Analysis of 3-D Urban Databases with Respect to Pollution Dispersion for a Number of European and American Cities

Ratti, C.(1), Di Sabatino, S.(2,4), Britter, R.(2), Brown, M.(3), Caton, F.(5) and Burian, S.(6)

(1) University of Cambridge, Department of Architecture, Martin Centre for Architectural and Urban Studies, 6 Chaucer Road, Cambridge, CB2 2EB, UK.
(2) University of Cambridge, Department of Engineering, Trumpington Street, Cambridge, CB2 1PZ, UK.
(3) Los Alamos National Laboratory, Energy and Environmental Analysis Group (TSA-4), MS F604, Los Alamos, NM 87545, USA.
(4) Cambridge Environmental Research Consultants, 3 King's Parade, Cambridge, CB2 1SJ, UK.
(5) University of Cambridge, Department of Applied Mathematics and Theoretical Physics, Silver Street, Cambridge CB3 9EW, UK.
(6) University of Arkansas, Department of Civil Engineering, 4190 Bell Engineering Center, Fayetteville, AR 72701, USA.

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

1. Introduction

Models to estimate pollution dispersion and wind flow in cities (both at the city-scale and above) require a parametrical description of the urban canopy. For instance, two key parameters are the aerodynamic roughness length z_0 and the zero-plane displacement height z_d, which are related, amongst others, to the surface drag coefficient, the scale and intensity of turbulence, the depth of the roughness sub-layer and the wind speed profile.

The calculation of z_0 and z_d, however, is not straightforward. The classical way to estimate them in open terrain is based on the measurement of wind profile data from a tall mast or, less accurately, on the inference from published 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 (well above the urban canopy) and to the irregularities of urban texture.

A promising alternative that has become available in recent years, due to increasing computing resources and the availability of high-resolution 3-D databases in urban areas, is based on the calculation of z_0 and z_d from the analysis and measure of the city geometry (urban morphometry). This method is reviewed for instance in Grimmond and Oke (1999), where values are calculated using different formulas and then compared with the results of field measurements.

Urban morphometry opens up 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 paper reviews a number of them and shows how they could be calculated from urban Digital Elevation Models (DEM) using image-processing techniques. It builds up on the recent work by Ratti et al. 2000, extending the number of case studies cities: London, Toulouse, Berlin, Salt Lake City and Los Angeles (cf. 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 at moderate cost. The Los Angeles building dataset shown in Figure 1, 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 datasets 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), although a lower one in elevation: 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 (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 (approximately 0.2 km^2 each) describe just central urban areas, although they are representative of larger portions.

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 dispersion in the urban environment are reviewed below.

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

A number of different parameterisation schemes are used in models at the city-scale and above 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 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 λ_F 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.

Here, 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; 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:

$$z_H = \frac{\sum height\ of\ the\ building * frontal\ area}{\sum frontal\ area}$$

   Note that z_H is a function of orientation.

3) The 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). In particular, we have adopted the formulas by Macdonald et al. (1998):

$$\lambda_F = \frac{\sum frontal\ area\ of\ the\ building}{total\ lot\ area}$$

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

$$\frac{z_d}{z_H} = 1 + \alpha^{-\lambda_P}(\lambda_P - 1)$$

   with $\alpha = 4.43$, $\beta = 1.0$, $k = 0.4$, $c_D \approx 1$. Note that z_0, z_d, λ_F depend on orientation.

4) Based on our interpretation of results from Hall et al. (1996), the z_0 values calculated with the above formulas should be corrected by a factor κ to take into account the variability in height of

the urban surface (the above formulas tend to underestimate z_0 in cities with great height variability):

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

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

4. Results and Discussion

Results are summarised in Figures 2, 3 and in Table 1. In the case-studies considered here, North American cities show a lower λ_P (built to un-built ratio), a greater maximum height and also a wider scattering of building heights than European cities. The scattering, in particular, can be observed by comparing the ratio of the standard deviation of building heights to their average (σ_H / H), which is approximately double in America than in Europe. The lowest value of this ratio is found in Berlin, where most buildings have a similar height ($\sigma_H / H = 0.23$). Differences in the urban vertical structure are also evident by comparing the roughness length, which is greater in American cities. The extremely high value for Los Angeles, however, raises some questions which we are now addressing (limit of applicability of the formulas, weighting of building heights with the frontal area).

Despite the greater height of buildings in American cities, the average view factor from streets to the sky is comparable with that in Europe, due to the lower built to un-built ratio λ_P. Local values, however, can be locally lower in America, (see darker colour in high-density downtown districts in figure 2), in accordance with Oke (1981), who reports values of the maximum urban heat island higher in America than in Europe. 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.

Acknowledgements

Carlo Ratti and Silvana Di Sabatino acknowledge support from the EU-projects Precis and TRAPOS.

References

Brown, M. and Williams, M. (1998) An urban canopy parameterization for mesoscale meteorological models. *2nd AMS Urban Env. Symp*., Albuquerque, NM.

Ca, V., Asaeda, T., and Ashie, Y. (1999) Development of a numerical model for the evaluation of the urban thermal environment. *J. Wind Eng. Ind. Aerodyn*., 81, pp. 181-196.

Davenport, A. (1960) Rationale for determining design wind velocities. *J. Struct. Div. Am. Soc. Civ. Eng.*, 86, pages 39-68.

Davenport, A., Grimmond, C.S.B, Oke, T. and Wieringa, J. (2000). The revised Davenport roughness classification for cities and sheltered country. 3rd *AMS Urban Env. Symp*., Davis, CA.

Grimmond, C.S.B. and Oke, T. (1999) Aerodynamic properties of urban areas derived from analysis of surface form. *J. Appl. Meteorol.*, 38, 1261-1292.

Hall, D.J., Macdonald, R., Walker, S. and Spanton, A.M. (1996) Measurements of dispersion within simulated urban arrays - a small scale wind tunnel study. Building Research Establishment (BRE), BRE Client Report CR 178/96.

Macdonald, R. W., Griffiths, R. F. and Hall, D. J. (1998) An improved method for estimation of surface roughness of obstacle arrays. Atmos. Environm., 32, 1857-1864.

Müller, C., Burian, S. and Brown, M. (1999) Urban database issues. LA-UR-99-5874.

Oke, T. R. (1981) Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observation. J. Climat., Vol. 1, pages 237-254.

Ratti, C. and Richens, P. (1999) Urban texture analysis with image processing techniques. Proc. CAADFutures99, Atlanta, GE.

Ratti, C.F., Di Sabatino, S., Caton, F. and Britter, R.E. (2000) Morphological Parameters for Urban Dispersion Models. 3rd *AMS Urban Env. Symp*., Davis, CA.

Sorbjan, Z. and Uliasz, M. (1982) Some numerical urban boundary-layer studies. *Bound. Layer Meteor*., 22, pp. 481-502.

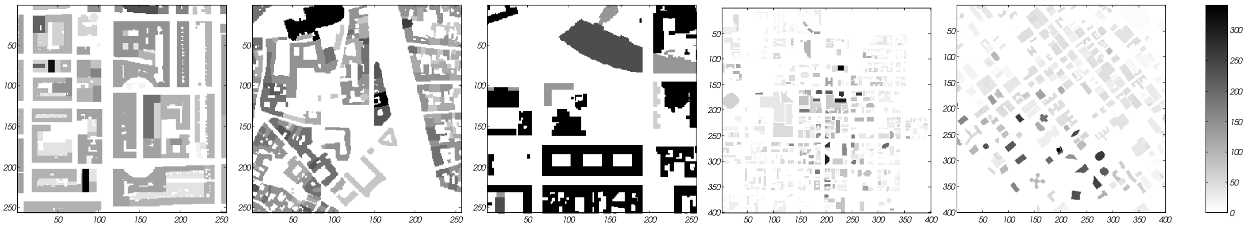

Figure 1 – In an urban DEM building heght is proportional to the level of gray. The colorbar refers to the Los Angeles DEM (far right), where the maximum height is h_{max}=341 m. In London h_{max}=40 m, Toulouse h_{max}=32 m, Berlin h_{max}=21 m, Salt Lake City h_{max}=98 m (from left to right respectively).

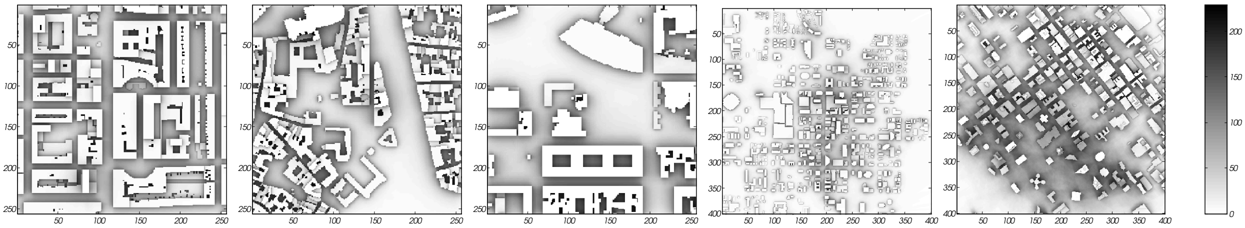

Figure 2 – Sky view factors in London, Toulouse, Berlin, Salt Lake City and Los Angeles.

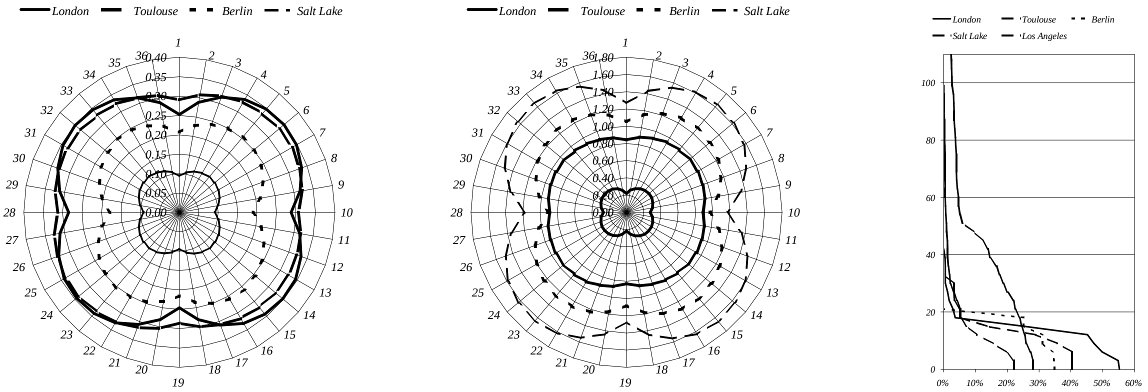

Figure 3 – Left and centre image: variation of λ_F and aerodynamic roughness length with azimuth respectively (Los Angeles data have been omitted). Right image: built to unbuilt ratio (percentage) at different heights (Los Angeles data have been truncated).

Table 1 – Numerical results for London, Toulouse, Berlin, Salt Lake City and Los Angeles.

	London	**Toulouse**	**Berlin**	**Salt Lake**	**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
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*)	0.30	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