of recent advances in digital photogrammetry and remote sensing, databases of the actual 3-D geometry of city centre areas are now increasingly available. In this work we outline a procedure to reduce this large amount of data to a structured input for urban pollution dispersion models, i.e. to extract the important flow and dispersion parameters from the urban databases. Based on a review of the scientific literature, we have identified a number of parameters relevant to the modelling of pollution dispersion and atmospheric flows in urban areas. These parameters are: the plan and frontal area densities, the plan and frontal area density as a function of height, the distribution of heights, their standard deviation, the aerodynamic roughness length and the sky view factor. These parameters are obtained by analysing urban Digital Elevation Models (DEMs) which are regularly spaced grids of elevation values. Examples of the parameters calculated from high-resolution databases (with pixel size of about 1 m) for three European (London, Toulouse and Berlin) and two North American (Salt Lake City and Los Angeles) cities are presented and discussed. The calculated aerodynamic roughness length was smaller for the European cities than for the North American ones. A multiplicative correction factor κ to the aerodynamic roughness length is proposed to include the effect of the variability of the building heights.

Keywords: aerodynamic parameters, Digital Elevation Models (DEMs), image processing, pollution dispersion, urban morphometry, urban roughness

1. Introduction

In the context of pollutant dispersion modelling the knowledge of the aerodynamic roughness length z_0 is of prime importance. The derivation of this aerodynamic property and others such as the zero-plane displacement height z_d from morphometry is quite recent. Cities are characterised by large values of z_0 and z_d. These

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properties directly influence the surface shear stress, the scales and intensity of turbulence, the depth of the roughness sublayer, the wind speed and the shape of the wind speed profile and the type of flow found within the urban canopy layer. Accurate knowledge of the aerodynamic characteristics of cities is vital to describe, model and forecast the behaviour of urban winds, turbulence and the dispersion of pollutants at all scales.

The calculation of z_0 and z_d, however, is not straightforward. The classical way to estimate them in open flat terrain is based on the measurements of wind speed profiles from a tall mast or, less accurately, on the inference from published aerodynamic roughness values for similar terrain elsewhere (Davenport, 1960; Davenport *et al.*, 2000). Both methods, however, are very difficult to apply to cities, due to the considerable height where wind measurements should be taken (two to three times the height of the average building height) and to the irregularities of urban texture.

A promising alternative that has become available in recent years, due to increased computing resources and the availability of high-resolution 3-D databases for urban areas, is based on the calculation of z_0 and z_d from the analysis and measure of the city geometry (urban morphometry). Grimmond and Oke (1999) discuss this method extensively; they used many available formulas and compared results with field measurements.

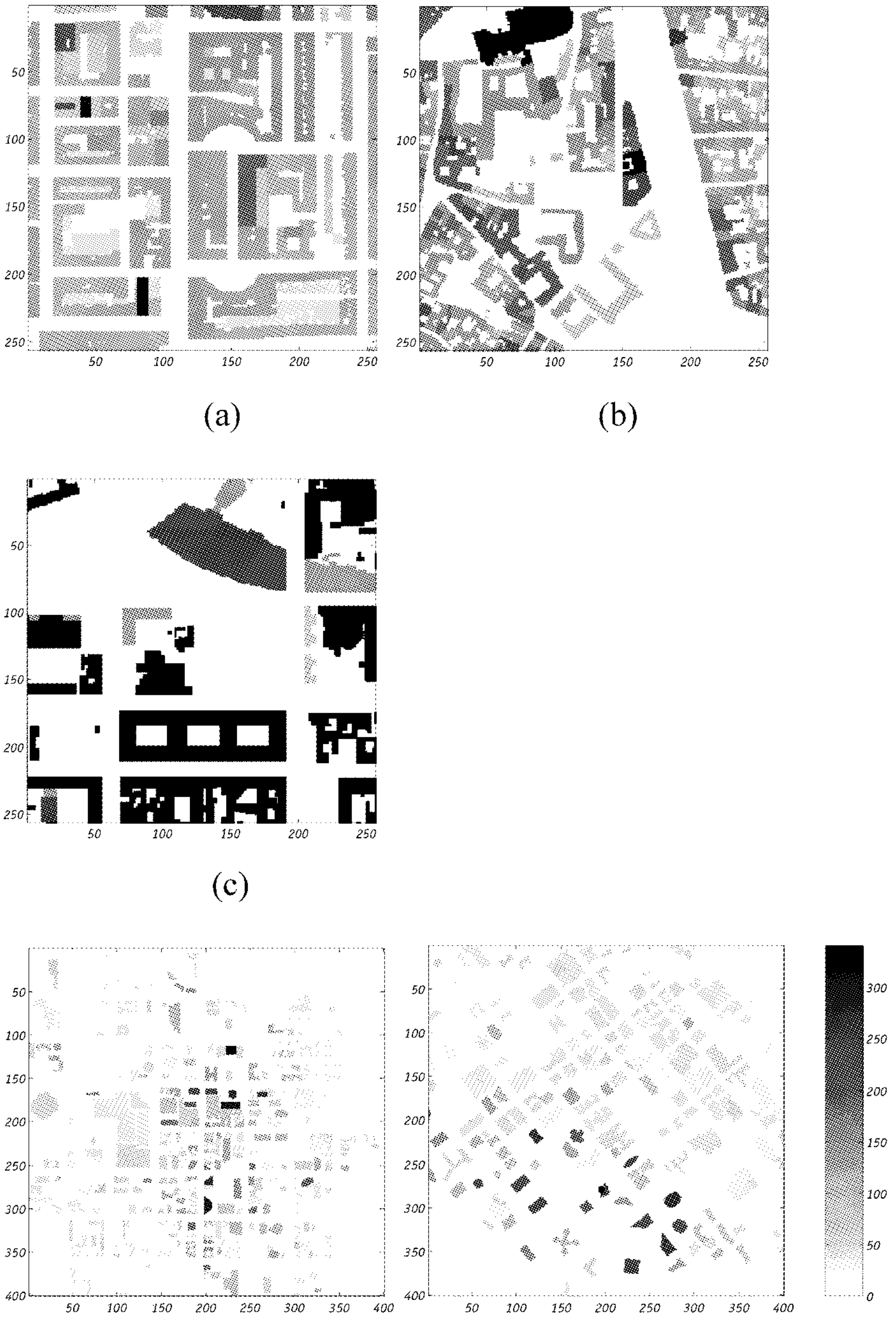
Urban morphometry provides a new range of parameters that can easily be calculated in urban areas and used as input for meso-scale and urban dispersion models. This article reviews a number of them and shows how they could be calculated from urban Digital Elevation Models (DEM) using image-processing techniques. It builds on the recent work by Ratti *et al.* 2000, extending the number of city case studies from London, Toulouse, Berlin to Salt Lake City and Los Angeles (see Figure 1).

2. Methodology and Data Set Description

The DEM is a digital image of a city, where each pixel has a grey-level proportional to the height of the buildings. It contains a full 3-D description of the urban surface on a 2-dimensional support (the image).

High resolution DEMs in urban areas are becoming increasingly available. The cost is still high but it is expected to decrease as the demand on such data is rapidly increasing.

The Los Angeles building data set shown in Figure 1e, for instance, is a commercial product by Aerotopia and contains building footprints and rooftop elevation information. Its resolution is 2 m horizontal and 1 m vertical and is indexed to universal transverse mercator (UTM) coordinates. The London, Berlin, Toulouse and Salt Lake City building data sets were produced in-house using satellite and high resolution aerial photographs (Müller *et al.*, 1999). They have a very high resolution in plan (6 inches/pixel in Salt Lake City), although a lower one in elevation:



(a) (b)

(c)

(d) (e)

Figure 1. In an urban DEM, building height is proportional to the level of grey. The shaded bar refers to the Los Angeles DEM (e), where the maximum height is $h_{\max} = 341$ m. In London (a) $h_{\max} = 40$ m, Toulouse (b) $h_{\max} = 32$ m, Berlin (c) $h_{\max} = 21$ m, Salt Lake City (d) $h_{\max} = 98$ m.

building heights were estimated by counting storeys from photographs and during visits to the city, and therefore have an uncertainty of a storey (~3.5 m).

The Los Angeles and Salt Lake City DEMs, which cover areas of 2 and 3.5 km^2, respectively, encompass the downtown regions with small pockets of adjacent high-density residential, industrial and commercial landuses. The European DEMs which are approximately 0.2 km^2 each, describe only the central urban areas, although they are representative of larger portions of the cities.

Urban DEMs can be analysed with image processing techniques using simple packages like the Matlab Image Processing Toolbox. A review of this method, which has similarities with raster GIS analysis, is contained in Ratti and Richens (1999). The orientation of facades, the amount of solar radiation falling on the city, the Fourier and Radon transforms, the estimate of energy consumption in buildings, the travelling-time in the street network, etc., can be calculated. Other parameters related to flow and pollutant dispersion in the urban environment are reviewed below in detail.

3. Parameters Related to the Urban Flow Field and Pollutant Dispersion

A number of different parameterisation schemes are used in meso-scale models to approximate the effects of the urban canopy on the flow field. At a minimum level, urban landuse information is needed to estimate the aerodynamic roughness length and the surface energy balance. More complex urban canopy parameterisations (e.g., Sorbjan and Uliasz, 1982; Brown and Williams, 1998; Ca *et al.*, 1999) require morphological information cross-correlated with landuse, average building height, plan area density, and building frontal area density. For example, the frontal area density is used in the momentum equations as part of the drag force term. Another important parameter is the sky-view factor, which can be used to determine the long-wave energy flux into and out of the urban canopy.

The following parameters have been calculated on the DEM using image processing techniques:

(1) The built to total area ratio (λ_P) at ground level and also its variation with height.

(2) The average building height ($\overline{H}$), the average of building heights squared ($\overline{H^2}$), the standard deviation of building heights (σ_H) and the average building height (z_H) where each building is weighted with its frontal area:

$$z_H = \frac{\sum \text{Height of the buildings} * \text{Frontal area of the buildings}}{\text{Total lot area}}$$

The parameter z_H is a function of the wind direction.

(3) The aerodynamic roughness length z_0 and the zero-plane displacement height z_d. They can be calculated from the above parameters plus the frontal area density λ_F. We have used the formulas from Macdonald *et al.* (1998) as these performed well in the comparison by Grimmond and Oke (1999):

$$\lambda_F = \frac{\sum \text{Frontal area of the buildings}}{\text{Total lot area}}$$

$$\frac{z_0}{\overline{H}} = \left[1 - \frac{z_d}{\overline{H}}\right] \exp\left[-\left[\frac{0.5\beta c_D \lambda_F}{k^2}\left[1 - \frac{z_d}{\overline{H}}\right]\right]^{-0.5}\right]$$

$$\frac{z_d}{\overline{H}} = 1 + \alpha^{-\lambda_P}(\lambda_P - 1) ,$$

with $\alpha = 4.43$, $\beta = 1.0$, $k = 0.4$, $c_D \approx 1$.
All those parameters (z_0, z_d, λ_F) are functions of the wind direction.

(4) A correction κ to z_0 to account for the height variability of the buildings. Based on our interpretation of results from Hall *et al.* (1996), the z_0 values calculated with the formulas above should be corrected by a factor κ where

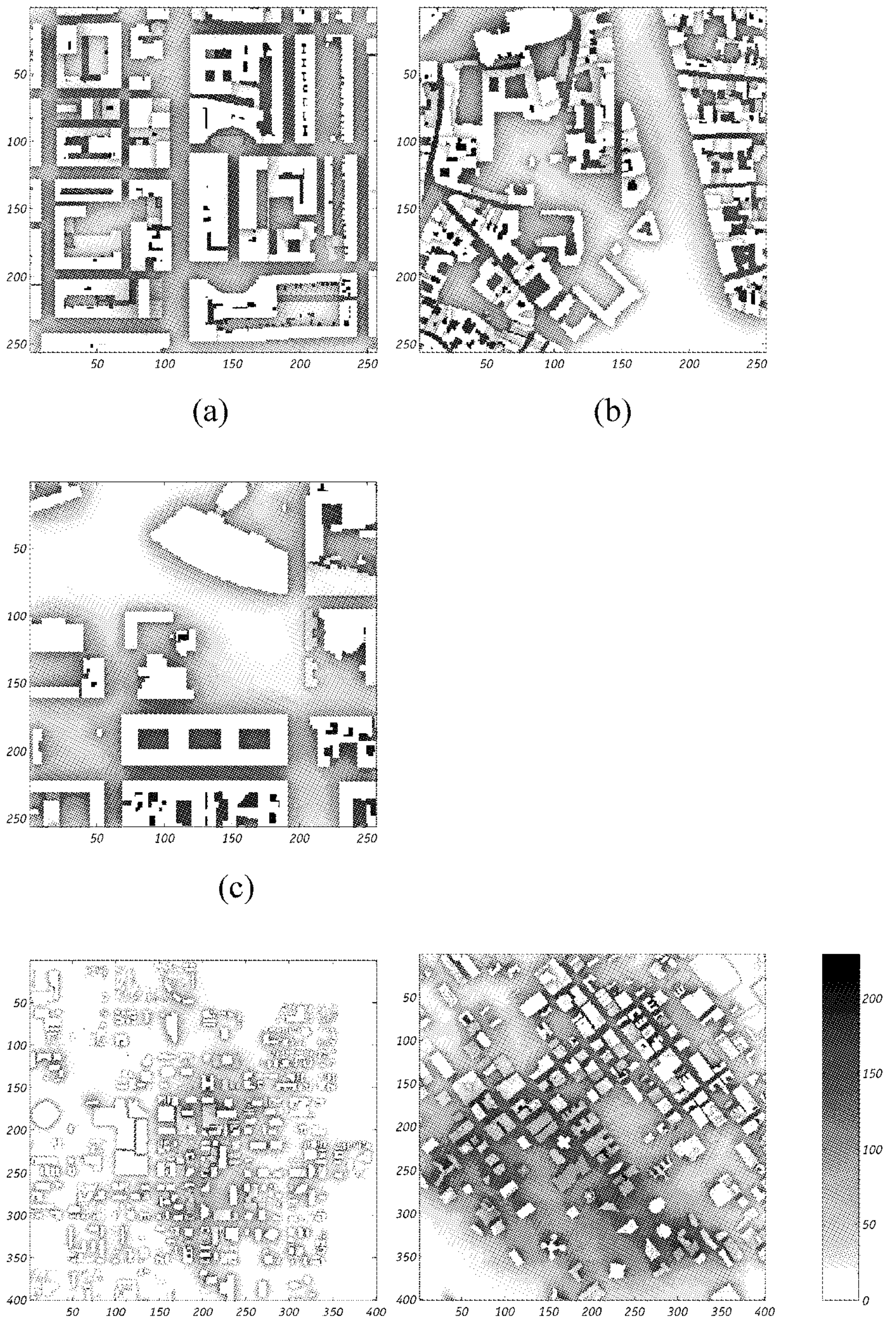
$$\kappa = \left(1 + 4\frac{\sigma_H}{\overline{H}}\right) .$$

(5) The sky view factor from the streets to the sky. This parameter can be calculated on the DEMs as explained in Ratti and Richens (1999). Its average value ψ_{sky} can be used to predict the maximum heat island intensity $\Delta T_{\text{max urban-rural}}$, using a formula by Oke (1981).

4. Results and Discussion

Our results are summarised in Figures 2–4 and in Table I. In the case studies considered here, North American cities show a smaller λ_P (built to non-built area ratio), a greater maximum height and also a larger variability of building heights than with the European cities. This is in agreement with what is qualitatively expected but here we have quantified these factors.

Looking at the calculated values of the aerodynamic roughness length in Table I we see that they are smaller for the European cities than for Salt Lake City and Los Angeles. According to Hanna *et al.* (2001) a value of z_0 around 1 m could be used for screening purposes for most cities. From Table I we see that z_0 has an unusually low value for London and an unusually high value for Los Angeles.



(a) (b)

(c)

(d) (e)

Figure 2. Sky view factors in London (a), Toulouse (b), Berlin (c), Salt Lake City (d) and Los Angeles (e).

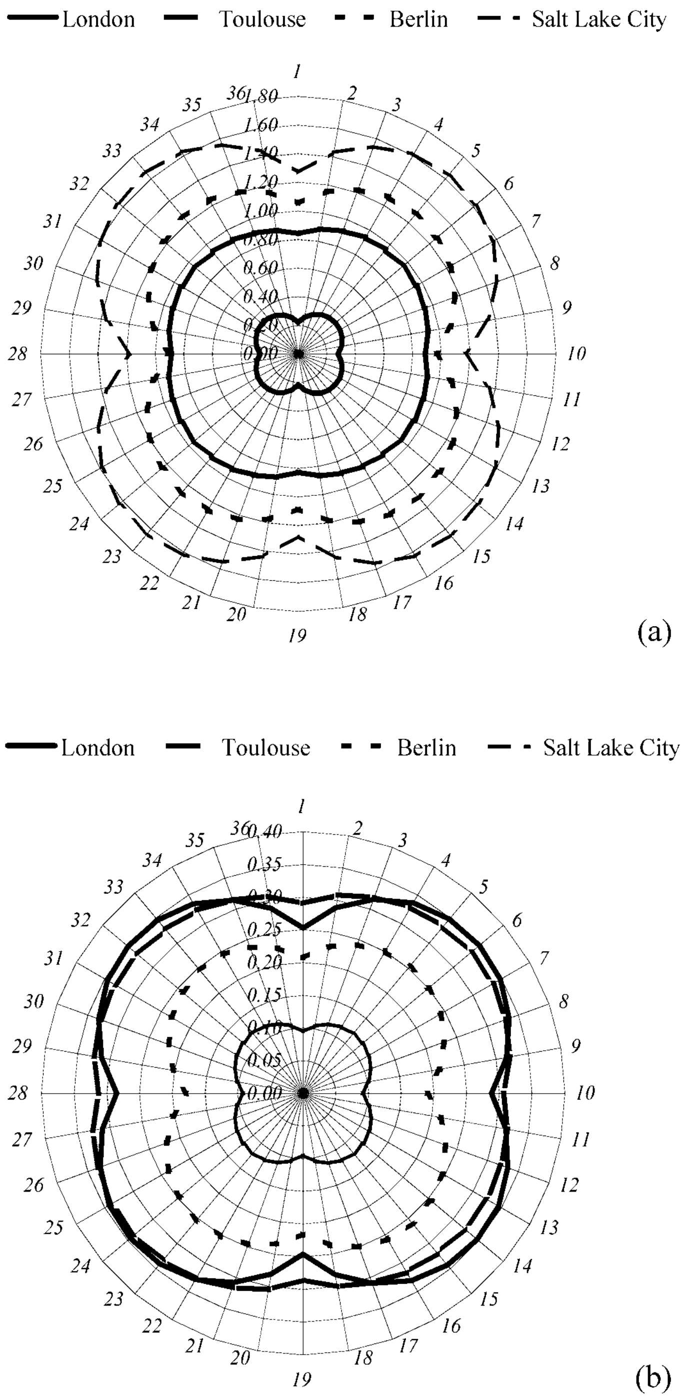


Figure 3. Variation of aerodynamic roughness length z_0 (a) and λ_F (b) with azimuth, respectively (Los Angeles data have been omitted).

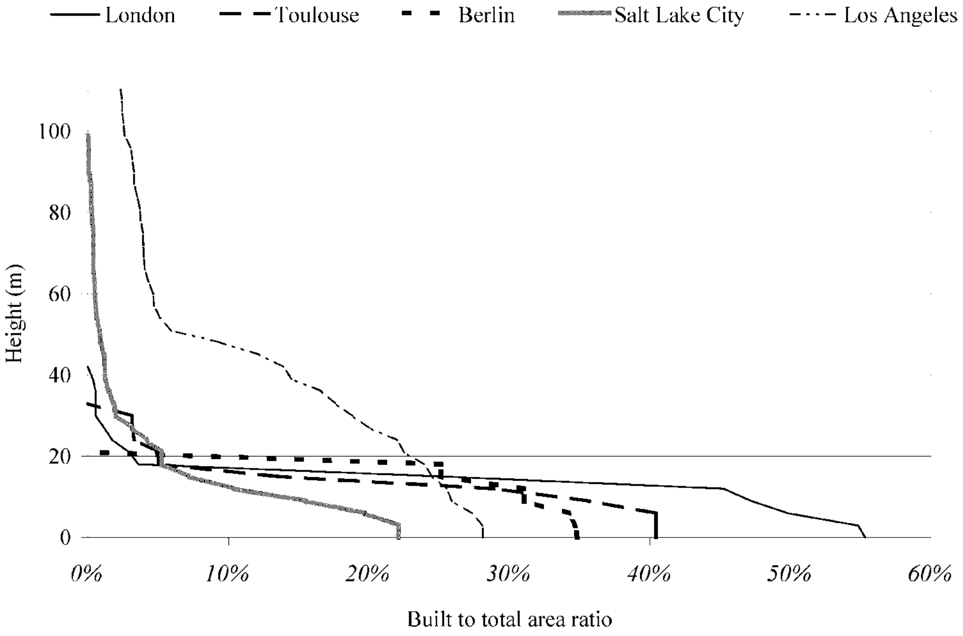


Figure 4. Built to non-built area ratio in percentage (c) at different heights (Los Angeles data have been truncated).

We have calculated the aerodynamic roughness length based on the formulas by Macdonald *et al.* (1998) shown earlier; in addition we have recalculated z_0 using the same formulas but replacing the standard average building height ($\overline{H}$) with z_H, i.e. the average building height weighted with the frontal area of the buildings.

Results in Table I show that z_H and $\overline{H}$ values are similar for the European data sets while they differ greatly for the North American data sets. Thus, the alternative use of z_H was not significant for the European cities; we obtained only a slightly larger z_0 value using z_H than we have obtained using $\overline{H}$. The use of z_H did not seem to be appropriate for Los Angeles; using $\overline{H}$ has still produced an unusually large value of z_0. There must be other factors that account for the unusually small value for London and the unusually large number for Los Angeles.

The small value for London arises because the formulas by Macdonald *et al.* (1998) that we have used imply $z_0 \rightarrow 0$ for $\lambda_P \rightarrow 1$ and London has the largest λ_P of the five cities analysed. The formulas we have used for z_0 do not account for the building height variability that is expected to have a large influence on the aerodynamic roughness length values, particularly for those cases with a large λ_P. Physically we expect cities with a large λ_P to be very sensitive to building height variability.

The height variability has been estimated by comparing the ratio of the standard deviation of building heights to their average height i.e. $\sigma_H/\overline{H}$. From Table I we see that the North American cities have approximately twice the height variability

TABLE I

Calculated parameters for London, Toulouse, Berlin, Salt Lake City and Los Angeles

	London	Toulouse	Berlin	Salt Lake City	Los Angeles
λ_P, built to total area ratio	0.55	0.40	0.35	0.22	0.28
$\overline{H}$, average of building heights (m)	13.6	15.3	18.6	16.3	51.3
$\overline{H^2}$, average of the heights squared (m^2)	211	270	364	464	5289
σ_H, standard deviation of the heights (m)	5.0	6.1	4.3	14.1	51.5
$\sigma_H/\overline{H}$ building height variability	0.37	0.40	0.23	0.87	1.00
σ_H/z_H building height variability	0.34	0.38	0.22	0.54	0.50
$z_H/\overline{H}$ building height ratio	1.09	1.05	1.07	1.60	2.01
z_H, average of the heights weighted with frontal area (also averaged all azimuth) (m)	14.8	16.1	19.9	26.0	103.0
λ_F, frontal area density (average all azimuth)	0.32	0.32	0.23	0.11	0.45
z_d, zero-plane displacement height (average all azimuth) (m)	11.9	10.9	12.1	11.4	54.3
z_0, roughness length (average all azimuth) (m)	0.29	0.89	1.08	0.94	7.2
z_0, calculated using z_H instead of $\overline{H}$, (also averaged all azimuth) (m)	0.30	0.92	1.18	1.50	14.36
κ, roughness length correction factor	2.47	2.59	1.92	4.48	5.02
ψ_{sky}, average view factor from the streets to the sky	0.529	0.646	0.720	0.866	0.602

of the European cities. This large difference between the two sets of data, however, may just be an artefact due to different coverage areas being represented by the sets of data i.e. 2 and 3.5 km^2 for Los Angeles and Salt Lake City against 0.2 km^2 for the European cities. From Table I, we see that $\sigma_H/\overline{H}$ and σ_H/z_H (where z_H is the average building height weighted with the frontal area of the buildings) values are similar for the European cities while they differ greatly for the North American cities. This means that the European data sets represent portions of cities with more homogeneous building shapes than the North American ones, possibly a further reflection of the different coverage areas.

To include the building height variability in the calculation of z_0 a multiplicative correction κ must be used. Our preliminary estimate of κ, based on our interpretation of results by Hall *et al.* (1996) was shown in the previous section. Using this formula we have obtained a correction to z_0 which seems appropriate for the

European data sets; by applying the correction to those cases we obtain values of z_0 around 1 to 2 m. Our use of κ is less satisfactory for Salt Lake City and Los Angeles as the application of the correction to those data sets would lead to very large values for z_0. The formula for κ is not a function of λ_P and we expect a λ_P dependence to be included. The refinement to the formula for κ, to link together the influence of the height variability and the building packing density, is currently under consideration.

In summary, the height variability formula is probably satisfactory for the z_0 values typical of the European cities. It is likely to produce over predictions for the λ_P of the North American cities. Additionally, and probably more importantly, some of the spatial inhomogeneities over the large coverage area of the North American data sets may not actually be contributing to z_0.

Despite the greater height of buildings in North American cities, the average view factor from streets to the sky is comparable with that in Europe, due to the lower built to non-built area ratio λ_P of the North American cities. Further work is currently in progress to determine and compare not only the average values of the view factors and the other urban parameters, but also their spatial variation.

5. Conclusions

Digital Elevation Models (DEMs) contain information on the urban morphometry. They provide data that can be analysed in a structured way to extract useful parameters linked to the structure of the urban canopy and the flow and pollutant dispersion characteristics within and above the urban canopy. Those parameters may be used as inputs for meso-scale and urban pollution dispersion models. In this article we have identified some of relevant parameters for this purpose and outlined a method to extract those from DEMs.

Data sets for three European cities (London, Toulouse and Berlin) and two North American cities (Salt Lake City and Los Angeles) have been analysed.

Our results showed that North American cities have a smaller λ_P, a greater maximum building height and also a larger variability of building heights than the European cities.

The calculated aerodynamic roughness length was smaller for the European cities than for the North American ones. A multiplicative correction factor κ to z_0 has been proposed to include the effect of the variability of the building heights. This correction does not explicitly account for variations in building packing density. The proposed formula is probably satisfactory for the z_0 values typical of the European cities that have, in our case, a large value of λ_P, while some refinement is required for its applicability to cases with smaller λ_P values.

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