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A review of urban roughness sublayer turbulence

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by

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Abstract

It is becoming increasingly important that we can understand and model flow processes in urban areas. Applications such as weather forecasting, air quality and sustainable urban development rely on accurate modelling of the interface between an urban surface and the atmosphere above.

This review gives an overview of current understanding of turbulence generated by an urban surface up to a few building heights, the layer called the roughness sublayer (RSL). High quality datasets are also identified which can be used in the development of suitable parameterisations of the urban RSL. Datasets derived from physical and numerical modelling, and full-scale observations in urban areas now exist across a range of urban-type morphologies (e.g. street canyons, cubes, idealised and realistic building layouts).

Results show that the urban RSL depth falls within 2 – 5 times mean building height and is not easily related to morphology. Systematic perturbations away from uniform layouts (e.g. varying building heights) have a significant impact on RSL structure and depth. Considerable fetch is required to develop an overlying inertial sublayer, where turbulence is more homogeneous, and some authors have suggested that the “patchiness” of urban areas may prevent inertial sublayers from developing at all. Turbulence statistics suggest similarities between vegetation and urban canopies but key differences are emerging. There is no consensus as to suitable scaling variables, e.g. friction velocity above canopy vs. square root of maximum Reynolds stress, mean vs. maximum building height. The review includes a summary of existing modelling practices and highlights research priorities.

1. Introduction and scope of review

It is becoming increasingly important that we can understand and model flow processes in urban areas. Applications such as weather forecasting, air quality, sustainable urban development and urban civil engineering rely on accurate modelling of the interface between an urban surface and the atmosphere above.

This review, commissioned by the Dispersion Group at The Met Office, aims to give an overview of current understanding of turbulence generated by an urban surface up to a few building heights. This layer is called the roughness sublayer and is currently not explicitly modelled in either the Unified Model or the NAME dispersion model. Thus the second aim of the review is to identify high quality datasets which can be used in the development of suitable parameterisations of the urban roughness sublayer for these models.

This review focuses on the dynamical characteristics of the urban roughness sublayer, i.e. flow, and reviews to a lesser extent the consequent scalar transport, i.e. heat, moisture. The review does not consider flow in the inertial sublayer, surface and mixed layer above urban areas. The review by Roth (2000) gives an excellent summary of the better quality studies conducted over the last 30 years, using the results to test the validity of Monin-Obukhov surface layer similarity theory. For general overviews of urban flow and dispersion, see Britter and Hanna (2003) and Belcher (2005). In terms of air pollution, the COST 715 action on Urban Meteorology Applied to Air Pollution Problems produced several worthy reviews with respect to urban surface energy balance, notably: Piringer et al. (2007) on parameterisations of surface energy balance and mixing heights; Seibert et al. (2000) on operational methods for determining mixing height. The review by Arnfield (2003) covers progress in urban climate including heat islands.

This review is organised in the following way: section 2 defines the urban roughness sublayer and urban canopy layers; sections 3.1 to 3.3 present a systematic review of results gleaned from physical modelling, CFD and full-scale measurements; section 3.4 presents existing models of urban roughness sublayer flow; and section 4 presents conclusions about the nature of urban roughness sublayer turbulence.

2. Defining characteristics of the urban roughness sublayer and urban canopy layer

In this section, roughness sublayers are defined in general, and canopy flows are described as an example of well studied roughness sublayer flow. The morphology of urban canopies is described.

2.1 Flow over rough surfaces

As a starting point, the turbulent boundary layer developing over an urban surface can be classified as a rough-wall boundary layer (Raupach et al. 1991). Both smooth- and rough-wall boundary layers have similar structure: an outer region, where the lengthscale is the boundary layer thickness δ, and an inner region, where the nature of the surface dictates the scaling variables. For smooth walls, the viscous lengthscale is used, given by ν/u_* where ν is the kinematic viscosity; u_* is the friction velocity, $u_* = (\tau/\rho)^{\frac{1}{2}}$ where τ is the tangential wall stress and ρ is fluid density. For rough walls, additional lengthscales are required to characterise the roughness elements, such as height H, lateral and longitudinal dimensions (L_X and L_Y) and inter-element spacing (W_X and W_Y) - see section 2.3 for nomenclature. At high Reynolds numbers when Reynolds number similarity is observed, as found for flows over urban surfaces, the viscous lengthscale can be neglected as viscous drag is far less important than form drag around elements in governing momentum transfer to the surface. Additionally, Perry et al. (1969) defined two types of roughness: “k-type”, typically a rough, random surface over which ejections (upward transport of slower moving fluid) dominate in the transfer of momentum; and “d-type”, where stable recirculating wakes form behind the roughness elements, and momentum transfer is dominated by sweeps (downward transport of faster moving fluid).

There is an overlapping layer between the two regions where the mean wind profile is derived through asymptotic matching of the inner and outer layer wind profiles (see Raupach et al. 1991 for derivation) and scales only on a single lengthscale, the height above the surface z. This is called the inertial sublayer (ISL), in which flow is spatially homogeneous and turbulent fluxes vary only weakly with height in the so-called “constant flux layer”. Beneath the inertial sublayer lies the roughness sublayer (RSL). It can be defined as the layer where flow is dynamically influenced by the characteristic lengthscales of the roughness elements and is the rough-wall equivalent of a smooth-wall viscous sublayer (Raupach et al. 1991). Flow is spatially dependent and turbulent diffusion is influenced by the wakes forming behind the roughness elements. When parameterised in terms of roughness element height alone, the RSL depth z_* typically ranges between 2 and 5H, based on idealised physical modelling studies or full scale measurements over vegetation canopies. The depth has been reported to be as much as 10 to 15H in unstable atmospheric conditions (see Table 2 in Roth 2000).

Whilst the roughness sublayer is effectively defined as the layer where surface roughness has its maximum influence on the inner region flow, its influence on outer region flow should be considered. According to Townsend’s hypothesis (1976), at high Reynolds numbers the outer layer flow is not influenced by surface roughness. Castro et al. (2006) recently reviewed evidence supporting and contradicting Townsend’s hypothesis and suggested that the ratio H/δ (the Jensen number, or immersion ratio) should be taken into account when quantifying the relative influence of surface roughness, and that there may be a critical value above which Townsend’s hypothesis might fail. Jimenez (2004) reviewed data for $H/\delta < 0.025$ which supported Townsend’s hypothesis; however there are very few data for larger values and the issue remains unclear, particularly in terms of differing turbulent organised structures. For urban areas, H/δ can be much larger due to the large roughness elements, and as such urban boundary layers may fall into a class of flows over “very rough walls” (Castro et al. 2006). Rotach (1999) also observed that the roughness sublayer over urban surfaces may be so deep that an inertial sublayer cannot develop. Indeed, the criterion for the presence of an ISL has been stated as $z_* < z < 0.25\delta$ (MacDonald et al. 2000). Given that $z_* \sim 2-5H$ and H may be 10s of metres, it is clearly plausible that the RSL may occupy the lowest 10% of the atmospheric boundary layer usually identified as the surface layer.

2.2 Flow above canopies

Vegetation canopies represent a relatively well studied example of roughness sublayer flow for which general characteristics and a theoretical framework have emerged (see reviews of Raupach and Thom, 1981; Finnigan 2000). As such, the canopy theoretical framework has already formed the basis of some models of urban flows (e.g. Coceal and Belcher 2004). The main features of canopy flows are highlighted briefly here (see Finnigan 2000 for formalism):

1) An essential characteristic of the canopy framework is that it incorporates the fact that momentum transfer takes place over a finite depth rather than just at the surface.
2) In the spatially dependent flow of the RSL, spatial averaging of flow is employed. This leads to two extra terms in the equation of motion due to considering Reynolds averaging with respect to both time and spatial averages. One of them, the dispersive stress, is the spatial counterpart of the Reynolds stress, and is defined as the covariance of time-averaged, spatial fluctuations in u and w around the overall time- and spatially-averaged mean. The second term is the drag of the canopy, which arises due to the non-commutativity of differentiation and volume averging in the multiply-connected canopy space (see Finnigan, 2000).
3) The spatially averaged profiles deviate from predictions using Monin-Obukhov surface layer similarity theory.
4) Turbulent transfer within the canopy is more efficient than surface layer turbulence, i.e. dimensionless wind profile scaled using the friction velocity $\phi_m < 1$ in neutral conditions.
5) Large turbulent eddies that scale on canopy depth H control the turbulent dynamics. The instability mechanism responsible for them is due to an inflection point in the windspeed profile near the top of the canopy. Work has shown (Raupach et al. 1996) a similarity to mixing layers in terms of the ensuing flow profiles.
6) Second and third order moments (Reynolds stress, variances, skewness etc.) depend strongly on height.
7) Aerodynamic drag on the foliage provides a short-cut mechanism diverting energy in larger scales of turbulence directly to leaf-scale, bypassing the inertial cascade mechanism. Additionally, dissipation within the canopy is large due to the foliage.
8) The “bluff body” effect occurs: momentum transfer is made more efficient through the additional form drag of the canopy, whereas scalar transfer is still diffusive and has no analagous enhancement. Hence, the ratio of diffusivities differs from unity.

Given the apparent similarity between urban and vegetation canopies, the urban RSL can be further subdivided into an urban canopy layer (UCL) up to mean building height (Rotach 1999). Throughout the review the observational evidence as to whether flow in an urban RSL is similar to a vegetation RSL will be discussed (sections 3.1 to 3.3), and urban canopy models are highlighted in section 3.4. Conclusions as to the suitability of a canopy framework are drawn in section 4.

2.3 The morphology of urban canopies

Whether treating flow over urban surfaces as a rough-wall boundary layer or canopy flow, the morphology of the urban canopy needs to be quantified. The packing density of the buildings is the urban counterpart of the leaf area index (LAI) used in vegetation canopy models, to which drag is related. The literature on flow over urban surfaces mostly considers flow around configurations of buildings which can be defined in terms of their specific morphology. In this review, the following classes of urban morphology are used:

2D:

Street canyon type roughness elements. A canonical street canyon consists of two rows of buildings of uniform height H, lateral dimension L_Y and longitudinal dimension L_X, and separation W_X, (in a co-ordinate system with x aligned with the cross-street direction normal to the front face of roughness elements, y aligned with the long axis of the street, and z vertical). Variants include different heights of buildings, or shape of roof (flat, pitched, etc.). NB: for street canyons with incident flow perpendicular to the long axis, the co-ordinate system is aligned with the flow such that x is the streamwise and y is the spanwise direction.

Bar roughness. Idealised surface consisting of repeated square bars, usually with $H = L_X$, and with L_Y equal to spanwise width of domain. Incident flow direction is normal to front face of the roughness elements.

Cavity. Instead of roughness elements protuding from the surface (which has height datum $z = 0$), a cavity is formed with depth $z = -H$, lateral length = L_Y and longitudinal width = W_X.

3D cuboids:

Cubes. Roughness element dimensions $H = L_X = L_Y$. Lateral and longitudinal separation W_X and W_Y depend on packing density and layout. Layout can be staggered or aligned.

Cuboids. Roughness elements where one or all dimensions H, L_X and L_Y are not equal. As for cubes, layout can be staggered or aligned. Roughness elements may not be identical and may be altered by addition of different roof shapes.

3D complex:

Idealised urban surface. A real urban surface may be idealised in shape of roughness elements but retaining layout, i.e. a building is approximated by a cuboid with average height roof; small scale roughness features (window ledges, chimneys etc) are omitted; trees and other street furniture are omitted.

Modelled urban surface. A real urban area is reproduced as far as model resolution will allow, i.e. including details of building shape, surface roughness, street furniture.

Real urban surface. Experiments are conducted in a real urban environment, including traffic, stability effects.

In addition to these morphological classifications, various morphological parameters can be defined to quantify the packing density of the roughness elements over a given area of the surface.

Plan area density:
The plan area of roughness elements per total lot area. Defined per element i:

$$\lambda_{P_i} = \frac{A_{Pi}}{A_{Ti}} = \frac{L_{Xi}L_{Yi}}{(W_{Xi} + L_{Xi})(W_{Yi} + L_{Yi})} \qquad (1)$$

In practice, λ_P is calculated across an array of n roughness elements such that

$$\lambda_P = \frac{\sum_{i=1}^{n} A_{Pi}}{\sum_{i=1}^{n} A_{Ti}} \qquad (2)$$

If calculated for a square gridbox then the denominator is the area of the gridbox.

Frontal area density:
The frontal area density per element is defined by:

$$\lambda_{F_i} = \frac{A_{Fi}}{A_{Ti}} = \frac{H_i L_{Yi}}{(W_{Xi} + L_{Xi})(W_{Yi} + L_{Yi})} \qquad (3)$$

where A_{Fi} is the cross-sectional area normal to incident flow. Across an array of roughness elements:

$$\lambda_F = \frac{\sum_{i=1}^{n} A_{Fi}}{\sum_{i=1}^{n} A_{Ti}} \qquad (4)$$

Note that λ_F is dependent on incident wind angle, whereas λ_P is not.

Aspect ratio:
This is usually defined for street canyons as the ratio of height to separation distance, H/W_X – throughout the literature, and this report, this is abbreviated to H/W as the separation distance is clearly between two lines of buildings, i.e. orthogonal to the long axis of the street.

Building aspect ratio:
These quantify the shape of the element, defined as the ratio of lateral length to height, L_Y/H, and longitudinal length to height, L_X/H.

Morphological parameters can be assessed for real urban areas by ground-based or aerial surveys. Such data are usually held by local authorities for planning purposes and can be difficult to access for academic purposes. However several authors have published morphological parameters for real urban areas. Ratti et al. (2002, 2006) used a digital elevation model (DEM) to calculate parameters for both European and American cities. The NUDAPT project (National Urban Database and Access Portal Tools) in the US includes compilation of morphological parameters for several US cities (Ching, 2007). In the UK, efforts are being made to relate morphological data to other proxy data, e.g. relating morphological parameters for London to the CEH Landsat surface cover database as part of the LUCID project[1].

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Another topic requiring attention is the definition of total lot area when defining packing densities: given the inhomogeneity of an urban surface, the calculated packing density may not be representative for a fixed gridbox in an area with multiple changes of urban canopy density. Such "surface texture" (Schmid and Bunzli, 1995) causes error in calculation of surface drag due to the non-linear changes in surface stress across roughness changes. One dynamically defined measure of the minimum extent of canopy required for such adjustment to take place is given by the urban canopy lengthscale L_C (Coceal and Belcher 2004). The canopy drag term added to the equations of motion in an urban canopy model (see section 3.4.1) can be expressed in terms of L_C, which is given by $L_C = (H/\lambda_F)(1-\lambda_P)$, assuming a roughness element drag coefficient $C_d \sim 2$. L_C can be interpreted as the half-distance over which flow deceleration or acceleration takes place in adjusting to the canopy. Coceal and Belcher (2004) estimated the distance required for full adjustment to a canopy to be $x \sim 3L_C\ln(K)$, where $K = (U_H/u_*)(H/L_C)$, U_H being the mean windspeed at the height of the canopy in the upstream profile. x is O(100m) for typical urban canopy packing densities. This is distinct from the estimates of fetch required to establish an ISL above the canopy which are at least an order of magnitude larger (Roth 2000; Cheng and Castro 2002b).

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[1] http://www.lucid-project.org.uk

3. Review of results

In the next three sections, results concerning urban roughness sublayers are reviewed according to research method: physical modelling, CFD and full-scale measurements. Section 3.4 then highlights the models of urban RSL flow which have been formulated based on the results.

3.1 Physical modelling

In this section, results are reviewed which use physical modelling techniques. Papers are grouped according to the morphology of the surface (2D or 3D, or 3D complex). A relevant review paper in this area is Kanda (2006b), giving an overview of both flow and surface energy balance experiments conducted using physical modelling. Papers are summarised in Table 1.

3.1.1 Research methods

Physical modelling involves simulation of a flow using wind-tunnel, water channel or other facility where flow can be controlled. It is the counterpart of numerical modelling, and issues such as model scale, domain size, boundary conditions all need to be considered. For urban flows, physical modelling has some advantages over numerical modelling or fullscale measurement:

1) as long as fully rough turbulent flow is achieved the complex turbulent structure of the RSL can be faithfully simulated without recourse to a turbulence closure model. The difficulty then lies in flow measurement – see below – as simultaneous determination of flow at all points in the domain is not possible.
2) complex urban morphology can be simulated in fine detail, i.e. including facades, arbitrary roof shape etc. The effect of trees as roughness elements within urban areas is an under-studied area but one where recent wind-tunnel work (Gromke and Ruck, 2007) has developed methods to model the effect of trees on dispersion.
3) compared to full-scale measurements, there are no limitations in where flow can be measured. Stationary flow conditions can be maintained throughout measurements.

The disadvantages or limitations of physical modelling are that:

1) it can be expensive, and the quality of the results depends on sufficiently meticulous building of the model urban surface. In addition, each wind-tunnel or water channel can have its foibles in terms of inlet flow turbulence levels or pressure gradient along the length. These difficulties can be counterbalanced by good tunnel/channel design.
2) the range of turbulence scales is limited, the largest being determined by the size of the wind-tunnel or water channel.
3) the range of stability achieveable is also limited – convective and stable conditions can be simulated provided strong heating or cooling of the model surface can be achieved without heat losses to the underlying substrate.

A full description of measurement methods is not intended here, except to describe the most common methods. Hot wire anemometry is the most commonly used method to measure turbulent flows, being cheap and having good time response. The disadvantage is that hot wires cannot distinguish all three components of three dimensional flow, leading to errors in regions of high turbulence intensity such as the RSL – pulsed hot wire anemometers can improve on this short-coming. Laser Doppler Anemometry (LDA) or Velocimetry (LDV) is an effective alternative, provided that the model shape allows access of the laser beams without undue reflections. Particle Image Velocimetry (PIV) allows fine resolution of 2D planes through a flow at high time resolution and is well suited to analysis of turbulence structures. It is the most costly and time consuming in set-up.

Finally, the upstream boundary conditions should be mentioned. Boundary layers can be grown over long fetches of a particular rough surface, the limitation being the length of the wind-tunnel. Alternatively, a suitable wind and turbulence profile can be generated upstream of a model (Counihan, 1973) using roughness elements, trip wire, vortex generators, fences or grids. It is becoming apparent that simulations of RSL turbulence can be sensitive to the turbulence scales simulated upstream (Schultz et al. 2005) – careful generation of urban-type boundary layers which approximate fullscale conditions is thus required (Feddersen, 2005).

3.1.2 2D (street canyon, bar roughness)

The street canyon is a well studied configuration in terms of mean concentration patterns from fixed sources, and many studies exist which report such data (e.g. Dabberdt and Hoydysh, 1991; Kastner-Klein et al.1997; Pavegeau and Schatzmann 1999; Pavageau et al., 2001). Here, key papers are highlighted which focus on flow characteristics.

Kastner-Klein et al. (2001) presented analysis of both mean and turbulent aspects of street canyon flow for the classic case with incident wind perpendicular to the street axis. A boundary layer wind profile was generated upstream of a single street canyon ($H/W = 1$; $L_Y/H = 5$ or 10) using vortex generators and roughness elements, such that $H/\delta = 0.24$. In contrast to some studies, the street canyon was open-ended, allowing advection along its length, despite the nominal 2D flow configuration. There were marked differences in vertical windspeed and turbulence profiles for short and long streets, implying that lateral transport due to corner vortices in the short canyon was influencing the flow. Velocity standard deviations peaked at $z \sim 1.2H$, consistent with flow displacement over the street canyon (see Fig.2, Kastner-Klein et al. 2001). Intercomparison with field data (Louka et al. 2000; Rotach 1993) was not particularly good, due in part to the reference windspeed being taken at roof height where shear is large. A cross section of flow across the street canyon width showed a mean recirculation, and reasonably uniform turbulence levels. The addition of traffic modified the flow patterns: two way traffic enhances turbulence levels in the lower half of the canyon; one way traffic produces a lateral flow component and little turbulent enhancement. Kastner-Klein et al. (2004a) presented further experiments with the same basic configuration, but with varying roof shapes. Adding a pitched roof on either side of the canyon shifted the main area of turbulent production downstream and reduced the intensity of the recirculation (see Fig. 3 in Kastner-Klein et al. 2004a).

Rafailidis (1997) specifically considered the influence of roofshape for street canyon flow. Measurements were made at the 21st street canyon in a series of 28 (with flat roofs, H/W=1, 2) to allow for flow to adjust to the new surface from the upstream logarithmic profile. Pitched roofs were added only to 5 buildings upstream and 2 downstream of the test canyon, which caused a new change in roughness and increased the aspect ratio (H/W=1.5, 3). The effect of adding a pitched roof was to cause a peak in shear stress just above the peak of the roof (although longitudinal location is not stated), compared to the flat roof case where there was little variation in shear stress with height (see Fig. 5 in Rafailidis 1997). Longitudinal and vertical turbulence intensity components increased smoothly down to the surface, showing an increase of c.3 to 4 times the flat roof values below $z \sim 2H$. Lateral circulations within the streets were also observed, despite efforts to avoid them, particularly associated with the pitched roofs.

Few papers have considered the adjustment of flow over a series of 2D elements. Brown et al. (2000) conducted wind-tunnel experiments for perpendicular incident flow over a series of six street canyons (H/W=1, L_Y = width of wind-tunnel). A logarithmic wind profile was generated upstream using spires and roughness elements, giving $H/\delta \sim 0.08$, and upstream $z_0 \sim 0.001$m, effectively giving a change from smooth to rough surface. A recirculation was observed on the roof of the first building where the upstream flow impacts and is displaced upward. This was not observed on subsequent buildings. Similarity in the shape of the vertical wind profiles was achieved by the 3rd street downstream of the roughness change. Vertical turbulent kinetic energy (TKE) profiles were similar by the 4th street for $z < H$, but similarity was not achieved by the last (6th) street for $z > H$ (see Fig. 5 in Brown et al. 2000). Such similarity in flow is to be differentiated from the growth of an internal boundary layer above the downstream surface: this study concentrated on the adjustment region, where flow is adjusting to the change in canopy drag (Coceal and Belcher 2004). The Brown study indicates that roughness sublayer flow is dependent on not only on the morphology of local roughness elements but also on distance downstream of a roughness change: however, this adjustment region appears to be relatively short, at least for the mean flow.

Barlow et al. (2004) simulated scalar transfer from a series of street canyons using naphthalene sublimation. Naphthalene represents a passive scalar released from the surfaces of roughness elements. Upstream wind profile was logarithmic, generated using roughness elements and spires, and street canyon aspect ratio was H/W = 0.75. The scalar transfer coefficient (or Stanton number) was defined as $C = \langle F \rangle / (\rho_S U)$, where $\langle F \rangle$ is the spatially averaged flux out of the street, ρ_S is the surface concentration of naphthalene vapour, and U is windspeed at a reference height. In the first canyon the transfer coefficient was significantly higher than the subsequent seven canyons, which were not significantly different. This is consistent with Brown et al (2000)'s observations of enhanced windspeeds and TKE in the first 2-3 street canyons, although additional inflow of scalar-free air into the first street canyon could further enhance scalar transfer. The growth of scalar internal boundary layers over urban-type roughness is as yet unstudied, despite its important role in urban heat island formation.

Cheng and Castro (2002b) studied flow adjustment from a low roughness upstream surface (λ_F = 0.028) to 2D bar roughness (λ_F = 0.11), focusing on internal boundary layer (IBL) development. The key finding of relevance was that an inertial sublayer in adjustment to the downstream surface was observed after a distance of ~ 400H downstream of the roughness change, meaning that IBL growth was faster when compared with previous results (Wieringa 1993). They also implied that inertial sublayers may not exist in urban areas where there are multiple roughness changes.

3.1.3 3D (cubes, cuboids)

Several studies have considered dispersion through arrays of cuboids – whilst the focus was not on RSL processes, some useful information on flow behaviour arose. Davidson et al. (1996) reported wind-tunnel simulations of flow through a limited array of cubes. Wind-tunnel simulations were completed in EPA and Cambridge wind-tunnels, both using six rows of cubes in both square and staggered configurations with λ_F = 0.11. For the EPA wind-tunnel, a boundary layer was generated upstream with normalised roughness length z_0/H = 0.022 and giving $H/\delta \sim 0.15$. The cube array was 19H spanwise and 16H streamwise in dimension – together with the limited boundary layer depth, flow was likely to be adjusting to the obstacle array without an established ISL. Indeed, vertical windspeed profiles measured along the centreline of the array were adjusting with distance. The mean windspeed at H/2 within the array slowed to c. 0.4 (staggered) and 0.45 (aligned) of the upstream value along the centreline: in both cases these windspeeds were measured in the recirculation zone behind cubes and thus are comparable (see Fig.5 in Davidson et al. 1996). Lateral profiles of windspeed at H/2 showed distinct channelling of faster moving air between elements of the aligned array, whereas elements in the staggered array blocked such flow. This may explain the slightly slower windspeeds within the staggered array. These simulations were done in comparison to full-scale measurements, reported in section 3.3.

The difference in bulk roughness parameters between square and staggered arrays was highlighted in MacDonald et al. (1998a), who derived new parameterisations for z_0/H and normalised displacement height d/H. Coefficients used in the parameterisations were derived from fits to data measured by Hall et al. (1996) for aligned and staggered arrays of cubes with 9 values of λ_F from 0.05 to 0.9, measured at $x/H = 22$. z_0/H for the staggered array was approximately twice that of the aligned array, with a peak (~0.14 cf. 0.08) when $0.1 < \lambda_F < 0.2$ (see Fig. 2 in MacDonald et al. 1998a). Such bulk roughness effects can be related to the differences in wake or channelling flow deep within the RSL shown in the Davidson et al (1996) study. It should be noted that the limited fetch (22H) may mean that there was not a developed ISL over the array and thus the roughness parameters may well be in error (Cheng et al. 2007).

MacDonald et al. (2000a) developed a model for the mean wind profile within an urban canopy, and compared predictions with data measured within and above aligned and staggered arrays of cubes (Hall et al 1998; MacDonald et al 1998c). Using the BRE wind-tunnel, a boundary layer was simulated upstream of the arrays, giving $z_0/H = 0.025$ and $H/\delta \sim 0.10$. Vertical wind profiles were measured at a fetch of $x/H \sim 20$ at 5 different lateral locations within the arrays, along a line encompassing wake and channelled parts of the flow. The spatially averaged wind profile was approximated by averaging these measurements. Arrays of five different packing densities were used with $0.05 < \lambda_F < 0.33$. The model identified the wake diffusion height z_w as the height where mean wind profiles deviate from the logarithmic form above the urban canopy, and found that $z_w \sim 2H$. The model is discussed further in section 3.4.

Profiles of both mean flow and turbulence within staggered and aligned arrays of cubes were carried out by MacDonald et al. (2000b) and the flow data are reported in Hanna et al. (2002). A hydraulic flume at the University of Waterloo was used with a power law upstream wind profile (exponent n=0.29), with equivalent $z_0/H \sim 0.05$. Boundary layer depth was unknown. Two densities were simulated, $\lambda_F = 0.16$ and 0.44 and measurements were taken after the 18th row, i.e. $x/H \sim 44$ and 27 respectively. Mean windspeed and turbulence intensity profiles were calculated from five lateral profiles within array, following the method of MacDonald et al. (2000). Turbulence intensities increased with height within the canopy, reaching a maximum at approximately $z \sim 1$ to 1.3H in the observations, with $I_u > I_v > I_w$ throughout. The peak value for I_u was approximately 0.18 for both staggered and aligned arrays with $\lambda_F = 0.44$. However for $\lambda_F = 0.16$, the peak values were higher for the staggered array (see Fig. 4 in Hanna et al. 2002) than the aligned array (see Fig. 6 of the paper). This may be linked to different wake dynamics in the more open array ($\lambda_F = 0.16$), showing difference between the two array configurations.

An excellent series of detailed papers report experiments conducted in the EnFlo and University of Southampton wind-tunnel facilities which focus on the RSL over arrays of cubes. Cheng and Castro (2002a) studied flow structure over several arrays of cubes with $\lambda_F = 0.25$, with different sizes, alignments and heights. The flow was allowed to develop an internal boundary layer over a considerable fetch of the surface roughness, in contrast to earlier studies where boundary layers were simulated upstream of the surface roughness. Turbulent statistics (shear stress, turbulence intensities, spatial correlations) are thoroughly reported in this and subsequent papers. One of the key results was that the dispersive stress was found to be negligible in the RSL – however their results only extended down to z = 1.25H, other authors have found these stresses to be important deep within the canopy. Also, the RSL depth – defined as the lowest height at which shear stress measurements taken over a repeating unit started to converge, indicating horizontal homogeneity - was larger over an array of non-uniform height buildings when compared to uniform height, both having the same packing density and mean height. The top of the inertial sublayer remained the same, therefore they conjectured that inertial sublayers in real urban areas might be "squeezed out" in cases of extreme height variability.

Castro et al. (2006) considered in more detail the turbulent flow over the 20mm cube staggered array case reported in Cheng and Castro (2002a), comparing the results with roughwalls and vegetation canopies. Measurements were made at x/H ~ 150, and H/δ ~ 0.14; at this point z_0/H ~ 0.055 and z_d/H ~ 0.85, consistent with moderately densely packed urban-type roughness. The RSL extended up to 1.8H, and the ISL maximum depth was 2.3H, the ISL being defined as the layer where spatially averaged shear stress varied in the vertical by less than 5%. Reynolds stress $-\overline{u'w'}$ increased with height within the canopy to peak at z ~H, as did the $\overline{v'^2}$ and $\overline{w'^2}$ components. The $\overline{u'^2}$ component peaked at z ~ 1.2H which is similar to Hanna et al. (2002)'s measurements of turbulence intensity components (see Fig. 4 in Castro et al. 2006). Integral lengthscales were deduced from two-point correlation measurements; all three components increased with height, L_u increasing most strongly above the canopy to a peak of ~3H at the top of the RSL. The other components were smaller (L_w ~ H, L_v ~ 0.6H). In contrast to vegetation canopies, it is interesting to note that L_w was larger than L_v. All three components were larger than values obtained over vegetation canopies and it was found that the convection velocity (defined as $U_C = L_X / T_X$, where T_X is the integral timescale determined from single point data) was larger than the mean velocity in the RSL (see Fig. 6 in Castro et al. 2006). A TKE budget was calculated for two profiles above the canopy – it was found that whilst production and dissipation terms are of similar size, the turbulent transport term is an increasingly significant sink of energy from z ~ 3.75H downwards, being c. 30% of the production term at z ~ 1.5H. Analysis of the Reynolds stress invariants showed greater isotropy than for 2D surfaces.

Reynolds et al. (in press) used PIV to measure flow over the same 10mm staggered cube array as Cheng and Castro (2002a) but in the University of Southampton wind-tunnel. Measurements were made at a similar location (x/H = 390) at which H/δ = 0.074, which is a slightly deeper IBL. Beyond intercomparisons of PIV derived flow with previous LDA and hot wire measurements, the paper presents highly resolved planes of two-point correlations and derived integral lengthscales for u and w components. The key result is that turbulence near z = H exhibited "two-scale" behaviour: the two-point correlation function for the streamwise component $R_{uu}(\Delta x)$ decayed firstly at a rate consistent with L_u/H = 0.8, then at a slower rate consistent with L_u/H = 3.0 – this indicates that smaller scale turbulence generated in the shear layer at the top of the roughness elements is also important alongside the larger scales. This is to be compared with the Castro et al. (2006) results which were not of sufficient resolution to identify the $L_u/H = 0.8$ scale.

Two other papers concentrate on other bulk aspects of the flow over cubes. Reynolds et al. (2007) analysed lateral profiles of the flow for the same 10mm staggered cube arrays (Cheng and Castro 2002a; Reynolds et al. in press) simulated in two wind-tunnels. For both wind-tunnels, spanwise variations of ± 5 % in mean windspeed and ± 10 % in turbulent quantities were found, associated with paired streamwise vortices. The spanwise wavelength of these regular variations was found to be an integer multiple of the repeating roughness unit initially, but then was modulated by the depth of the growing boundary layer. They observed that beyond fetches sufficient to give at least $H/\delta \sim 0.1$, the amplitude of the spanwise variations were small or undetectable. Cheng et al. (2007) extended the work of Cheng and Castro (2002a) in measuring RSL depths over two densities ($\lambda_F = 0.25$ and 0.0625, H = 20mm, staggered and aligned arrays): they found RSL depth to be relatively invariant (c. 1.8H). The exception was the sparse, aligned canopy ($\lambda_F = 0.0625$) for which they could not define a horizontally homogeneous ISL and therefore concluded that the RSL extended up to $z \sim 4H$. This was likely to be due to the spatial inhomogeneity of the flow between elements. The paper also considered in depth the derivation of roughness parameters from the logarithmic wind profile using values of friction velocity derived from different measurements (pressure tappings and floating drag balance), raising some issues about the validity of data presented in MacDonald et al. (2000a).

A final study over cubes was completed by Schultz et al. (2005; 2007) at the University of Hamburg. An aligned array of cubes with $\lambda_F = 0.25$ was used, and profiles were measured after row 43 (i.e. $x/H = 85$). Schultz et al. (2005) examined the sensitivity of IBL development to upstream wind profile, and found that IBL growth is much faster given a more turbulent upstream profile. This is to be compared with the Castro and Cheng (2002b) results, where slower IBL growth was reported for an upstream profile that was free of turbulence. Schultz et al. (2007) considered the effect of changing roof shape on RSL depth, placing pitched roofs of alternating orientation on every second row of cubes. The key result is that a shear stress peak was observed at the height of the largest roughness elements $z = H_{max}$, rather than at mean building height $z = H$ (see Fig. 4 in Schultz et al. 2007). Subsequent profiles averaged from 4 profiles taken within the array showed better collapse when scaled using H_{max}. Hence, taller roughness elements can dominate the stress profile, which is consistent with the results of Cheng and Castro (2002a) and key LES results discussed in section 3.2 (Xie et al. 2008).

3.1.4 3D (complex)

In terms of wind-tunnel studies simulating flow over modelled urban surfaces, three studies stand out as focusing on flow properties within the RSL.

Kastner-Klein and Rotach (2004b) presented a wind-tunnel study at the University of Karlsruhe of the centre of Nantes, France in support of the Nantes '99 field campaign. The model scale was 1:200 and a logarithmic profile was generated upstream. Using LDA, 23 profiles were measured across the model which represented c. 400m diameter area at full-scale which had an average value of $\lambda_P \sim 0.45$. Profiles could be separated out into intersection- and street canyon-type flows, the former demonstrating higher mean windspeeds and TKE within the canopy. Shear stress maxima were observed at $z \sim 1.2H$ (see Fig. 5 in Kastner-Klein and

Rotach 2004b). On the basis of these observations, a parameterisation was developed which is based on the height and magnitude of the shear stress peak. A shear stress displacement height d_s was introduced to take into account the regions of the lower canopy where negligible momentum transfer takes place. The details of the model are discussed in section 3.4.

Wind-tunnel simulations supporting the BUBBLE campaign (Rotach et al. 2005) in the centre of Basel are reported in the excellent PhD thesis of Feddersen (2005). The aim of this campaign was to study RSL flow processes and thus it is of key importance here. Simulations were done using the Wotan wind-tunnel at the University of Hamburg. Upstream of the model, spires and roughness elements were used to generate a turbulent boundary layer corresponding to fullscale measurements using a RASS for the predominant north-westerly flow direction. The model (1:300 scale) was of 2.4 x 1.2 km of central Basel, centred on the central street canyon where intensive fullscale flow measurements were made (Sperrstrasse, reported in Christen 2005). The mean height of buildings was 14.6m within 17H of the Sperrstrasse site, with $\lambda_F = 0.37$ and $\lambda_P = 0.54$. A grid of either 96 or 180 measurements was taken over an area representing 24 x 14 H at five different heights between 1.8H and 4.7H. Such a dense network of measurements allowed spatial averages to be constructed and spatial variations of the RSL to be studied. Additionally, 10 vertical profiles located in street canyon locations were measured, to contrast with the Sperrstrasse site. The RSL depth was determined to satisfy two criteria across all 10 vertical profiles: a) the lowest height with the minimum scatter in stress values across all profiles, and b) the height above which shear stress was near constant (although no quantitative definition of "near constant" is given). RSL depth was thus determined as 3.3H (see Figure 6.4 in Feddersen 2005), the spread determined from the 10 profiles being 3.3H ± 0.6H. It should be noted that non-uniform building heights might explain the relatively large RSL depth, consistent with the findings of Cheng and Castro (2002a). It was found that ejections dominated over sweeps in the ISL, which is consistent with the study of Castro et al. (2006). This was linked to Townsend's (1976) suggestion that ejections predominate for d-type roughness behaviour (e.g. surface such as bar roughness) rather than k-type (e.g. surface such as random roughness). The turbulent transport term in the TKE budget was evaluated and increased down towards the canopy top, reaching c. 0.3 of the production term at $z \sim 1.7H$, which is similar to the Castro et al. (2006) study over cubes. As well as lateral variations in RSL properties, lateral variations in ISL mean flow and turbulence were identified, suggesting 100m scale inhomogeneity in the flow due to the underlying roughness. This variability is consistent with the fullscale flux observations of Schmid et al. (1991) over suburban Vancouver.

Klein et al. (2007) presented wind-tunnel measurements simulating extremely complex canopy flow due to intersections and tall buildings. One half of the measurements consisted of idealised intersection configurations, using flat roof buildings and a street aspect ratio of $H/W = 1$. The relatively straightforward channelling patterns along the streets were modified near the intersection by corner vortices. The addition of a tall building near the intersection produced additional lateral flows at street level. The second half of the paper reported measurements from a scale model (1:300) of the area in central Oklahoma City where the Joint Urban 2003 experiment took place (see overview by Allwine et al., 2004). The Park Avenue site can be considered a "complex street canyon" with large differences in building height on either side, and a nominal aspect ratio of $H/W \sim 2.6$. Agreement between field and wind-tunnel data was fair, differences arising from instationarity in the complex lateral flow recorded at fullscale: small shifts in wind direction caused large changes in street level flow pattern. The street canyon model of Dobre et al. (2005) was tested. Given that the model approximates street canyon flow by a simple helical vortex driven by rooftop flow, even the fair agreement between field data and model predictions was surprising. Whilst general conclusions cannot be drawn from such a site-specific study, the impact of tall buildings and intersections on mean flow patterns within urban canopies clearly needs further study.

3.2 Computational Fluid Dynamics (CFD)

3.2.1 Research methods

The use of CFD to simulate urban-type flows at building-resolving scales is relatively recent, with the vast majority of papers reviewed here being published after the year 2000. However, it is a rapidly developing field with an increasing number of new studies each year. There are three main numerical approaches – Reynolds Averaged Navier-Stokes (RANS), Large-Eddy Simulations (LES) and Direct Numerical Simulations (DNS) – which have their advantages and disadvantages. Most of the studies to date have been on simple, and usually regular geometry, such as street canyons and regular arrays of cubes. Very few have looked at flow over complex/random geometries. Even with simple geometries only a small sample of morphological parameter space has been investigated so far. It is still not clear what are the important geometrical parameters for characterising urban morphology, besides simple generic measures such as H/W, λ_P and λ_F. For example, the effects of building shape have not been properly characterised using CFD. It is now known that the layout of buildings (e.g. whether they are aligned or staggered) can make a large difference to the flow pattern and statistics, but there have been no systematic studies/attempts to identify the relevant controlling parameters. Similar remarks apply to the effects of variable building height, which have only recently started to be documented. Another limitation in the currently published literature is that most papers have only considered a flow direction perpendicular to the buildings, although new studies are now beginning to look at a range of wind directions. The papers are summarised in Table 2.

3.2.2 2D (cavities, canyons, bars)

RANS studies

Two noteworthy studies employing the RANS method over 2D geometry are those by Kim and Baik (1999) and Lien, Yee & Cheng (2004).

Like most authors using RANS, Kim and Baik (1999) employed a k-ε closure. Their simulation domain included 2 buildings, and a number of cases were studied with building and cavity aspect ratio of H/W = 0.4, 0.5, 1, 1.5, 2, 2.5, 3, 3.5. The width of the buildings and canyon were kept constant while the heights were varied. The main conclusion was that the flow field is mainly characterised by the number and intensity of vortices in the canyon, with the number of vortices increasing with the aspect ratio of the canyon (see Fig 3. of Kim and Baik 1999). The vertical velocity approaches zero at the roof level of the canyon. TKE is higher near the downwind building than near the upwind building because of stronger wind shears. Shear production and dissipation are high at the roof level. There is a critical value of the ambient wind speed above which the number and pattern of vortices remain the same (see Fig 9 of the paper). A limitation of this study is that it was not well validated against experimental data, with only a comparison of mean ascending and descending vertical velocities (2 numbers) for H/W = 1.2 with wind-tunnel results of Hoydysh and Dabberdt (1988) being given.

Lien at al. (2004) assessed the performance of four different k-ε models (standard, Kato-Launder, RNG and non-linear) using standard values for the closure constants without any adjustment. Their numerical domain included 7 buildings, with a building and cavity aspect ratio of H/W=1. The simulations were compared with wind-tunnel measurements of Brown et al. (2000). There was good agreement of mean velocity profiles and many qualitative features of the mean flow, but TKE was under-predicted, especially within the cavity. The simulations were able to reproduce qualitative features such as flow speed-up over the first building top, a thin separation layer near the surface of the first rooftop, mean vortex in the street canyon, the strong thin shear layer at the building height and a recirculation zone behind the last building.

Also of relevance are papers by Kovar-Panskus et al. (2002) and Santiago & Martin (2005). Kovar-Panskus et al. (2002) simulated a single cavity with different aspect ratios of H/W= 0.5, 1, 1.4, 2, 3.3 with no leading edge to represent 'buildings' as such. They undertook detailed comparison with their own wind-tunnel measurements, obtaining very good agreement above the cavity, but less so within the cavity. Their main findings were that the skimming flow regime occurred for all cases considered (both in the simulations and in the wind-tunnel), with a large vortex within the canyon. For H/W ≥1.4, a weaker secondary vortex appeared beneath the main vortex. Santiago & Martin (2005) extended earlier studies by introducing asymmetry induced by a tall building in a sequence of five 2D canyons, although their study was limited by lack of validation and limited resolution. Like Kim and Baik (1999) they found multi-vortex patterns in canyons of high aspect ratio, but noted that the presence of a taller building affects the flow considerably.

More recent studies have demonstrated the limitations of RANS for simulating urban flows, especially within the canopy region where TKE and mean velocities were underpredicted and drag profiles had exaggerated peaks near the canopy top (Xie & Castro, 2006). Recognizing these problems with the RANS method, coupled with the fact that it is inherently incapable of capturing the flow unsteadiness, researchers are now increasingly turning to LES.

LES studies

The most noteworthy work on LES of 2D canyons falls into three sets: Walton et al. (2002) Part I & Walton and Cheng (2002) Part II, Liu & co-workers (Liu & Barth, 2002; Liu et al., 2004; Li et al., 2007) and Cui et al. (2004). Also of interest is the paper of Cui et al. (2003) in the engineering literature.

Walton et al. (2002) and Walton and Cheng (2002) used a dynamic SGS model and wall functions with CFX code to perform LES over the following configurations: (I) Single cavity (roof garden) with H/W = 0.63 and periodic boundary conditions in the horizontal. (II) Building and cavity H/W = 1.2 and periodic boundary conditions to simulate an infinite sequence of 2D canyons. They showed good agreement between mean velocity, turbulence intensities and Reynolds stress profiles and measurements on the roof garden. For both cases, they also demonstrated that the LES performed better than the k-ε model. The latter predicted a weaker vortex and under-predicted turbulence intensities compared to the LES. For case (II), the vortex within the cavity was unsteady, with its centre precessing in the same sense as the mean flow and the vortex meandering along the length of the canyon. TKE peaked at the top of the upwind face of the downstream building. The LES predicted noticeably higher TKE in the vortex core compared to the RANS, and this led to better mixing and a more uniform distribution of pollutants, consistent with measurements (see Fig 11 in Walton and Cheng 2002). The turbulent flow produced intermittent rather than smooth removal of pollutants from the canyon.

Liu and Barth (2002) simulated perpendicular flow in one cavity with H/W = 1 in a domain with streamwise periodic boundary conditions to simulate an infinite sequence of street canyons, taking both L and W to be equal to H (see Fig 4 in the paper, their B equivalent to W here). They demonstrated good agreement of predicted mean velocity, turbulence intensities and Reynolds stress profiles with wind-tunnel measurements. Good spatial resolution of the flow field allowed the authors to study scalar transport in the street canyon. Liu et al. (2004) extended this study to canyons of aspect ratio H/W = 0.5, 1 and 2. They found similar flow patterns for canyons of aspect ratio 0.5 and 1, namely a primary recirculation in the canyon centre and secondary recirculations in the ground-level corners. For the canyon of higher aspect ratio, H/W=2, there were two primary recirculations above each other and two ground level secondary recirculations. Li et al. (2007) extended these studies to even higher canyon aspect ratio of up to 3, obtaining reasonable agreement of mean velocities and fluctuations with water channel experiments for H/W = 1, 2. They found that three vertically-aligned primary recirculations were formed in the canyon with aspect ratio 3, their strength decreasing with decreasing height. The magnitude of the mean velocities near the ground was only 0.5% of the free stream velocity. There were local maxima of turbulence intensities at the interface between the free surface layer and the upper primary recirculation, and the interface between the upper and middle primary recirculations.

Cui et al. (2004) employed the RAMS code to perform LES over one cavity with aspect ratio H/W = 1, applying periodic boundary conditions to simulate an infinite sequence of infinitely long canyons. Comparison of u, w, TKE, skewness and kurtosis with wind-tunnel data of Brown et al. (2000) gave good agreement of u, w, TKE and reasonable agreement of skewness and kurtosis. The main flow feature predicted by the LES was a slightly asymmetric primary eddy within the canyon. The mean vertical velocity was high and downward along the downstream wall and low and upward along the upstream wall. TKE was high on the downstream wall and low on the upstream wall. Quadrant analysis below the rooftop at the canyon centre revealed that a few sweep events dominated the momentum transfer, although there was a greater frequency of weaker ejection events. This is opposite to what occurs in boundary layers, but similar to what is observed in the roughness sublayer over vegetation canopies (e.g. Finnigan, 2000). Analysis of the spatio-temporal variations of u', w' and $u'w'$ using flow visualization and wavelet analysis revealed that their variations are highly intermittent and are associated with multi-scale events. The smallest period of the eddies containing high TKE was attributed to Kelvin-Helmholtz instabilities.

Cui et al. (2003) is an LES study in the engineering literature which is principally concerned with the flows connected to so-called d-type and k-type behaviour, their turbulence structure, the interaction between the roughness layer and the outer flow and the relation between the flow and the so-called roughness function (see definition in next section) associated with the velocity profile averaged in space and time. They simulated channel flow over 3, 6 or 10 square bars depending on separation, and three different canyon aspect ratios of H/W = 0.11, 0.25, 1, corresponding to k-type roughness, intermediate between k- and d-type, and a d-type roughness respectively. Good comparison of mean velocity and turbulence intensities was demonstrated with two experimental datasets for boundary layers. The authors characterized the structure of the time-averaged flow with the following observations. For d-type roughness, with H/W = 1, the cavity is filled by a relatively weak eddy that does not interact with the flow outside the cavity. For k-type roughness, corresponding to H/W < 0.25, the main eddy in the canyon is about 4 bar heights long, and there are several smaller eddies. There is strong interaction between the flow in the canyon and the outer flow for this type of roughness, in contrast to the d-type roughness. The authors also concluded that the bar roughness elements impose their own characteristic lengthscales (bar height and cavity length) on flow structures in the roughness sublayer.

DNS studies

Published DNS work on 2D geometry are all from the engineering literature, but the data and some of the findings are relevant to urban studies. The most noteworthy are a series of papers by P. Orlandi and collaborators, of which two are reviewed here (Leonardi et al., 2003; Burattini et al., 2008). Also of relevance are the papers by Nagano et al. (2004) and Ikeda and Durbin (2007).

Leonardi et al. (2003) performed a series of direct numerical simulations of channel flow with square bars on one wall and periodic boundary conditions in both horizontal directions. A wide range of canyon aspect ratios were investigated, with H/W = 0.053, 0.1, 0.11, 0.125, 0.14, 0.18, 0.25, 0.33, 0.48, 1, 1.67, 3, in a domain of size 40H x 10H x 5H. Detailed validation was not shown, but there was reasonable agreement of inferred *roughness function* with three different experiments. The roughness function ΔU^+ is the shift in the mean velocity profile due to roughness, relative to that over a smooth wall:

$$U^+ = \kappa^{-1} \ln y^+ + C - \Delta U^+ \qquad (5)$$

where C and κ are constants and + denotes normalization by $U_\tau \equiv (\tau/\rho)^{1/2}$ or υ/U_τ. The wall shear stress τ is equal to the sum of viscous drag and form drag.

The authors found that for H/W ≤ 0.14, the bars were isolated since the strength and size of the main recirculation zone no longer depended on H/W. The minimum viscous drag and maximum form drag occurred for H/W = 0.14, when the reattachment on the bottom surface occured immediately upstream of the next bar. For H/W ≥ 0.5, the viscous drag on the crest of the bars comprises most of the total drag, whereas for 0.053 < H/W < 0.2 the form drag was responsible for almost all of the total drag. A recent paper by Burattini et al. (2008) performed a DNS as well as wind-tunnel measurements over the square bars at one particular canyon aspect ratio of H/W = 0.33. Extensive comparison between the DNS and the experimental data was made, yielding generally good agreement of mean velocities, turbulence intensities, skewness, kurtosis, TKE budget terms and spectra. The turbulent energy production was found to be always positive, and the production and dissipation were dominant and approximately in balance in a wide region near the roughness.

Nagano et al. (2004) also performed a DNS of channel flow with bars on one wall and periodic boundary conditions in both horizontal directions. Additionally, they considered cases with different building aspect ratios L_X/H of 0.25, 0.5, 1 and canyon aspect ratios of H/W = 0.08, 0.16, 0.33, 0.05, 1. Although the science in the paper focused mainly on passive heat transfer, a lot of flow statistics were also reported on the mean velocity, Reynolds stress, turbulence intensities, and TKE budgets.

Recently, Ikeda and Durbin (2007) have reported a DNS of channel flow over 4 square bars in a domain of size 40H x 20H x 17H and H/W = 0.11, with periodic boundary conditions in the horizontal. They achieved reasonable agreement between mean velocity and Reynolds stresses and the experimental data of Hanjalic & Launder (1972). The paper presented a number of statistics including mean velocity profiles, turbulence intensities, momentum and TKE budgets and examined the structure of the vorticity field. Confirming the result of Leonardi et al (2003), the authors found that form drag dominated over viscous drag on the rough surface. Compared to smooth walls, the 2D roughness was found to disrupt vortical streaks in the streamwise and wall normal directions, as well as inducing irregular spanwise vortex shedding (see Figs 13 & 14 of the paper). The 2D roughness thus produced three-dimensional unorganised vortical motions that reduced near-wall anisotropy and led to high energy production.

3.2.3 3D (cubes, cuboids)

RANS studies

Building upon their previous work on 2D geometry (Lien et al., 2004), Lien & Yee (2004) performed a high-resolution RANS simulation using two variants of the k-ε model, the standard and Kato-Launder models. The geometry consisted of 7 rows of 11 cubes in an aligned layout and with $\lambda_p = 0.25$ which represented the ‘skimming flow’ regime. The simulation predictions were compared with the wind-tunnel data of Brown et al. (2001): profiles of u, w were generally in good agreement with the data, but TKE was consistently under-predicted, by up to a factor of two. Exploiting the good spatial resolution and good agreement of the mean velocities, the authors explicitly computed dispersive stresses (which arise from the spatial heterogeneity of the mean flow) within and above the building array. Above the array their results confirmed those of Cheng & Castro (2002a), that the dispersive stresses were insignificant. However, they found that within the array the magnitude of the dispersive stresses was comparable to that of the spatially averaged Reynolds stresses. The consequence for modelling is that the dispersive stresses need to be accounted for, and some form of parameterisation of these stresses is needed. In parts II & III of the paper, the authors present a spatially-averaged model which will be reviewed in section 3.4.

A similar study was published by Santiago et al. (2007) and Martilli and Santiago (2007) using the FLUENT model with a standard k-ε closure. The wind-tunnel configuration of Brown et al. (2001) was again modelled, this time using 7 cubes in an aligned layout with lateral symmetry conditions and with $\lambda_p = 0.25$ as in Lien & Yee (2004). Good agreement of mean streamwise velocity was obtained with the wind-tunnel measurements. The mean vertical velocity was underestimated inside the canyons and overestimated above. TKE was underestimated inside the canyons and overestimated above. The authors noted a more complex three-dimensional flow pattern compared to that over 2D geometry. Downward motion at the upwind-facing wall was found to be stronger than upward motion at the downwind-facing wall, and generated divergent horizontal flow close to the ground. The centre of the canyon vortex was found to be displaced to 0.75H and towards the downwind building wall, in contrast to 2D cases with H/W=1 (same streamwise separation of buildings as here), where it is located close to the centre of the canyon (Sini et al., 1996; Brown et al., 2001; Santiago & Martin, 2005). Martilli & Santiago (2007) analysed in detail the spatially averaged properties of the flow and obtained similar results to Lien & Yee (2004) regarding the importance of the dispersive stress within the building array. They also proposed a modified drag coefficient, based on the total velocity (including fluctuating components), which is potentially more robust than the usual definition based only on mean velocities. This will be reviewed in section 3.4.

Hamlyn & Britter (2005) used the FLUENT code with a RANS 2nd order Reynolds Stress Model closure to model the experiments of Macdonald et al (2000) and LES of Hanna et al. (2002). The domain they used consisted of two columns (and 10 or 20 rows) of aligned half-cubes (with W=H/2) with lateral symmetry conditions and with three different values of λ_p = 0.0625, 0.16, 0.44. The columns of half-cubes were arranged so that each column protruded from one of the boundaries with lateral symmetry conditions imposed – in effect representing a repeating unit in an infinite array of cubes. They found reasonable agreement of mean and rms velocity with the experimental data of Macdonald et al. (2000b). The mean flow behind the cubes was found to be dominated by large vortical flow patterns, whose form depended strongly on the packing density. The authors suggested that the form of these vortical patterns could influence the effectiveness of the upward mixing within the building array.

The paper of Kim & Baik (2004) provides an interesting variation in that it is one of very few papers to consider oblique winds. They used an RNG k-ε model, with a configuration of 16 cubes in an aligned layout and with λ_p = 0.25, similar to the studies of Lien & Yee (2004) and Santiago et al (2007). Several wind directions were considered, from 0° to 45° every 5°. The case with perpendicular flow ($\theta = 0°$) was validated against the wind-tunnel data of Brown et al. (2001), and in common with many RANS studies, reasonable agreement was obtained for the mean flow pattern, u and w, and with the TKE being under-predicted. The authors noted three different general flow patterns in the street canyons. For perpendicular wind direction ($\theta = 0°$), the flow is symmetric about the centre of the canyon. A symmetric so-called ‘portal vortex’ exists behind the upwind building with its ends near the lower edges of the downwind building. For wind direction $5° \le \theta \le 20°$, the portal vortex is slightly tilted and asymmetric, with one footprint located near the street centre and the other near one edge of the upwind building (see Fig 4 in the paper). For $25° \le \theta \le 45°$, the footprints of the portal vortex are located behind the end and side walls of the upwind building.

Milliez and Carissimo (2008) performed simulations incorporating real meteorological conditions observed during a near full-scale experiment conducted in Utah’s West Desert area, known as the Mock Urban Setting Test (MUST). They used the Mercure_Saturne code to perform RANS with a k-ε closure. The setting involved 12 rows of 10 equal-sized cuboids (aspect ratio L_X:L_Y:H ~ 1:5:1) in aligned layout. Different combinations of wind speed and wind direction were simulated, corresponding to observed cases. The comparison with the MUST field data yielded generally good agreement for mean velocity and TKE. This study was more focused on pollutant dispersion.

LES studies

Hanna et al. (2002) was one of the earliest LES studies over groups of 3D buildings, designed to simulate the water flume experiment of Macdonald et al. (2000b). The LES employed a finite element code (FEFLO) with unstructured tetrahedral grids. Four simulations were performed on regular arrays (8 rows) of cubes in both aligned and staggered layouts with λ_p = 0.16 and 0.44, representing a sparse and dense urban configuration. Comparison of mean and rms velocity profiles with the data was marginally good, with discrepancies of up to about

40%. General flow features were well captured, including the strong wind shear and maximum turbulence at the canopy top. Mean wind speeds within the denser array were two to three times lower than in the sparser array. In the square arrays, there were higher velocities in the longitudinally oriented ‘street canyons’ between cubes, since the flow was relatively unimpeded compared to the obstructed arrangement in the case of staggered arrays.

Another early study was performed by Stoesser et al. (2003) in the engineering literature, using the finite volume code LESOCC. Two simulations were performed: (i) Small channel depth – one cube of side h in a domain of size 4h x 4h x 3.4h using periodic boundary conditions to simulate an aligned array with $\lambda_p = 0.0625$. (ii) Large channel depth – a staggered array of 32 cubes in a domain of size 15h x 7.5h x 13h and $\lambda_p = 0.25$. Comparison with experiment yielded good agreement of profiles of mean streamwise velocity and turbulence intensity.

Kanda et al. (2004) and Kanda (2006a) performed a comprehensive series of large-eddy simulations at a wide range of packing densities over aligned and staggered arrays of cubes using their code LES-CITY. Kanda (2006a) also considered height variations of the buildings. However, the resolution used in the LES was somewhat low, with 10 gridpoints per cube in each direction. Kanda et al. (2004) presented limited comparisons with lab measurements of Uehara et al (2000) of total stress and streamwise and vertical turbulence intensities, showing reasonable agreement. The domain included a variable number of cubes in an aligned layout (up to 72 cubes) and variable domain sizes (up to 18h x 6h x 14h) with periodic boundary conditions in the horizontal. The packing densities investigated were $\lambda_p = 0.11$, 0.15, 0.20, 0.25, 0.30, 0.33, 0.35, 0.44. Kanda (2006a) extended this to staggered as well as aligned cubes and including height variations, for λ_p ranging from 0.03 to 0.44. Statistics were spatially averaged and a study of turbulent organized structures was undertaken using flow visualization and quadrant analysis. In common with other studies (e.g. Lien & Yee, 2004), the dispersive stresses were found to be large within the building arrays and small above. Although flow regimes commonly characterized as isolated, wake interference and skimming flow were identified in the mean, the intermittency of the canyon flow was found to be quite large at all packing densities, and the flow patterns were never persistent. Turbulent organized structures were identified by flow visualization, consisting of elongated low speed streaks and shorter streamwise vortices. These were similar to those observed in surface layer flows, rather than to the mixing-layer type eddies that exist over vegetation canopies (Finnigan 2000). Kanda (2006a) compared results for aligned and staggered arrays by interpreting them in terms of d-type and k-type roughness respectively (see section 2.1 for definitions). He found that the drag coefficients for staggered arrays were sensitive to building area density, whereas those for aligned arrays were not (see Fig 3 of the paper). At the canopy top ejections dominated the momentum transfer for staggered arrays whereas sweeps dominated for aligned arrays. The ratio of ejections to sweeps was sensitive to the packing density for staggered arrays but insensitive for aligned arrays. Height variations of the buildings drastically increased the drag coefficient and modified the organized structures.

Xie & Castro (2006) undertook a detailed numerical study of flow over two different geometries – a regular staggered array of four cubes, and a staggered array of 16 cuboids of different heights (see Fig 1 of the paper) – using both high resolution LES, and RANS with two different closures (standard k-ε and RSM). The plan area density λ_p and frontal area density λ_f were both 0.25 in both cases, and periodic boundary conditions were applied in the horizontal directions. Detailed comparison with wind-tunnel data of Cheng & Castro (2002a) and Castro et al. (2006) and the DNS of Coceal et al. (2006) were presented. There was generally good agreement of profiles of mean velocity, turbulence intensities, pressure drag, mean flow patterns and spectra. The results showed that the Reynolds number dependency of urban-type flows is very weak, mainly because form drag dominates and turbulence production is at scales comparable to the building scales. Hence, the authors concluded that LES is able to simulate such flows at high Reynolds numbers with grids that would be far too coarse for corresponding smooth-wall flows. RANS simulations, on the other hand, were found to be inadequate, especially within the building canopy.

Xie et al. (in press) examined in detail the flow statistics over a staggered array of cuboids of random heights similar to that in Cheng & Castro (2002a) and Xie & Castro (2006). They used the FLUENT code with a hexahedral mesh and STAR-CD code with a polyhedral mesh. The simulation domain consisted of four 'repeating units' of 16 cuboids of different heights in a regular staggered arrangement, with periodic boundary conditions in the horizontal (see Fig. 1 from Xie and Castro 2006). There was generally good agreement of mean and rms velocities with the wind-tunnel data of Cheng and Castro (2002a). A number of statistics were computed, including spatially-averaged mean velocity, TKE, Reynolds stresses and dispersive stresses and were compared with the authors' previous studies for a regular arrays of staggered cubes at the same packing density using LES (Xie & Castro, 2006) and DNS (Coceal et al., 2006). The flow within the building canopy was found to be significantly more complex than in the case with uniform building heights. Spatially averaged statistics and spatial deviations from these averages were quite similar for the regular and random arrays below the mean building height (see Fig 12 of the paper), but detailed flow features were quite different. The tallest building was shown to exert a disproportionate amount of drag (far in excess of its frontal area fraction) as well as a large fraction of the TKE above the mean building height (see Fig 9 & 10 of the paper).

Finally, two recent conference papers are worthy of brief mention. Claus et al. (2008) present a preliminary LES study of two simulations with wind at an oblique angle: (i) Regular array of 16 staggered cubes with periodic boundary conditions and λp = 0.25 for 0° and 45° (ii) Irregular geometry: scale model of the DAPPLE site in London for wind directions of 51° and 90°. There is no experimental or DNS data to validate against yet, but it is part of ongoing work that will include in-house wind-tunnel experiments. Kono et al. (2008) presented an LES study using a dynamic SGS over aligned and staggered arrays of cubes with periodic boundary conditions and a range of packing densities λ_p = 0.05, 0.11, 0.16, 0.20, 0.25, 0.33. They obtained good agreement of profiles of mean velocity, shear stress and pressure drag with the wind-tunnel data of Cheng & Castro (2002a) for the case with λ_p = 0.25. In addition to a number of spatially averaged statistics, they computed profiles of sectional drag coefficient and effective mixing length profiles for both aligned and staggered arrays at all packing densities – very useful information for canopy-type models. They found that both the drag coefficient and effective mixing length were insensitive to packing density for the aligned array, but depended significantly on the packing density for staggered arrays in the range investigated (see Figs 12 & 13 of the paper).

DNS studies

Few published DNS studies over 3D urban-like geometries currently exist. Coceal et al. (2006, 2007a, 2007b, 2007c) published a series of papers in which they simulated the flow over the aligned and staggered arrays studied in the wind-tunnel by Cheng & Castro (2002a). Due to the large amount of wind-tunnel data available, the DNS was well validated. In Coceal et al. (2006), regular arrays of cubes (aligned, square and staggered) with λ_p = 0.25 and domain sizes of 4H x 4H x 4H, 4H x 4H x 6H and 8H x 8H x 4H were simulated. Periodic boundary conditions in the horizontal and free slip at the top were imposed in all simulations. Good agreement of profiles of drag, mean velocity, Reynolds and dispersive stresses and sectional drag coefficient against wind-tunnel data of Cheng & Castro (2002a) was achieved. A number of important findings were made. Flow visualization revealed fine features of the flow with vortical structures both within and above the building arrays. It was noted that the unsteadiness of the flow was very significant and that the instantaneous flow departs significantly from the long-time mean flow. The mean flow patterns around the cubes in the staggered array were very different and more three-dimensional than in the aligned and square arrays. A number of spatially-averaged statistics and related quantities were computed, including mean velocities, TKE, Reynolds and dispersive stresses, pressure drag and drag coefficient. The flow within the canopy was shown to be highly heterogeneous both spatially and temporally, with turbulent fluctuations dominating over the mean flow at the bottom of the urban canopy, putting into question the significance of mean flow patterns in the lower urban canopy. The statistics for the square and aligned arrays were very similar, but large differences existed with the staggered array – for example the sectional drag coefficient was an order of magnitude higher in the staggered case (see Fig 20 of the paper). An effective mixing length computed from the DNS revealed large variation within the building canopy, with a minimum at the canopy top and a maximum at half the building height, the maximum value being about 18 times the minimum value. This highlighted a major difference from dense vegetation canopies, in which the mixing length is roughly constant within the canopy, and was consistent with the view of the shear layer at the building top acting as a blocking layer in the relatively close-packed array. Coceal et al. (2007b) further documented the spatial structure of the time-averaged flow and its spatial variability within both aligned and staggered arrays.

Coceal et al. (2007a) focused on the staggered geometry, performing further simulations on a larger domain with a total of 48 cubes in a domain of size 16H x 12H x 8H. Further comparisons with the wind-tunnel data of Cheng & Castro (2002a) and Castro et al. (2006) were undertaken, and good agreement of mean velocity profiles, pressure drag, turbulence intensities, spectra and two-point correlations was demonstrated. The paper performed a detailed study of the turbulent structure of the flow using a number of statistical methods including spectral analysis, quadrant analysis, 2-point correlations and conditional averaging, as well as flow visualization, demonstrating a remarkable similarity of the flow structure above the urban-type roughness to that over smooth walls. Coceal et al. (2007c) complemented this study with a conceptual model of the unsteady flow both above and within the building canopy (see Fig 10 of the paper), supported by further analysis and flow visualization within the building canopy.

Recently, Orlandi and Leonardi (2008) have published a paper in the engineering literature that includes a DNS over cubical obstacles. A variety of 3D obstacles were considered, including regular arrays of staggered and aligned cubes. Published statistics included velocity and stress profiles. The main aim of the paper was to find a new parameterization that includes a simple expression for the roughness function and the root mean square of the normal velocity fluctuation at the top of the roughness.

Very recently, Leonardi and Castro (2008) have reported in a conference paper preliminary results from a series of DNS over staggered arrays of cubes at a range of packing densities λ_p = 0.04, 0.11, 0.13, 0.16, 0.2 and 0.25. They use periodic boundary conditions in the horizontal and free slip at the domain top, with a domain height of 8H and containing 12 cubes. Good agreement was shown of the mean velocity profile against the wind-tunnel data of Cheng and

Castro (2002a) and DNS of Coceal et al. (2006). They showed that the form drag prevailed over the frictional drag, with the latter being negligible for all but the sparsest array. The friction velocity and roughness function were shown to be maximal for $\lambda_p = 0.11$.

3.2.4 3D (complex, random)

Very few credible numerical studies currently exist on flow over complex geometry that attempt to represent realistic urban configurations.

RANS studies

Neophytou and Britter (2005) reported in a conference paper a RANS simulation with the FLUENT code using a Reynolds Stress Model to simulate a 1:200 scale model of a 250m-radius area of central London (studied during the DAPPLE campaign) with 42 buildings, and $\lambda_P \sim 0.5$, $\lambda_F \sim 0.25$. No validation of the simulations was presented, hence it is not known how well it captures the real flow. A finite-volume approach with a high resolution unstructured, tetrahedral mesh was employed, with a typical cell edge size of 0.03H and a total of nearly 4 million grid cells. An inflow condition with an inlet logarithmic wind profile, and a pressure outlet condition was applied. The authors employed flow visualization using massless particles in the mean flow and velocity contours to infer the following qualitative conclusions. Large vortical structures were seen to dominate the mean flow, and their size varied depending on the building obstacle area from one part of the domain to another (see Figs 3 & 4 of the paper). The authors believed that these large vortical structures play an important role in air exchanges between the in-canopy and above-canopy flows, as well as in cross-canopy exchanges. The vortex patterns appeared to originate from the canyons behind buildings, and were different from the archetypal 2-D canyon vortices.

LES studies

As a first step towards representing the effect of building randomness in large-eddy simulations, Xie & Castro (2006) and Xie et al (2008) considered a staggered array of 16 cuboids with random variations in their building heights, as already discussed above.

As presented at recent meetings, Xie & Castro have recently performed an LES of a scale model representation of the DAPPLE area as in Neophytou and Britter (2005) and obtained very good agreement with wind-tunnel data. This work is not published yet, but is briefly mentioned in Claus et al. (2008).

3.3 Full-scale measurements

In this section, results from measurements in full-scale urban areas are reviewed, and are summarised in Table 3. Papers are grouped according to the morphology of the surface, as in previous sections. Roth (2000) presents an extensive review of measurements in the inertial sublayer, comparing the results to Monin-Obukhov similarity theory for the surface layer: here, focus is made on literature reporting RSL measurements only.

3.3.1 Research methods

Investigations are made through "field" campaigns of varying duration with mostly mast-based instrumentation. The advantages of full-scale measurement in investigations of RSL turbulence are:

1) All the scales of turbulence are present, up to boundary layer scale convective motions, across the full range of stabilities. The limitations of an inappropriate numerical turbulence scheme or insufficiently high wind-tunnel flow rate are avoided. Relative to the turbulence scales, spatial resolution of measurements can be high, e.g. in the roof region where large gradients can exist. "Real world" influences such as traffic can be observed.
2) Scalar transfer processes in particular are not constrained by insufficiently high Reynolds number when compared to physical or numerical modelling.

The disadvantages of full-scale measurements are clear:

1) Observations are often very difficult and expensive to set up and enact, and location of measurements is highly constrained by urban infrastructure and permissions from authorities. Long-term measurement campaigns are challenging.
2) The spatial coverage of measurements is low, being generally confined to individual masts of limited vertical extent. In particular, the inertial sublayer can be hard to observe given that it may well lie above the vertical extent of the mast.
3) The real urban atmosphere is often not in a stationary state – given the intermittent nature of RSL turbulence this can cause greater uncertainty in turbulence statistics.

In terms of flow measurement, the instrument of choice is the sonic anemometer. It is robust and can be relatively easily deployed on masts, taking into account flow distortion. Sampling rates of 10 to 20 Hz are generally sufficient to capture most of the scales of turbulence present in urban canopies, although new models with smaller measurement path lengths (i.e. less than 10cm, cf. c. 20cm) are being developed by Kaijo Denki in Japan. Sonic temperature can be derived from the speed of sound measurement and is approximately equal to the virtual temperature – the heat flux derived from covariance of the vertical wind component and sonic temperature means that a local stability parameter is easy to estimate. Cup anemometers and wind vanes are still used but are limited as they measure only horizontal components at low sampling rates, and are limited by their start-up speeds in the relatively low winds of urban areas. Remote sensing methods such as scintillometry, sodars and lidars are growing in popularity given their ability to overcome some of the siting limitations, but much research is needed to relate their spatially-averaged measurements of turbulence to point measurements.

3.3.2 2D (street canyons)

The literature on full scale street canyon flow measurements can be grouped into shorter term campaigns (days to a few weeks) which considered the more "classical" street canyon recirculation over a limited range of incident wind directions; and longer term measurement campaigns (one year or more) from which average profiles of turbulent statistics have been calculated. Discussion here is limited to papers which consider both mean and turbulent aspects of the flow – there are other papers which consider only mean flow or only limited turbulence statistics (DePaul and Sheih 1986; Yamartino and Wiegand 1986; Hunter et al. 1992; Ca et al. 1995; Nakamura and Oke 1988).

Short term measurements

Louka et al. (1998; 2000) completed a study of a semi-rural street canyon at the traffic-free Hall Farm site near Reading, UK. The street canyon aspect ratio was H/W = 4.2/6m = 0.7, the building aspect ratios $L_Y/H = 6.4$, $L_X/H = 2.4$ and the buildings had low pitched roofs with angle 13.5°. Measurements were made using a sonic anemometer at different heights at the centre of the street canyon, referenced to a measurement at z = 2.26H, at which height u_* was determined. Spectral analysis showed a shift in the peak towards higher frequencies near roof level, as well as a broader peak, suggesting a range of scales were active in this region – this agrees with the results of Rotach (1995) reviewed in the next section. Using propellor anemometers, the vertical windspeed at roofheight was measured across the street for perpendicular flow conditions. Louka et al. (2000) observed a recirculation when averaged over 30 minutes, but demonstrated the variability in recirculation for 1 minute averages. Such intermittency was thought to be driven by shear layer instability. Peaks in shear stress and σ_w / u_* were observed at roof level, thought to be associated with the pitched roofs (see Fig. 3 in Louka et al. 2000). The TKE budget analysis showed similarity to vegetation canopies, with a finite transport term near the shear layer, transporting TKE upward and downward away from the high production in the shear layer.

Other authors have studied street canyon flow in more realistic UK street canyons complete with traffic. Longley et al. (2004) studied an asymmetric street canyon in central Manchester, UK. Evidence for channelling flow at street level was presented, as well as an asymmetric recirculation. Turbulence intensity showed a weak increase with height. Vertical flows due to the recirculation were unsteady. Boddy et al. (2005) and Smalley et al. (in press) studied flow and pollutants in two street canyons in York, UK with considerable influence from side streets on the street canyon flow. The Gillygate street has H/W = 0.8, and is relatively short with $L_Y/H \sim 4.6$ of uninterrupted buildings. A reference sonic was placed at z = 19.5m ~1.8H at a distance of 125m away from the street. Two masts with two sonics each were placed either side of the Gillygate street. A helical flow was observed for oblique incident wind directions. The key deviation from a classical recirculation was the presence of updraughts on both sides of the street for perpendicular flow. This was attributed to the convergence of flows channelled down two side streets parallel to the incident wind, combined with end vortices generated at either end of the short street.

Smalley et al. (in press) presented a scaling analysis of within-street turbulence at Gillygate with respect to the reference measurement. This is one of few papers which does not assume that an ISL exists above the measurement site and uses the reference TKE and windspeed instead of local friction velocity as scaling variables (and to determine directions for which flow appears not to be affected by roughness changes upstream). The recirculation appeared to be reasonably steady (in contrast to Longley et al. 2004 in the asymmetric street canyon, and Louka et al. 2000 for the semi-rural street canyon), apart from directions for which convergence of flow from side streets also occurs. It was suggested that the relatively steady recirculation in an urban canyon is due to fully adjusted rough-wall flow, whereas the Louka et al (2000) study might represent flow adjusting to a series of bluff bodies, likely to produce a fluctuating shear layer. In-street TKE scaled using reference windspeed was reasonably homogeneous except for when strong perpendicular flow was occuring. Using Anisotropic Invariant Map (AIM)analysis, it was demonstrated that the turbulence is reasonably isotropic throughout the street canyon for helical flows, in contrast to when flow convergence was occuring and the typical structure was “rod-like” or axisymmetric.

Long term measurements

Some of the best work on RSL turbulence in and above street canyons appeared from two campaigns held in Switzerland, associated with the work of Matthias Rotach. The first is the Zurich Urban Climate Program (Nov ’86 to May ’88) and the second is the BUBBLE campaign (2001-02).

Rotach (1993a, b; 1995) reported results from the Anwand street canyon site in Zurich. The street canyon had aspect ratio H/W = 18.3/15 = 1.2. Buildings near the site had an average height of 20m and were “regularly distributed”: typical H/W ~1, $L_Y/H \sim 3$-5. The estimated zero plane displacement z_d ranged from 0.5H to 0.88. Two masts of instruments (cup anemometers, sonics) were erected within the street, with one on a nearby rooftop, the highest reference at z = 2.1H. The key result of Rotach (1993a) was to show that stress increased with height within the RSL (see Fig. 4a in Rotach 1993a), and he produced a parameterisation of the mean wind profile using a parameterisation of the stress profile and local scaling. Another important methodological point from this paper is the approximation of a spatial average by averaging profiles over all wind directions. Whilst this is a practical treatment of fullscale profile measurements, the equivalence has not been demonstrated. Finally, the measurements were entirely within the RSL – the value of u_* estimated at the reference level was thought to underestimate the real value by c. 20%. However, when local scaling was used, Rotach (1993b) showed that the Monin-Obukhov dimensionless wind profile fitted reasonably well to data in the upper part of the RSL, ie above roof level. This point is developed further by Christen (2005).

Rotach (1995) focused on the stability influence on mean and turbulent profiles. He observed that there was an inflection point in the mean wind profile at z ~ 1.2H, similar to vegetation canopies (see Fig. 2 in Rotach 1995); shear appeared to be larger near rooftop for perpendicular compared to parallel incident flow, an effect which was enhanced in near neutral conditions. Mean rms velocity component profiles $\sigma_u(z)$ and $\sigma_v(z)$ showed a weak increase with height and negligible sensitivity to direction or stability; however $\sigma_w(z)$ was strongly dependent on stability, with peak values at z ~ 0.8H for near neutral cases, and minimum values at the same height for unstable cases. This may imply that vertical mixing is linked to the strength of the shear layer. Spectral results showed shifts in peaks to smaller frequencies with reducing height for streamwise and vertical components, consistent with break-up of larger eddies near canopy top. The ratio of spectral energy densities S_w / S_u was smaller than the expected inertial subrange value of 4/3 at all heights, in agreement with other studies (e.g. Mulhearn and Finnigan, 1978; Högström et al. 1982) on flow entirely within an RSL.

The BUBBLE campaign (Rotach et al. 2005) was a major effort in observation of turbulence and wind profiles within and above an urban canopy, as well as surface energy balance. Comments here are limited to the work on RSL dynamics by Christen (2005) and Christen et al. (2007) relating to the Sperrstrasse street canyon. This work is to be compared with the wind-tunnel simulations of the BUBBLE site by Feddersen (2005) reported in section 3.1.

The Sperrstrasse street canyon had a mean building height of H = 13 m, and aspect ratios H/W = 1 and $L_Y/H = 13$. The surrounding neighbourhood consisted of typical continental European row houses with courtyards, mean height 14.6m, $\lambda_P = 0.54$, $\lambda_F = 0.37$, 50% flat or pitched roofs. A tower was erected with a profile of 6 sonics for a year, supplemented by 2 more sonics for a month-long Intensive Observation Period in summer 2002, heights ranging from 0.25H to 2.17H. There were also 12 cup anemometers, and several psychrometers, gas analyzers and radiation instruments which are not discussed here. These represent the highest quality full-scale flow profile measurements recorded in an urban RSL to date.

Christen's excellent thesis (2005) contains many results, of which the key ones are the "family portrait" of turbulence profiles; and his division of the RSL into three (sub-sub!)layers: canyon, roof and above roof. He employs the same methodology as Rotach (1993a, b) in approximating spatial averages by averaging over all wind directions. The "family portrait" – namely, profiles of scaled first, second and third order flow statistics – show many similarities to vegetation canopies (see Finnigan 2000; and see Fig. 5.1 in Christen 2005). The above roof layer characteristics are that the mean wind profile is logarithmic and turbulence statistics approach Monin-Obukhov similarity theorem empirical results for rural surface layers . Both shear and buoyant production of TKE are important. The roof layer consists of strong gradients and an inflected wind profile, and thus shear production of TKE dominates. TKE is exported upward and downward and thus the turbulent transport term is considerable. Correspondingly, local dissipation is lower than locally produced turbulence. In the canyon layer, local shear and buoyant production are of minor importance – most TKE is due to downward transport from the shear layer or intermittent large coherent motions penetrating downwards from above (see Christen et al. 2007). The traditional recirculation is only present when averaged, and, for certain incident wind directions, its behaviour is sensitive to roof shape as this varied between flat and pitched on either side of the street.

In terms of stress profiles, local u_* showed an increase with height, reaching quasi-constant values from z ~ 1.5H upwards, when scaled with $u_*(2.2H)$. This is in qualitative agreement with Rotach (1993a). In contrast to Rotach (2001) it is not assumed that the top of the RSL is marked by the maximum local stress. The wind-tunnel work of Feddersen (2005) showed that the neighbourhood scale RSL depth was $z_* \sim 3.3H$ where H is neighbourhood mean building height (see Fig. D2, Appendix D of Feddersen (2005)): the individual shear stress profile for the Sperrstrasse site shows a near constant stress layer within the range 1.5H < z < 2H identified by Christen (2005) but more complex structure between z ~ 2H and 3.3H. Whilst this suggests that local determinations of RSL depth based on limited mast height measurements are questionable, the Feddersen profile was not spatially averaged and the comparison is not entirely conclusive. Christen (2005) even estimated the dispersive stress, and it was found to be negligible compared to Reynolds stress for z > H but significant in the lower canyon, and the dispersive stress divergence was opposite in sign to the Reynolds stress divergence. Overall, the work has many implications for modelling RSL turbulence – a particular conclusion is that third order moments should be considered when simulating urban RSL turbulent exchange.

Christen et al. (2007) focused on coherent motions present in urban RSL turbulence. In terms of lengthscales, they found the smallest scales present at z ~ H, corresponding to small scale turbulence generated in the shear layer. Exchange of momentum was dominated by sweeps (i.e. positive u' correlated with negative w'), and ejections (i.e. negative u' correlated with positive w') were only dominant at the uppermost level, z = 2.2H. In contrast, for heat, ejections dominated for z > 1.2H, demonstrating differences in the turbulent transfer of heat and momentum, consistent with the bluff body effect (see Finnigan 2000). Larger lengthscales were found in the lower part of the canyon, where flow is most influenced by along-street channelling. The intermittency of turbulent processes in this layer was found to be partially due to large coherent motions, penetrating the street canyon from above and influencing all levels almost simultaneously. Such observations are to be linked with full study of coherent motions achieveable only in numerical simulations (e.g. Kanda et al. 2004; Coceal et al. 2007c).

Year long measurements in a narrow street canyon (H/W = 2.1) were made in Gothenburg (Eliasson et al. 2006; Offerle et al. 2007). A grid of 9 sonics with thermocouples was placed across the width of the street canyon and at the spanwise centre. This unusual set-up allowed analysis of recirculation patterns for a high aspect ratio canyon for which some numerical simulations (e.g. Sini et al. 1996, Baik and Kim 1999) have predicted counter rotating vortices. An additional mast was placed on a nearby roof, with the highest reference measurement at z = 29m = 1.9H. The mean height of buildings either side of the canyon is H = 15m, ranging from 13 to 17m. The building aspect ratio L_Y/H was 3.3, meaning that the street was relatively short and there may have been effects due to corner vortices forming at side streets. In the surrounding study area of $(250m)^2$, 30 degree sector-averaged values of λ_P ranged from 0.24 to 0.58, and λ_F ranged from 0.22 to 0.51. Eliasson et al. (2006) highlighted that there was no clear evidence for counter rotating vortices when hourly or 5 minute averages were considered, although intermittent "events" were identified, lasting O(20s). Largely the flow in the lower half of the canyon was weak, somewhat decoupled from the upper half, and with a significant along-street component, even for perpendicular incident winds. These quantitative results were supported by flow visualisation. In terms of turbulence, TKE values across the street were fairly uniform except on the front wall of the downstream building towards roof-height in cases of strong perpendicular flow.

The paper by Offerle et al. (2007) considered the effect of wall heating on flow within the Gothenburg street. Again, based on measurements located 1.4m = 0.2W away from the walls, no evidence was found to corroborate some numerically simulated predictions of double vortex structure extending out from the walls into the street. This is consistent with results from the Nantes '99 experiment, reported by Louka et al. (2002), where numerical simulations overestimated the depth of influence of heated walls when compared with flow visualisation using balloons in a full-scale street – buoyant effects were confined to a thin layer of depth 0.2m near to walls. Offerle et al. (2007) showed some evidence that the influence of heated walls for perpendicular incident wind extended further into the street near the wall of the downwind building (due to enhanced turbulence) compared to near the wall of the upwind building, where buoyant effects were confined to a thin layer near the wall. Overall, the paper concluded that strong mixing in the street by shear layer and recirculation meant that heat fluxes are relatively insensitive to heat source location, supporting the use of bulk aerodynamic resistance methods to simulate heat fluxes based on average canyon surface temperatures (e.g. Harman et al. 2004).

3.3.3 3D (cube, cube-like)

Two early UK studies presented full-scale measurements of flow around limited arrays of cubes with the aim of studying dispersion. The counterpart wind-tunnel study to the full-scale measurements of Davidson et al. (1995) of dispersion around aligned and staggered arrays of cubes has already been discussed in section 3.1. The comparison between wind-tunnel and full-scale mean canopy winds, $U(H/2)/U_{ref}(H/2)$ where the reference was c. 4H upstream, was very good. MacDonald et al. (1997) presented flow results from a similar experiment using a limited array of aligned cubes with $\lambda_P = 0.16$ with incident flow either normal to or at 45° to the front face of the cubes. With respect to a reference measurement 6-10H upstream, values of $U(H)/U_{ref}(H)$ converged within 4 rows for the normal flow case, and within 1 row for the 45°

case. There was also a greater difference between flow measured behind a cube compared with flow in a gap for the aligned array. Such observations of oblique winds are rare and suggest substantially different flow dynamics (cf. Kim and Baik 1999). The results from MacDonald et al. (1997) using U(H) showed more variability than the U(H/2) measurements of Davidson et al. (1995), presumably because of the large gradient across the shear layer at $z \sim H$ and fluctuations in shear layer position causing greater uncertainty in U(H) than U(H/2).

Mention should be made of as yet unpublished results from the excellent Japanese COSMO project, consisting of extensive, long term flow measurements over an extensive array of 1:5 scale model concrete cubes. The investigations were initiated by M. Kanda, and include unique surface energy balance and scalar transfer results (Kanda et al. 2007; Kawai et al. 2007). A conference paper on coherent motions observed above the cubes is available (Inagaki and Kanda, 2006) and another on turbulence is expected (Inagaki and Kanda, in press).

3.3.4 3D (complex)

In this category are profile measurements over more complex arrays of buildings; measurements above roof level but within the RSL; and measurements deep within the canyon sublayer.

Oikawa and Meng (1995) made some of the first observations of coherent motions over urban canopies. They made profile measurements in a neighbourhood of regularly spaced typical Japanese houses in Sapporo with mean height 7m for the months of July and November 1991. A profile of 5 measurements between 0.77H and 6.4H was made using sonics. The vertical profile of turbulence intensity component σ_u peaked just above the canopy at 1.5H, whilst other components σ_v and σ_w were constant with height. The Reynolds stress peaked at 1.5H, reducing above (see Fig. 4 in Oikawa and Meng 1995) – according to Kastner-Klein and Rotach (2004) a peak in stress can be associated with flow adjusting to a rougher surface, as the stress divergence term is non-zero in the momentum budget equation. The crane and mast-based profile measurements were apparently sited in a reasonably large gap amongst the buildings, therefore the flow may well have been adjusting, causing a non-constant stress profile. The most notable result of this paper was the observation of a microfront associated with a sweep-ejection pair that was observed at all heights to penetrate down into the urban canopy.

A series of interesting papers based on profile measurements at the Kugahara site in Tokyo, Japan considered different aspects of scalar transfer (Moriwaki and Kanda 2004; Kanda and Moriwaki 2005; Moriwaki and Kanda 2006a,b,c; Moriwaki et al. 2006) as well as dynamic processes (Moriwaki and Kanda 2006d; Kanda and Moriwaki 2006). The latter two papers are reviewed here.

The Kugahara site lies in a low-rise residential area of Tokyo. A 29m high profile mast was placed in the backyard of a house. Within 500m, $\lambda_P = 0.3$ and $H = 7.3\text{m} \pm 1.3\text{m}$, which shows the uniformity typical of Japanese dwellings. Sonics were placed at heights of 4.1, 3, 2.1 and 1.6H, as well as temperature at four slightly different heights. Moriwaki and Kanda (2006d) presented seven months' data, assessing the validity of Monin-Obukhov similarity theory, and reached some surprising conclusions. Reynolds stress profiles showed a decrease from the lowest level across all stabilities (see Fig. 3 in Moriwaki and Kanda 2006d). This is consistent with Oikawa and Meng (1995) for a similar surface, but in contrast to the near constant shear stress profiles over 1.5 to 2.2H for Christen (2005), and over 1.5H to 3.2H for Feigenwinter (1999). Given the extensive fetch of similar surface around Kugahara, it is unlikely that the flow was still adjusting to local roughness, therefore there may have been other influences on vertical structure of the flow (e.g. sea breeze; winter-time inversions, etc.). Based on this, they found the mean wind profile to fit better to the standard logarithmic form when scaled with a surface shear stress derived from extrapolating measured values to z = H, rather than local scaling. This is a similar approach to Cheng and Castro (2002a) for their wind-tunnel measurements and to Kastner-Klein and Rotach (2004) in that the peak stress is used as scaling velocity. Moriwaki and Kanda (2006d) found that the dimensionless profile of temperature collapsed reasonably well using Monin-Obukhov scaling, but for wind there were some deviations. They also found that the ratio of eddy diffusivities for heat and momentum was near one. This result is more similar to flow over flat, rural surfaces than canopies, however, as their lowest measurement was still above the canopy at 1.6H, the effect of the canopy may not have been captured.

Kanda et al. (2006) reported results on spatial variability within the RSL at the Kugahara site. Four other towers with measurements of velocity and temperature at height 1.8H were added to the site, at least 200m away from the main tower. 20 days of data were chosen for which there was 80% sunshine hours during the day – the dataset was predominantly wintertime, and it was already shown that unusually strong stable profiles existed at this site (Moriwaki et al. 2006c). By analysing the coefficient of variation for u_* and standard deviations of velocity components, they concluded that spatial variability was similar to quoted values for a pine forest – however, this is probably dependent on height of measurement within the RSL, as shown by Feddersen (2005). Spatial variability decreased with increasing u_*. However, spatial variability in heat flux was higher than for a vegetation canopy, which they concluded was related to the more extreme heterogeneity in heat sources within an urban canopy compared to a vegetation canopy. Spatial variability in all variables was large during night-time stable conditions, and small during the day, presumably due to increased turbulent mixing over longer lengthscales as the boundary layer grows.

Roth and Oke (1993a,b) reported some of the earliest results thoroughly testing Monin-Obukhov similarity results for profiles and spectra at a site in a Vancouver suburban RSL, particularly for humidity. The Sunset site was well used in a number of classic studies by students of Tim Oke, who went on to contribute hugely to urban and canopy climate studies (e.g. Schmid et al. 1991, Grimmond and Oke 1991). The study site consisted of a homogeneous distribution of residential houses with mean height H = 8.5m and predominantly pitched roofs of different slopes. From the morphological data which they reported out to a radius of 2km, $\lambda_P \sim 0.2$, $z_0 \sim 0.52$m, and d/H ~ 3.5m, giving d/H ~ 0.4, indicating a less densely packed surface. Turbulence sensors were placed at two heights, z = 1.6 and 2.6H. Sonics and other sensors to measure temperature and humidity were thoroughly assessed, ensuring high data quality in this study. Spectra for vertical and horizontal wind components were similar to homogeneous surface layer spectral results, whereas humidity showed significantly higher spectral density at low frequencies. At 2.6H, the efficiency of momentum transfer as shown by the correlation coefficient R_{uw} was found to be higher than that over a rural surface. The dissipation rate was also lower than for a rural surface, implying that transport terms were important. All three results led the authors to consider that measurements were still within the RSL. Roth and Oke (1993b) found that normalised standard deviations of velocity (using local scaling) increased with instability but with magnitudes smaller than rural site values.

Roth et al. (2006) went on to derive a new urban form for the dimensionless dissipation rate in particular, for use with scintillometers employed near roof level in the BUBBLE project. The new form differed somewhat from that derived by Kanda et al. (2002) for the same purpose, based on data from Vancouver and Tokyo, however, the reason why was not known.

Two papers are worthy of note from the ESCOMPTE project (Mestayer et al. 2005) which took place in Marseille, France in June-July 2001. Grimmond et al. (2004) reported results from measurements made in the above roof layer, from which they estimated the depth of the RSL. The site was located in a densely packed urban location, with a vegetation cover fraction of only 0.11 to 0.14, mean building height 15.6m, estimated $z_0 \sim 2.5$m, d ~ 11m giving d/H ~ 0.7, a value consistent with the high density. A mast was erected with two sets of eddy covariance instrumentation separated in height by 6m which could be raised to two different positions. This gave measurement heights of 2.8 and 2.4H (upper), 2.2 and 1.8H (lower). The key result is that whilst in the upper position, the ratio of local friction velocity at each height was near unity, from which the authors concluded that both measurements above 2.4H were in the ISL, whilst this was not the case for the lower position. More interestingly, the heat flux ratio was near unity in the upper position for daytime, but showed large divergence at night-time. This also highlighted the difference in momentum and scalar transfer in the RSL and the different effect of stability on either. Salmond et al. (2005) went on to use wavelet analysis to show that heat was vented intermittently from street canyons at night by large coherent turbulent structures.

Feigenwinter et al. (1999, 2005) reported results on coherent structures in the RSL over Basel based on measurements during the BASTA project from July 1995 to February 1996. The site was not far from the BUBBLE Sperrstrasse site, and in a domain encompassed by the wind-tunnel measurements of Feddersen (2005). Within 500m of the site the average building cover was 0.5 and the mean building height H ~ 24m. Three sonics were put on a mast at heights 1.5, 2.1 and 3.2H. The profile of local u_* values showed an increase in local friction velocity up to a height of z = 2.1H (see Fig. 4 in Feigenwinter et al. 1999). Normalised standard deviations, scaled using the uppermost value of u_* were lower than predictions by Monin-Obukhov similarity but similar to other urban sites. Spectral ratios S_w/S_u were close to 4/3 in the inertial subrange of the spectrum at all heights, apart from in stable conditions. This is in contrast to other studies (eg Roth and Oke 1993) where a clear deviation from this was observed and taken to be a signature of RSL turbulence. Feigenwinter and Vogt (2005) studied coherent structures in the same dataset and found that ejection-sweep cycles occurred for 45% of the time in the momentum flux time series. The timescale for these features (calculated over 116 events) was 100 seconds. The coherent structures produced the largest fluctuations in temperature and longitudinal velocity component at lower heights, decreasing above. The authors concluded that the coherent structures are similar in nature to those over vegetation canopies, but have a longer timescale, perhaps consistent with the higher roughness of the urban surface.

Finally, two papers have considered measurements deep within the canyon layer in highly inhomogeneous urban morphologies (Dobre et al. 2005, Klein and Clark 2007).

Dobre et al. (2005) reported results from the DAPPLE project, the first campaign of which took place over 5 weeks in spring 2003. The experiment focused on flow around an intersection of two street canyons and is unique in this respect. The mean building height out to a radius of 250m was H = 21m, $\lambda_P \sim 0.5$, $\lambda_F \sim 0.2$. A reference measurement of windspeed was placed on a nearby roof at z = 0.8H. 4 sonics were deployed, 2 at either side of the intersection at z = 0.3H, 2 in adjoining street canyons at z = 0.2H. The paper highlighted the strong fluctuations in wind direction that can occur deep within the canopy layer. Firstly, in street canyons with near perpendicular winds, the along street flow component reversed immediately (for 5 minute averages) when the incident flow shifted slightly from being perpendicular +10° to -10°. Such "flow rectification" highlights the importance of wind direction variability and along-street transport, often neglected in street canyon studies, particularly those which are 2D simulations. Secondly, the wind direction at the intersection site switched intermittently to be aligned with either of the perpendicular streets. Wind-tunnel flow visualisation later showed this to be due to shifting of overlying vortices generated by nearby buildings, showing the high spatial variability of flow at the intersection. Despite the complexity, a simple linear model was proposed for street canyon flow, which explained much of the flow behaviour at the two street canyon sites despite their being located only approximately one building height away from the intersection.

Klein and Clark (2007) presented measurements at the Park Avenue street canyon site at the heart of the Joint Urban 2003 project, which took place in Oklahoma City, US. The accompanying wind-tunnel simulations were reported in section 3.1 (Klein et al. 2007) and were used to test the linear street canyon model of Dobre et al. (2005) with only fair results. The street canyon had H/W ~ 2.6, with large variations in building height on either side (mean H ~ 65m, range between 4 and 127m). Throughout the length of the street (between major intersections) there were side streets, causing the uninterrupted length to be relatively short at L/H ~ 2.4. Two masts of 5 sonics were placed on either side of the street, at heights from 0.02H to 0.24H. They found that the flow was dominated by along street components at these heights, and small shifts in external wind direction led to large changes in flow patterns. This is similar to the Dobre et al. (2005) result, showing the dominant influence of the street network in determining flow; and to Christen (2005) who showed the intermittency in turbulence at lower levels. It was also found that turbulence statistics showed little dependence on stability when a rooftop reference was used, as opposed to a reference at some height above the street (z ~ 3.8H). This is consistent with other findings that the above roof layer can follow Monin-Obukhov surface layer predictions reasonably well when suitably scaled, whereas the roof layer and canyon layer are driven by local turbulence generation mechanisms (ie the shear layer at roof top; vortices shed from buildings; flow rectification). Further results are considered in Nelson et al. (2007a, b) Ramamurthy et al. (2007) and Pol and Brown (2008).

There are a number of studies which consider wind-tunnel experiments, full scale measurements and parameterisations of traffic produced turbulence (Kastner-Klein et al. 2000; Vachon et al. 2002; Di Sabatino et al. 2003; Kastner-Klein et al. 2003), however this topic is outwith the scope of this review.

3.4 Models of RSL flow

Compared to the large number of experimental and numerical studies, there are relatively few studies that attempt to construct simple models of the mean flow and turbulence in the urban RSL. Most of the existing studies can be categorized into three broad groups: urban canopy models, empirical parameterisations and models based on assumptions about the mean flow structure.

3.4.1 Urban canopy models

The exponential velocity profile (Macdonald et al., 2000a)

While the mean velocity profile is logarithmic in the inertial sublayer, within the roughness sublayer it deviates appreciably from log behaviour (although a number of authors, including Cheng & Castro, 2002a, have noted that spatially averaged profiles still have a logarithmic form in the above-roof region of the RSL over regular urban-type roughness). Within the canopy layer the velocity profile is definitely not logarithmic. Macdonald et al. (2000a) exploits an analogy with vegetation canopies, using an approach originally due to Cionco (1965), to derive a simple analytical expression for the spatially-averaged mean velocity profile in an urban canopy. The model is based on the balance of obstacle drag force and local shear stress at each height within the canopy. Macdonald discusses a sectional drag coefficient $c_d(z)$, which is a function of height in the canopy. The derivation relies on a simple Prandtl mixing length model for the turbulence lengthscale l_c. With the further assumptions that c_d and l_c are both constant with height within the canopy (both questionable – see e.g Coceal et al., 2006; Kono et al., 2008), the spatially-averaged mean velocity profile $U(z)$ is shown to have an exponential form within the canopy:

$$U(z) = U_H \exp\{a(z/H - 1)\} \tag{6}$$

where U_H is the mean velocity at the canopy height H, and a is the so-called attenuation coefficient. The expression was validated using Macdonald's wind-tunnel data for flow over cubes, but using line averages instead of area averages. Based on these results, Macdonald suggested a linear variation of the attenuation coefficient a with packing density as a suitable approximation for crude calculations:

$$a = 9.6\,\lambda_f \tag{7}$$

Later work pointed out some problems with the exponential parameterization of the mean wind profile, and with the assumptions on which its derivation is based. For example, explicit computation of spatially averaged mean velocity profiles from the DNS of Coceal et al. (2006) and the wind-tunnel experiment of Castro et al. (2006) showed that the area averaged profile was not exponential. Coceal et al. (2007b) and Kono et al. (2008) also found important differences between area averages and the line averages used by Macdonald et al. (2000a). Nevertheless, the exponential profile is convenient as a first approximation, hence its wide use in the literature.

The in-canopy velocity U_c and exchange velocity U_E (Bentham & Britter, 2003)

Bentham & Britter (2003) proposed an even simpler model than Macdonald et al. (2000a), based on the formulation of a spatially-averaged mean velocity U_c which was constant with height within the canopy. By considering the drag within a control volume in the canopy, a simple expression can be obtained for the variation of U_C with packing density (with some assumptions about the drag coefficient of the buildings):

$$\frac{U_C}{u_*} = \left(\frac{2}{\lambda_f}\right)^{1/2} \tag{8}$$

An alternative form is given for sparse arrays in terms of the roughness length z_0, by assuming the Lettau (1969) relationship $z_0/H = 0.5\ \lambda_f$, which is a good approximation for sparse arrays.

$$\frac{U_C}{u_*} = \left(\frac{z_0}{2H}\right)^{-1/2} \qquad (9)$$

The model was compared with a variety of experimental data and yielded a surprisingly good fit. The model also allows an expression to be derived for the exchange velocity U_E between in-canopy and above-canopy flow. The authors caution that it is not suitable for localised dispersion applications.

Distributed drag parameterisations (Various authors)

A number of studies have employed 'urban canopy models' to parameterise the effects of urban areas in larger scale models (eg Brown, 2000; Martilli et al, 2002). For example, Martilli et al (2002) formulated an urban parameterization scheme for mesoscale models that included a 'distributed drag' representation of the effects of buildings on momentum. An extra drag force term was introduced in the volume-averaged Navier-Stokes equations for the conservation of momentum of the form

$$\vec{F} = -\rho C_d A |U| \vec{U} \qquad (10)$$

where A is the total frontal area of the walls of the roughness elements per unit volume and C_d is a drag coefficient. See Raupach et al. (1991), Appendix, for a full derivation of this drag force term after volume averaging is applied to the equations of motion within the distributed drag of a canopy. One of the problems is that the drag coefficient for urban agglomerations is largely unknown: a constant value is assumed for all heights and all urban configurations (for example Martilli et al. (2002) use a value of 0.4), but clearly the drag coefficient is a function of many parameters and varies with height within the canopy.

Urban canopy models are usually formulated in terms of a sectional drag coefficient $c_d(z)$ (Macdonald et al., 2000a). One problem with using $c_d(z)$ is that it varies very much with height and becomes very large near the ground. This is because the mean velocities are very small near the ground. Martilli & Santiago (2007) proposed a modified drag coefficient $c_d^{mod}(z)$ that takes into account additional velocity scales: 'turbulent' and 'dispersive' velocity scales. In effect they used a velocity based on the total kinetic energy of the flow: mean + TKE + DKE (dispersive kinetic energy). They found that $c_d^{mod}(z)$ varied much less with height. Santiago et al (2008) showed this with DNS data and a series of RANS simulations at different packing densities: in some cases $c_d^{mod}(z)$ was nearly constant with height. The authors obtained an empirical expression for the variation of $c_d^{mod}(z)$ with packing density based on a fit to the RANS data, but the results are only expected to be correct to within a factor of 2 or so – more accurate work using LES is desirable (cf Kono et al., 2008). Another problem with this approach is that the TKE and DKE are generally difficult to know in practice.

Flow adjustment to an urban canopy (Belcher et al, 2003; Coceal & Belcher, 2004/2005)

While most authors have only considered the drag effect of a canopy in equilibrium with the boundary layer, Belcher et al. (2003) were interested in the adjustment of the boundary layer to a canopy of roughness elements. They developed a quasi-linear model for the adjustment of the spatially-averaged mean flow, where the time- and spatially-averaged momentum equations were solved analytically with the addition of an extra distributed drag force:

$$U_j \frac{\partial U_i}{\partial x_j} + \frac{\partial P}{\partial x_j} = \frac{\partial \tau_{ij}}{\partial x_j} - f_i, \qquad \frac{\partial U_i}{\partial x_i} = 0. \tag{11}$$

where the turbulent stress was parameterized with a mixing length model (with the mixing length $l_m = \kappa(z-d)$ above the canopy and $l_m = \text{constant}$ within) and the drag represented in terms of a canopy drag lengthscale L_C :

$$f_i = \frac{|U| U_i}{L_c} \tag{12}$$

where L_c is inversely proportional to the packing density λ_f and the sectional drag coefficient $c_d(z)$, and is a function of height within the canopy.

Scaling arguments demonstrated three regions of adjustment: (i) an *impact region* upwind of the canopy, where the pressure gradient decelerates the flow (ii) an *adjustment region* of length of order L_C downwind of the leading edge of the canopy, when the flow decelerates rapidly until it reaches equilibrium between downward transport of momentum by turbulent stresses and removal of momentum by the drag of the canopy elements (iii) a *roughness change region*, where the canopy acts as a change of roughness, leading to the development of an internal boundary layer. The model of Belcher et al. (2003) agreed well with experimental data quantitatively, although the values of drag coefficient that were needed for a good fit were somewhat higher than expected.

Based on the formulation of Belcher et al. (2003), Coceal & Belcher (2004, 2005) developed a numerical model to calculate spatially-averaged mean winds within and above urban areas. In performing the formal spatial average, the averaging volume was taken to be thin in the vertical, and large enough in the horizontal to include a number of buildings, but not so large as to lose the spatial development of the velocity field due to the effect of the canopy drag. The authors took care to formulate parameterizations of the drag and turbulence that were more appropriate for urban areas. Unlike Belcher et al. (2003), Coceal & Belcher (2004) did not assume the mixing length to be constant within the canopy (which is appropriate for deep and dense vegetation canopies). Instead they assumed a form that was linear close to the ground and that tended to a constant in the upper part of the canopy. The canopy drag lengthscale L_C in this model was given by

$$L_c = \frac{2H}{c_d(z)} \frac{(1-\beta)}{\lambda_f} \tag{13}$$

where *H* is mean building height and β is the volume fraction occupied by buildings within the canopy (for a array of uniform buildings, it is equal to λ_p). The model required only a few parameters as input - λ_f, λ_p, *H* and the height-averaged mean sectional drag coefficient $\overline{c_d}$. The drag coefficient was based on values deduced from the wind-tunnel experiment of Cheng & Castro (2002a). The model accounted for the adjustment to an urban canopy as well as fully adjusted winds. The spatially-averaged mean winds were found to adjust to the canopy within a distance of order $3L_c$, and captured well the wind deceleration through a canopy of cubes. Figures 12 and 13 of Coceal & Belcher (2004) show how the model performs against data from the field and wind-tunnel experiments of Davidson et al. (1995, 1996). Coceal & Belcher (2005) applied the model to actual cities using observed morphological data, and considering variations in canopy density and canopy height.

Di Sabatino et al. (2008) used a similar approach to Coceal & Belcher (2004) and Macdonald et al. (2000a), with the mixing length assumed to be constant within the canopy. They did not consider flow adjustment to an urban canopy, focusing instead on adjusted wind profiles. The novel feature was that they considered the variation of λ_f with height, using data from digital elevation models (DEMs) as input to their simulations. The model was used to calculate spatially averaged wind profiles over London, Toulouse, Berlin and Salt Lake City. Figures 6 and 7 in the paper give examples of the profiles of λ_f (z) and the computed velocity and stress profiles over London.

As an interesting variation, Lien & Yee (2005) applied the spatial averaging formalism to derive systematically a modified k-ε model in which the effect of building drag in an urban canopy is incorporated as extra terms into the equations for TKE (k) and dissipation rate (ε). These additional terms are derived explicitly from the transport equation for the spatially-averaged velocity, rather than being imposed in an ad hoc way. The model was then applied to simulate neutrally-stratified flow over a 3D array of regular cubes (Lien et al., 2005), and compared to results from CFD computations that explicitly resolved the buildings in the array. The appendix of Lien & Yee (2005) contains an interesting discussion of a model for the dispersive stress tensor.

3.4.2 Empirical parameterisations

The work of Macdonald et al. (1998) is one of several approaches to morphometric parametrisations of urban roughness (see Grimmond & Oke, 1999 for a review). The authors provide expressions for roughness parameters d and z_0 in terms of morphological parameters λ_f, λ_p , h and c_d. The expression for d is an empirical fit to wind-tunnel data for cubes

$$\frac{d}{h} = 1 + A^{-\lambda_p}\left(\lambda_p - 1\right) \tag{14}$$

where *A* is an empirical constant that has the value of 4.43 for regular staggered arrays of cubes, and 3.59 for regular aligned arrays of cubes. This expression has the correct limiting behaviour for both sparse and very dense arrays, giving $d \approx 0$ and $d \approx h$ respectively.

A simple analytical derivation for z_0 from basic principles generalised Lettau's earlier relationship ($z_0/h = 0.5\ \lambda_f$) to an expression which depends explicitly on the displacement height *d* and drag coefficient C_D, in addition to λ_f:

$$\frac{z_0}{h}=\left(1-\frac{d}{h}\right)\exp\left[-\left(0.5\beta\frac{C_D}{\kappa^2}(1-d/h)\lambda_f\right)^{-0.5}\right] \qquad (15)$$

where here β is an empirical factor which encapsulates the dependence of the drag coefficient on several factors (e.g. incident wind profile, turbulence intensity, wind angle etc). This equation captures the characteristic maximum in the z_0/h vs λ_f curve as observed experimentally (se e.g. Raupach et al, 1991), and show a good fit to wind-tunnel data over a wide range of packing densities (see Figure 4 in Macdonald et al. (1998) for best fit curves to the data). This parameterisation is very widely used in the urban literature (although sometimes in questionable contexts, e.g. for 2D geometry).

Summarising the results of a number of experiments (Rotach, 1993a,b; Oikawa and Meng, 1995; Feigenwinter et al., 1999), Rotach (2001) presented a conceptual sketch of the shear-stress profile in the urban boundary layer. He pointed out that the shear-stress is not constant in the RSL, but increases to a maximum at some height above the urban roughness (rather than at the ground, as over smoother surfaces) and then decreases to a value of nearly zero at the zero plane displacement height *d* (see Fig. 1 of Rotach 2001). The rapid decrease of the shear stress to zero in the canopy is due to form drag exerted by the buildings, and can be essentially reproduced in numerical simulations of the urban canopy using a distributed drag term (e.g. Martilli et al., 2002). More surprising is the fact that the peak in the shear-stress occurs *above* the canopy top, and not *at* the canopy top as for other rough surfaces such as vegetation canopies. Rotach (2001) suggests that this is because most urban surfaces are heterogenous, with buildings of different heights, so that the form drag acts up to the level of the tallest buildings and not up to the mean building height. The height at which the shear stress peaks is then dependent on the distribution of building heights: however, this factor is not considered further in this study. Based on the three datasets mentioned above, Rotach (2001) proposed an empirical parameterization for a local, height-dependent friction velocity $u_{*l}(z)\equiv\sqrt{-\overline{u'w'}(z)}$, based on height and magnitude of the shear stress peak and given by

$$\left(\frac{u_{*l}(z)}{u_{*m}}\right)^b=\sin\left(\frac{\pi}{2}\frac{z'}{z'_{*m}}\right)^a \qquad (16)$$

where $z'=z-d_0$, $z'_{*m}=z_{*m}-d_0$, z_{*m} is the height of the shear stress maximum, $u_{*m}(z)\equiv\sqrt{-\overline{u'w'}_{\max}}$ and a and b are empirical constants determined from the data, with a = 1.28, b = 3.0 (see Fig 2 of Rotach, 2001). The displacement height d_0 was taken to be the level of zero stress, rather than that of mean momentum absorption as defined by Jackson (1981). Note that the form of the equation as written is ambiguous: the right hand side is better represented by either $\left\{\sin\left(\frac{\pi}{2}\frac{z'}{z'_{*m}}\right)\right\}^a$ or $\sin\left(\frac{\pi}{2}\left(\frac{z'}{z'_{*m}}\right)^a\right)$ to ensure that $\left(\frac{u_{*l}(z)}{u_{*m}}\right)^b=1$ when $\frac{z'}{z'_{*m}}=1$.

Kastner-Klein & Rotach (2004) proposed a shear-stress parameterization based upon wind-tunnel measurements they performed over a detailed model of an area in central Nantes, France (reviewed in Section 3.1). The measured shear-stress profiles were found to be characterized by small values within the urban canopy, a strong increase in the upper canopy and a pronounced peak above mean roof height. Based on this data, the authors proposed a self-similar parameterisation of the shear-stress of the form:

$$\frac{\overline{u'w'}}{\overline{u'w'}_s} = \left(\frac{\hat{z}}{\hat{z}_s}\right)^2 \exp\left[2\left(1-\hat{z}/\hat{z}_s\right)\right] \tag{17}$$

where $\hat{z} = z - d_s$ and the length scale $\hat{z}_s$ and shear-stress scale $\overline{u'w'}_s$ are related to the height at which the peak in shear stress is observed and its magnitude respectively, with $\overline{u'w'}_s \equiv \overline{u'w'}(z_s)$. Here d_s is the shear-stress displacement height as discussed by Jackson (1981). Note that this parameterization does not include dependence on boundary layer depth, $\hat{z}_s$ being the only lengthscale.

The values of the scaling parameters d_s, z_s and $\overline{u'w'}_s$ can be determined from the measured velocity profiles. Figures 9 and 10 in the paper demonstrate the comparison of this parameterization with the wind-tunnel data and with other full-scale and wind-tunnel data in the literature. The authors point out that the fit is generally good except near the maximum, which is intentional since they wanted to exclude the effects of local flow disturbances (which are responsible for the extremes in the peaks).

For practical parameterizations, it would be very useful to have relations between these scaling parameters and morphometric parameters characterizing the urban area. The authors employ simple expressions that are consistent with their data, but caution that they are not intended as general parameterizations.

3.4.3 Models based on mean flow structure

Caton et al (2003) derived an analytical model for dispersion mechanisms of a passive tracer in a 2D street canyon. The work focused on the transfer between the canyon and the external flow, and highlighted the importance of the shear layer and the turbulence characteristics of the incident flow on this exchange. The study was well supported by experimental measurements and flow visualization using PIV. The dispersion model was based on insight provided by these observations, and predicted results were quantitatively in good agreement with the measurements. The main feature of the model is a constant vorticity core inside a canyon of aspect ratio H/W=1. The authors did not discuss how this generalises to different aspect ratios, and did not take into account the unsteadiness of the vortex. The model is similar in principle to that of Soulhac (2000), who used numerical simulations of shear layers. An equation for the streamfunction was solved analytically under different conditions, and the results showed that the transfer between the canyon and the external flow depends on the turbulent properties of the incoming flow, in addition to the mean velocity.

Based on observations in London (DAPPLE project), Dobre et al. (2005) formulated a simple model of oblique flow in a street canyon. These full-scale measurements indicated that the main large-scale features of the mean flow were channelling along the street and a recirculating vortex across the street, similar to what is observed in idealised 2D street canyons. The flow within the street was then analysed as the vector sum of the channelling and recirculating component. The channelling component scaled linearly on the along-street component of the roof-top reference velocity, and the cross-street recirculation scaled linearly on the across-street component of the roof-top velocity. The authors pointed out that, although simple in essence, the model applied to real streets of non-ideal geometry.

Soulhac et al (2008) developed an analytical model for flow along a 2D street canyon at any angle. The authors first considered incident wind parallel to the street axis. A key assumption was that the flow in the canyon depends only on the external flow and the distance to the nearest wall. This led to two different flow regimes, with the dynamics influenced either by the ground or by the walls. Solution of the Reynolds-Averaged Navier-Stokes equation using a gradient diffusion model then leads to two different velocity profiles. The model agreed well with numerical simulations using the RANS code MERCURE. The model was then generalized to an arbitrary wind direction with respect to the street axis. Numerical solutions showed that the streamlines of the mean flow in the street have a spiral form. For most angles, the mass flux along the street scaled on the component of the external wind resolved parallel to the street. However, the authors pointed out that not all features of the flow can be modelled as a linear superposition of the flow parallel to the street and flow perpendicular to the street.

In a series of conference papers and reports (most recently at the 7th AMS Symposium on the Urban Environment), Michael Brown and collaborators have presented details on the development, validation and application of a fast response model (QUIC-URB). The model relies on simple empirical parameterizations of different flow regimes associated with flow around buildings. Based on the upwind velocity, an initial wind field is prescribed taking into account different flow regimes in the building geometry (e.g. canyon, wake cavity etc – see Figure 1 in Addepalli et al., 2007). The final velocity field is obtained by enforcing mass consistency. For simple geometries, the resulting 3D velocity field resembles the time-averaged field obtained in experimental results. For more complex cases, e.g. with large differences in building heights, the agreement of the velocity field structure and mean velocity profiles is not so good (see for example Figures 6-16 and in Addepalli et al., 2007, available on the website of the AMS 7th Symposium of the Urban Environment).

4. Conclusions

It can be seen that many high quality datasets are now available across a range of urban morphologies, and some general characteristics of urban RSL flows are starting to emerge. The next sections are an attempt to synthesise the results, assess the current state of RSL modelling and identify next steps in the research.

4.1 Synthesis of results

Treatment of an urban surface as a rough-wall boundary layer:

1) It has been noted (Castro et al., 2006) that the ratio H/δ may be relevant to the nature of urban turbulence, and possibly that urban surfaces are in a special class of "very rough walls". One consequence may be that an inertial sublayer may not form, particularly when the roughness elements exhibit height variability. The connection between RSL flows and the outer region of a full-scale boundary layer is unknown.

2) The urban surface is inhomogeneous, and various wind-tunnel and full-scale results have shown that considerable fetch is required before an inertial sublayer is established – hence RSL turbulent qualities may dominate over ISL qualities at full-scale. However, some of the full-scale studies have demonstrated measurements high enough to exhibit ISL turbulent behaviour. Flow adjustment directly after a roughness change has been shown to affect flow and turbulence deep within the urban canopy and should be taken into account.

3) The relationship between the depth of the RSL and urban morphology is not easily generalised, especially as authors define the depth in different ways. However, the depths reviewed here generally fall in the range suggested by Raupach of 2-5H. Distinction should be made between the definition of RSL depth based on a single profile measurement site, and RSL depth based on the convergence of many profiles across a neighbourhood. Many full-scale measurements can only yield the former, whilst numerical or physical modelling studies can be used to determine the latter. Only in the BUBBLE study, with matching full-scale and wind-tunnel measurements, have the differences been investigated (Feddersen 2005; Christen 2005).

4) Many studies, especially recent CFD studies, have tried to investigate the nature of turbulent organised structures over urban areas. Consensus has not yet been reached as to their nature, whether sweeps or ejections dominate in the vicinity of an urban canopy, or even the mechanisms producing them: current results appear to depend on experimental or numerical set-up and local morphology.

Treatment of an urban surface as a canopy

1) Various studies have presented evidence to support the treatment of an urban canopy within a framework similar to vegetation canopies. There is phenomenological evidence to suggest that flows are similar in some respects (e.g. Christen 2005). However, the mixing layer analogy which forms the basis of vegetation canopy models depends on large organised structures being generated at canopy top which dominate the whole canopy, causing mixing length to be constant with height. Evidence from several studies for urban canopies was presented which contradicts this, showing smallest lengthscales at canopy top, and integral lengthscales increasing both down into the canopy, and upward above it.

2) Spatial averages are required in the canopy framework – an approximation to this is achieved in full-scale studies by averaging over all wind directions (e.g. Rotach 1993a,b, Christen 2005), but has not been proven as a surrogate. In addition, the relatively large, bluff roughness elements in an urban canopy produce large flow perturbations, and thus large spatial variability. Together with the temporal unsteadiness and intermittency which characterise the lower canopy layer, the mean may be meaningless within an urban canopy. Modelling approaches relying on steady mean flow structures may fail deep within the canopy.

Other features of urban RSL turbulence

1) Profiles of RSL turbulence for different surfaces show some similar features (e.g. increase of shear stress with height; peak value near or above canopy top), but choosing suitable scaling variables is an issue. For example, for the shear-stress profile, authors have variously used maximum stress (Kastner-Klein and Rotach 2004), ISL friction velocity u_* (e.g. Rotach 1995; Louka et al. 2000), local scaling (Rotach 1993b), form drag across a roughness element (Cheng and Castro 2002a); and some evidence is emerging that mean canopy height may be insufficient as a heightscale, some modification based on the variability in roughness element heights being preferable (Schultz et al. 2007). Several authors have shown success in using surface layer similarity relationships with some kind of scaling in the above roof layer.

2) The roof layer is highlighted as a region of high TKE production, low dissipation, and significant transport of turbulence. This has implications for modelling approaches assuming local equilibrium between production and dissipation. Results have shown highly efficient turbulent transfer in this region, despite the small turbulent lengthscales.

4.2 Current status of RSL modelling and future research needs

It is clear that universal characteristics of urban flows captured by a single theoretical framework have not yet emerged. It was shown in section 3.4 that there has been some progress in modelling urban RSL flows. Urban canopy models have shown some success in reproducing the mean flow characteristics, even for an adjusting flow. However, there is uncertainty about how to represent canopy drag – in particular the drag coefficient is hard to parameterise. Current results demonstrate that it varies strongly with depth, and some work is starting to show how it varies with morphology (Kono et al. 2008), layout or incident flow direction. In terms of turbulence, a generalised model is lacking. The valuable contribution of Rotach (1993a, 2001) and Kastner-Klein and Rotach (2004) has been to attempt empirical parameterisation of shear stress profiles in urban canopies.

Overall, a parallel might be drawn with research into vegetation canopies – experimentally, observations of turbulent profiles within real and simulated canopies increased in sophistication, allowing the “family portrait” to be drawn up. Theoretically, the application of spatial averaging to the equations of motion for canopy flows exposed new terms associated with canopy-specific flow processes, i.e. leaf-scale production and dissipation of TKE, dispersive stresses. Observations of turbulent organised structures near canopy top led to the development of the mixing layer analogy (Raupach et al. 1996) which forms the basis of a model of canopy turbulence based on a single lengthscale, the vorticity thickness. The recent roughness sublayer model proposed by Harman and Finnigan (2007) is a simple but elegant summary of understanding gained through prior investigations, namely: standard surface layer flux-profile relationships are coupled to a mixing layer model for canopy turbulence. This requires a single turbulence lengthscale to be defined; canopy drag to be represented by a single lengthscale L_c; and the dimensionless combination u_*/U_H to be determined. The influence of the roughness sublayer is thus represented as a modification to existing surface layer similarity functions, and its influence decays over a specific heightscale. One important prediction of the model is that roughness parameters z_0 and d show stability dependence, which has implications for modelling approaches fixing these parameters *a priori* based on landuse or morphology: by not allowing the roughness parameters to vary with stability, exchanges of momentum and scalars with the canopy surface may be substantially in error.

It thus makes sense to use elements of the research framework for vegetation canopies to identify future research needs for urban RSL flows. Some key tasks have been identified:

1) Given the variety of datasets now available, spanning different research methods, an attempt can be made to establish the "family portrait" of urban turbulence profiles. Whilst Christen's (2005) portrayal of the BUBBLE dataset in this format is ground-breaking, it is a single family member – and the family may well be dysfunctional! The aim of the exercise is to test current scaling suggestions (velocity, heightscale) across a range of urban morphologies and establish whether universal characteristics of flow can be identified. It should be determined whether urban canopies represent a "special class" of roughwall or canopy flows by identifying significant differences in scaling requirements, e.g. addition of a height variability parameter or H/δ in addition to mean canopy height.

2) An important task is to develop a theoretical model for urban RSL turbulence. It remains untested as to whether the mixing layer analogy holds for urban canopy turbulence. Despite earlier comments about multiple lengthscales having been observed within urban canopies (e.g. Christen 2005, Coceal et al. 2007c), the hypothesis might still hold with only minor modification to allow for these observations.

3) As the basis of RSL flow parameterisations is dependent in part on the morphology of the urban surface, it is clear that only a small part of the morphological parameter space has been explored. Whilst packing density has been the focus of many studies of urban roughness, height variability, roughness element shape, roughness element arrangement (i.e. aligned or staggered), fetch and heterogeneity have all been identified as having significant impacts on turbulence characteristics. One route for progress is to test new combinations of dimensionless morphological parameters which might result in more universal collapse of the data. Such tests could assist experimental designs for the future by identifying key combinations of relevance to real urban areas out of a potentially large parameter space.

4) Finally, simple parameterisations of urban canopy turbulence should be attempted. Poggi et al. (2004) formulated a parameterisation of canopy turbulence as a function of canopy density, based on identifying different regions of the flow where different turbulence production mechanisms were operating in a series of water channel experiments. Authors such as Christen (2005) and Coceal et al. (2007c) have already identified different layers of urban RSLs with distinct turbulence characteristics, which could underpin such an approach.

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Table 1: Physical Modelling (2D street canyon, bar roughness, 3D cuboid, 3D complex)

Paper	Location	Surface type	Flow measurements	Flow parameters	Comments
2D (Street canyon, bar roughness)					
Kastner-Klein et al. (2001)	Uni. Karlsruhe	Single, open-ended street canyon $H/W=1$, $L_Y/H=5, 10$ Simulated BL upstream	Laser Doppler Velocimetry (LDV), uvw $0.1< z/H < 1.75$ x-z cross-section at y=0	$H/\delta=0.24$	Tracer gas, traffic motions also simulated
Kastner-Klein et al. (2004a)	Uni. Karlsruhe	As for KK et al. 2001, plus $L_Y/H=15$, and pitched roofs Simulated BL upstream	As for KK et al. 2001		Comparison with street canyon data of Brown et al. 2000, Nantes model (KK and Rotach 2004)
Rafailidis (1997)	Uni. Hamburg (4 x 1.5 x 1)	Series of 28 street canyons, H/W=1, 2 (flat) H/W=1.5, 3 (pitched roof), 7 roofs only model scale 1:500 Simulated BL upstream	Laser Doppler Anemometry (LDA), hot film anemometer $x \sim 40H$	$H(flat)/\delta=0.12$ $H(pitched)/\delta=0.18$	
Brown et al. (2000)	Environmental Protection Agency, US (EPA) (18.3 x 3.7 x 2.1)	Series of 6 street canyons, H/W=1 Model scale 1:250 Simulated BL upstream	Hot wire anemometers (HWA): cross wire, pulsed $0 < z/H < 3$ $-3.5H < x < 24.5H$ ($x = 0$ at front edge of 1st building)	$H/\delta \sim 0.08$, $z_0 \sim 0.001$m upstream	

Barlow et al. (2004)	Uni. Reading 1.5 x 0.23 x 0.23 m	Series of 8 street canyons $H/W=0.75$ Simulated BL upstream	Naphthalene sublimation	$H/\delta=0.1$	Scalar transfer experiment
Cheng and Castro (2002b)	EnFlo A (6 x 0.9 x 0.6)	Upstream roughness: Vertical flat plates, H=2mm, $H/D = 0.08$ Downstream: Bar roughness, H=5mm, $H/W= 0.125$	Hot wire (HW) anemometer Vertical profiles at different fetches over both surfaces	Fetch x~2400mm Upstream: $x/H \sim 1200$, $H/\delta \sim 0.03$ Downstream: $x/H \sim 480$, $H/\delta \sim 0.04$	Growth of internal boundary layer experiment
3D (cubes, cuboids)					
Davidson et al. (1996)	EPA (18 x 3.7 x 2.1)	Cubes, 6 rows, staggered and aligned $\lambda_F = 0.11$ Simulated BL upstream	HW (cross, pulsed) $\sim 0.1 < z/H < 5H$ at $y=0$ Lateral, longitudinal profiles at $z = H/2$	$H/\delta=0.15$	Tracer gas
MacDonald et al. (1998a) (data from Hall et al. (1996))	Building Research Establishment (BRE), Watford (22 x 4.3 x 1.5)	Cubes, staggered and aligned $\lambda_F = 0.05$ to 0.9, 9 values Simulated BL upstream	unknown $x \sim 22H$, vertical profiles		
MacDonald et al. (2000a) (data from Hall et al. (1998))	BRE	Cubes, staggered and aligned $\lambda_F = 0.05$ to 0.33, 5 values Simulated BL upstream	HW (pulsed) $x \sim 20H$, vertical profiles, 5 lateral locations	$H/\delta=0.1$	Tracer gas

MacDonald et al. (2000b) (as reported in Hanna et al. 2002)	Uni. Waterloo Hydraulic flume	Cubes, staggered and aligned $\lambda_F = 0.16, 0.44$ Simulated BL upstream	Acoustic Doppler Velocimeter (ADV) x ~ 44H, 27H, vertical profiles, 5 lateral locations		
Cheng and Castro (2002a)	EnFlo A (4.5 x 0.9 x 0.6)	Cubes, aligned and staggered, H=10 and 20mm; cuboids varying height, mean H=10mm $\lambda_P = \lambda_F = 0.25$	HW (cross): H=20mm, $2.4 < z/H < 5H$. H=10mm, $1.3 < z/H < 10H$ LDA: $2.6 < z/H < 4.5$ Spatial averages over repeating units. Pressure tapped cube.	H=20mm, $x/H \sim 149$, $H/\delta=0.14$ H=10mm, $x/H \sim 314$, $H/\delta=0.075$	
Castro et al. (2006)	EnFlo A	Cubes, staggered, H=20mm $\lambda_P = \lambda_F = 0.25$	LDV, HW (cross) x ~ 150H	$H/\delta=0.14$	
Reynolds et al. (in press)	Uni Southampton (4.5 x 0.9 x 0.6m)	Cubes, staggered, H=10mm $\lambda_P = \lambda_F = 0.25$	Particle Imaging Velocimetry (PIV), LDV, HW (cross) x ~ 390H	$H/\delta=0.074$	Reproducing Cheng and Castro (2002a) expt., different tunnel
Reynolds et al. (2007)	Uni Southampton EnFlo A	Cubes, staggered, aligned, H=10, 20mm, uniform and varying height $\lambda_P = \lambda_F = 0.25$	HW (single wire, cross) Vertical and lateral profiles	H=20mm, S: $x/H \sim 152$, $H/\delta=0.14$ H=10mm, S: $x/H \sim 313$, $H/\delta=0.085$ A: $x/H \sim 322$, $H/\delta=0.095$	
Cheng et al. (2007)	EnFlo A	Cubes, staggered and aligned, H=20mm $\lambda_P = \lambda_F = 0.25, 0.0625$	HW (cross) x ~ 150H	$H/\delta \sim 0.15$ $1.8H < z_{ISL} < 2.2 – 2.4H$ NB: no ISL for $\lambda_F = 0.0625$, aligned	

Schultz et al. (2005, 2007)	Uni. Hamburg (Wotan) (28 x 4 x 2.75m)	Cubes, staggered and aligned, pitched roofs added $\lambda_p = 0.25$, $\lambda_f = 0.25, 0.32$ Simulated BL upstream	LDV $x \sim 85H$ 9 vertical profiles within array, $0.2 < z/H < 4$		
3D (complex)					
Kastner-Klein and Rotach (2004)	Uni. Karlsruhe	Nantes, 1:200 scale, 400m diameter around Rue de Strasbourg. $\lambda_p \sim 0.45$ Simulated BL upstream	LDA 23 vertical profiles across model $0.25 < z/H < 3.5$		
Feddersen (2005)	Uni. Hamburg (Wotan) (18 x 4 x 2.75-3.25m) Test section	Basel, 1:300 scale, 2.4 x 1.2km around Sperrstrasse. $\lambda_p = 0.54$, $\lambda_f = 0.37$ Simulated BL upstream matching full-scale	LDV Grid of up to 180 points at 5 heights $1.8 < z/H < 4.7$ 10 vertical profiles, $1.6 < z/H < 14$	$H/\delta \sim 0.07$	
Klein et al. (2007)	(1) Uni. of Karlsruhe (2) Uni. Hamburg (Wotan) (18 x 4 x 2.75-3.25m) Test section	(1) Intersection, flat roof $H/W = 1$, roof shape variations. Simulated BL upstream (2) Oklahoma City, 1:300, 250 x 250m around Park Avenue Simulated BL upstream	LDA (1) horizontal planes of flow at intersection (2) reproducing street canyon flow in Klein and Clark (2007); vert./hori. cross sections; differing wind direction		

Table 2: Computational Fluid Dynamics (2D, 3D cuboid, 3D complex)

Paper	Numerics & setup	Validation
2D (canyons, bars)		
Kim and Baik (1999)	RANS: k-ε, 2 buildings, with building and cavity H/W = 0.4, 0.5, 1, 1.5, 2, 2.5, 3, 3.5	Almost none, apart from comparison of mean ascending and descending vertical velocities (2 numbers) for H/W = 1.2 with wind-tunnel results of Hoydysh & Dabberdt (1998).
Kovar-Panskus et al (2002)	RANS: k-ε, 1 cavity H/W= 0.5, 1, 1.4, 2, 3.3 (no 'buildings')	Detailed comparison with own wind-tunnel measurements. Very good agreement above cavity, less good within cavity.
Lien, Yee & Cheng (2004)	RANS: Comparison of four different k-ε models (standard, Kato-Launder, RNG and non-linear). 7 buildings, with building and cavity H/W=1.	Compared with wind-tunnel measurements of Brown et al (2000). Good agreement of mean velocity profiles and many qualitative features of mean flow, but tke is underpredicted, especially within the cavity.
Santiago & Martin (2005)	RANS: RNG k-ε using FLUENT code, 6 buildings, building H/W = 2 and cavity H/W = 1, 2, 4. Includes asymmetric cases with one of the buildings with H/W = 3.	None
Walton et al (2002): Part I Walton and Cheng (2002): Part II	LES: dynamic SGS model + wall functions with CFX code. (I) Single cavity (roof garden) with H/W = 0.63 and periodic boundary conditions in the horizontal. (II) Building and cavity H/W = 1.2 and periodic boundary conditions to simulate an infinite sequence of 2D canyons.	Good agreement of mean velocity, turbulence intensities and Reynolds stress profiles with measurements on the roof garden.

Liu & Barth (2002)	LES: One cavity with H/W = 1 in a domain of length and width H and with streamwise periodic b.c. to simulate an infinite sequence of street canyons.	Good agreement of mean velocity, turbulence intensities and Reynolds stress profiles with wind-tunnel measurements.
Liu et al (2004)	LES: Extension of Liu & Barth (2002) to H/W = 0.5, 1, 2.	None presented here, but previous work (Liu & Barth, 2002) was validated against wind-tunnel data as noted above.
Li et al (2007)	LES: Extension of Liu et al (2004), using a wall model and applying to high canyon aspect ratio H/W = 1, 2, 3.	Reasonable agreement of mean velocities and fluctuations with water channel experiments for H/W = 1, 2.
Cui et al (2003)	LES: Channel flow. Dynamic SGS. 3, 6 or 10 square bars depending on separation. H/W = 0.11, 0.25, 1	Good comparison of mean velocity and turbulence intensities with two experimental datasets for boundary layers.
Cui et al (2004)	LES: Uses RAMS code. One cavity with H/W = 1 and periodic b.c.s to simulate an infinite sequence of infinitely long canyons.	Comparison of u, w, TKE, skewness and kurtosis with wind-tunnel data of Brown et al (2000). Good agreement of u, w, TKE and reasonable agreement of skewness and kurtosis.
Leonardi et al (2003)	DNS: Channel flow with square bars on one wall and periodic bcs in both horizontal directions. Aspect ratios investigated were H/W = 0.053, 0.1, 0.11, 0.125, 0.14, 0.18, 0.25, 0.33, 0.48, 1, 1.67, 3, in a domain of size 40H x 10H x 5πH.	Reasonable agreement of roughness function with three different experiments.
Leonardi et al (2004)	DNS: bars	

Nagano et al (2004)	DNS: Channel flow with bars on one wall and periodic bcs in both horizontal directions. ‘Building’ aspect ratios of 0.25, 0.5, 1 and ‘canyon’ aspect ratios of H/W = 0.08, 0.16, 0.33, 0.05, 1.	None.
Ashrafian et al (2004)	DNS: Channel flow with square bars on both walls – perhaps not relevant here.	
Krogstad et al (2005)	DNS: As in Ashrafian et al (2004) – hence not relevant here.	
Orlandi et al (2006)	DNS: Among other obstacle shapes, square bars with H/W = 1 and flow direction of 0° and 90°.	Smooth wall channel flow test case compares well against DNS of Kim et al (1987). Rough wall cases not validated against experimental data.
Burattini et al (2008)	DNS: Square bars with canyon aspect ratio H/W = 0.33.	Extensive comparison with own experimental data for the same flow conditions, yielding generally good agreement of mean velocities, turbulence intensities, skewness, kurtosis, TKE budget terms and spectra.
Ikeda and Durbin (2007)	DNS: Channel flow simulation over 4 square bars in a domain of size 40H x 20H x 17H and H/W = 0.11, with periodic bcs in the horizontal.	Reasonable agreement of mean velocity and Reynolds stresses with experimental data of Hanjalic & Launder (1972).
3D (cubes, cuboids)		
Kim & Baik (2004)	RANS: RNG k-ε, 16 cubes in aligned layout with $\lambda_p = 0.25$. Wind directions from 0° to 45° every 5°.	Reasonable agreement of mean flow pattern, u and w with wind-tunnel data (Brown et al, 2000); TKE is under-predicted.
Lien and Yee (2004): Part I Lien et al. (2005): Part II Lien and Yee (2005): Part III	RANS: k-ε, 7 rows of 11 cubes in aligned layout with $\lambda_p = 0.25$.	Profiles of u, w are generally in good agreement with wind-tunnel data (Brown et al, 2001), but TKE is consistently under-predicted, by up to a factor of two.

Hamlyn & Britter (2005)	RANS: RSM using FLUENT code. Two columns of aligned half-cubes (10 or 20 rows) with lateral symmetry conditions and λ_p = 0.0625, 0.16, 0.44.	Reasonable agreement of mean and rms velocity with experimental data of Macdonald et al (2000).
Santiago et al (2007): Part I Martilli and Santiago (2007): Part II	RANS: k-ε, 7 cubes in aligned layout with lateral symmetry conditions and λ_p = 0.25.	Good agreement of mean streamwise velocity with wind-tunnel measurements of Brown et al (2001). Mean vertical velocity underestimated inside canyons and overestimated above. TKE underestimated inside canyons and overestimated above.
Milliez & Carissimo (2007)	RANS: k-ε using Mercure_Saturne code. 12 rows of 10 equal-sized cuboids (aspect ratio approx 1:5:1) in aligned layout (MUST array). Simulated different combinations of wind speed and wind direction corresponding to observed cases.	Comparison with MUST field data. Generally good agreement for mean velocity and TKE.
Hanna et al (2002)	LES: Unstructured tetrahedral grids, finite element code (FEFLO). Four simulations performed on regular arrays (8 rows) of cubes in aligned and staggered layouts with λ_p = 0.16 and 0.44.	Comparison of mean and rms velocity profiles with water flume data of Macdonald et al. (2000). The agreement was not particularly good, with discrepancies of up to about 40%.
Stoesser et al (2003)	LES: Finite volume code LESOCC. Two simulations: (i) Small channel depth – one cube of side h in a domain of size 4h x 4h x 3.4h using periodic bcs to simulate an aligned array with λ_p = 0.0625. (ii) Large channel depth – a staggered array of 32 cubes in a domain of size 15h x 7.5h x 13h and λ_p = 0.25.	Good agreement of profiles of mean streamwise velocity and turbulence intensity with measurements.

Kanda et al (2004)	LES: Mask method using LES-CITY code. Periodic bcs. Variable number of cubes in aligned layout (up to 72 cubes) and variable domain sizes (up to 18h x 6h x 14h) and with λ_p = 0.11, 0.15, 0.20, 0.25, 0.30, 0.33, 0.35, 0.44.	Somewhat limited comparisons with lab measurements of Uehara et al (2000) of total stress and streamwise and vertical turbulence intensities.
Kanda (2006a)	LES: Extension of Kanda et al (2004) to staggered as well as aligned cubes and including height variations, for λ_p ranging from 0.03 to 0.44.	None.
Xie & Castro (2006)	LES: Finite volume unstructured grid; wall model. Two geometries: staggered arrays of 4 cubes, and 16 cuboids of different heights. Also compare with RANS simulations using standard and modified k-ε and RSM models.	Detailed comparison with wind-tunnel data of Cheng & Castro (2002a) and Castro et al (2006) and DNS of Coceal et al (2006). Generally good agreement of profiles of mean velocity, turbulence intensities, pressure drag, mean flow patterns and spectra.
Xie et al (2008)	LES: Using hexahedral mesh (FLUENT) and polyhedral mesh (STAR-CD). Four 'repeating units' of 16 cuboids of different heights in a regular staggered arrangement, with periodic bcs in the horizontal.	Generally good agreement of mean and rms velocities with wind-tunnel data of Cheng & Castro (2002a).
Xie & Castro (2008)	LES: As in Xie et al (2008)	Not discussed, but see Xie et al (2008) above.
Claus, Xie & Castro (2008)	LES: Two simulations with wind at an oblique angle: (i) Regular array of 16 staggered cubes with periodic bcs and λ_p = 0.25 for 0° and 45° (ii) Irregular geometry: scale model of DAPPLE site for 51° and 90°.	No experimental or DNS data to validate against yet. Ongoing work that will include own wind-tunnel experiments.

Kono et al (2008)	LES: Dynamic SGS. Aligned and staggered arrays of cubes with periodic bcs and λ_p = 0.05, 0.11, 0.16, 0.20, 0.25, 0.33.	Good agreement of profiles of mean velocity, shear stress and pressure drag with wind-tunnel data of Cheng & Castro (2002a).
Coceal et al (2006)	DNS: Periodic bcs in horizontal and free slip at the top. Regular arrays of cubes (aligned, square and staggered) with λ_p = 0.25 and domain sizes of 4H x 4H x 4H, 4H x 4H x 6H and 8H x 8H x 4H	Good agreement of profiles of drag, mean velocity, Reynolds and dispersive stresses and sectional drag coefficient against wind-tunnel data of Cheng & Castro (2002a).
Coceal et al (2007a)	DNS: Staggered array of cubes with periodic bcs in horizontal and free slip at domain top and λ_p = 0.25. Total of 48 cubes in a domain of size 16H x 12H x 8H.	Good agreement of mean velocity profiles, pressure drag, turbulence intensities, spectra and two-point correlations against wind-tunnel data of Cheng & Castro (2002a) and Castro et al (2006).
Coceal et al (2007b)	DNS: Combination of Coceal et al (2006) and Coceal et al (2007a).	Not discussed here, but see Coceal et al (2006) and Coceal et al (2007a)
Coceal et al (2007c)	DNS: As in Coceal et al (2007a)	As in Coceal et al (2007a)
Orlandi & Leonardi (2008)	DNS: A variety of 3D obstacles, including staggered and aligned cubes with H/W = 1.	None presented.
Leonardi & Castro (2008)	DNS: Six staggered arrays of cubical obstacles with λ_p = 0.04, 0.11, 0.13, 0.16, 0.2 and 0.25. Periodic bcs in horizontal and free slip at the top. Domain is of height 8H and always contains 12 cubes.	Good agreement of mean velocity profile against wind-tunnel data of Cheng & Castro (2002a) and DNS of Coceal et al (2006).

3D (random, complex)		
Neophytou & Britter (2005)	RANS: RSM using FLUENT code. Simulation of a 1:200 scale model of a 250m-radius area of central London (DAPPLE campaign) with 42 buildings, $\lambda_p \sim 0.5$, $\lambda_f \sim 0.25$.	None.

Table 3: Full-scale measurements (2D street canyons, 3D cube and cube-like, 3D complex)

Paper	Location	Surface type	Flow measurements	Flow parameters?	Comments
2D (street canyons)					
Louka et al. (1998, 2000)	Reading, UK	Street canyon, H/W = 0.7, $L_Y/H = 6.4$, $L_X/H = 2.4$, pitched roofs 3-4 streets upstream	Ref sonic at z = 2.26H 1xsonic at 6 diff. heights $0.67 < z/H < 2.26$, x = 0.5W, y = 0.5 L_Y Hori. profile z = H, $-0.5W < x < 0.5W$, $y = 0.5L_Y$	$z_0/H \sim 0.1$, $d/H \sim 0.7$	No traffic, farm buildings located in rural area.
Longley et al. (2004)	Manchester, UK	Asymmetric street canyon, $\overline{H}$ ~20m H(south) 22-28m, H/W~1.5 H(north) 10-18m, H/W ~0.8, L_Y/H~6.2, various roof shape, city centre	2x sonic at 9 diff. heights $0.1<z/\overline{H}<0.9$, Offset to south side. Ref. sonic at z~1.5 $\overline{H}$, 38 $\overline{H}$ away		With traffiic flow analysis. Aerosol flux measurements also.
Boddy et al. (2005) Smalley et al. (in press)	York, UK	Street canyon (Gillygate), H/W=0.8, L_Y/H~4.6, city centre	2x masts either side street with 2 sonics, Ref. sonic at z~1.8H, 125m away		With traffiic flow analysis. Pollutant measurements also.
Rotach (1993a, b; 1995)	Basel, Switzerland (Urban Climate Program)	Street canyon, H/W = 1.2, Surrounding H/W~1, L_Y/H ~3-5	1x mast on roof, 4 cup/sonics at $1.1<z/H<2.1H$, 1x mast in street, $0.4<z/H<1.3$	d/H~0.5 – 0.88H	Traffic passing under bridge on which street mast mounted.

Christen (2005) (1) Christen et al. 2007) (1) Roth et al. (2006) (2)	Basel, Switzerland (BUBBLE)	Street canyon, $H/W \sim 1$, $L_Y/H \sim 13$, varying roofshape Surrounding $H=14.6$, $\lambda_p = 0.54$, $\lambda_f = 0.37$	(1)1x mast with 6 sonics at $0.3 < z/H < 2.2$, $x/W \sim -0.13$, c. 1 year (2) 2x small aperture scintillometer, pathlength = 116m, one over roofs, one over street	$d/H \sim 0.8 – 0.9$ $z_0/H \sim 0.08 - 0.19$	Weak traffic flow. Also carbon dioxide fluxes, surface energy balance
Eliasson et al. (2006) Offerle et al. (2007)	Gothenburg, Sweden	Street canyon, $H/W \sim 2.1$, $L_Y/H \sim 3.3$, varying roof height Surrounding $\lambda_p \sim 0.2$-0.6, $\lambda_f \sim 0.2$-0.5	Grid of 9 sonics in x-z plane across street 1x mast on roof, 3 sonics, $1.2 < z/H < 1.9$	$d/H \sim 0.5$-1 $z_0/H \sim 0.1$-0.15 based on wind direction sectors	Weak traffic flow. Thermocouples and heat fluxes also studied. Some flow visualisation.
3D (cube, cube-like)					
Davidson et al. (1995)	Cardington, UK	Cubes in a field, 6 rows, staggered and aligned. $H = 2.3$m, $\lambda_F = 0.11$	Sonics, U(ref) at $x = -4H$, $z = 1.7H$, U(canopy) at $-4 < x/H < 23$, $z/H=0.5$	$z_0 \sim 0.005$m upstream	Flow visualisation of smoke plume from point source
MacDonald et al. (1997)	Lancashire, UK	Cubes in a field, aligned 8 x 8 cubes, $\lambda_F = 0.16$ 10x10, $\lambda_F = 0.44$ 7x7, $\lambda_F = 0.0625$	Sonics, U(ref) at $x = -6$-$10H$, $z = H$, U(canopy) at $4 < x/H < 24$, $z/H=1$	Upstream roughness $z_0 \sim 0.023$m (neutral) $z_0 \sim 0.009$m (unstable)	Tracer gas experiments, flow visualisation using smoke, from point sources
Inagaki and Kanda (2006)	COSMO site, Japan	Cubes in a field, concrete on flat base 50 x 100m, aligned, 32 rows. $H=1.5$m, $\lambda_F = 0.25$	5x sonics, $1<z/H<4H$, centre of array. 16x sonics, $-8 < y/H < 8$, flow aligned with long axis of array		Surface energy balance measurements, direct measurement of scalar transfer coefficients.

3D (complex)					
Oikawa and Meng (1995)	Sapporo, Japan	Residential area, H=7m	5x sonics, $0.8<z/H<6.4$, 2 months		
Moriwaki and Kanda (2006d) (1) Kanda and Moriwaki (2006) (1) Kanda et al. (2006) (2)	Tokyo, Japan (Kugahara site)	Residential area, H = 7 ± 1m, $\lambda_P = 0.3$ within 500m	(1) 4x sonics, $1.6<z/H<4.1$, 7 months (winter) (2) 4 extra masts added c. 200m away from central mast 1x sonic each at z = 1.8H		Also temperature, carbon monoxide and humidity.
Roth and Oke (1993a,b)	Vancouver, Canada (Sunset site)	Residential area, H = 8.5, mainly pitched roofs, $\lambda_P \sim 0.2$	2x sonics, z = 1.6 and 2.6H	$z_0/H \sim 0.06$, $d/H \sim 0.4$	Also temperature, humidity
Grimmond et al. (2004) Salmond et al. (2005)	Marseille, France (ESCOMPTE)	City centre, H = 15.6m, vegetative fraction $\lambda_V \sim 0.1$	2x sonics in two positions: (1): z = 2.4 and 2.8H (2): z = 2.2 and 1.8H	$z_0/H \sim 0.16$, $d/H \sim 0.7$	Also temperature, humidity
Feigenwinter et al. (1999, 2005)	Basel, Switzerland (BASTA)	Residential area, H ~ 24m within 500m, $\lambda_P \sim 0.5$	3x sonics, z = 1.5, 2.1 and 3.2H	$d/H \sim 0.9$	
Dobre et al. (2005)	London, UK (DAPPLE)	City centre, intersection H = 21m, $\lambda_P \sim 0.5$, $\lambda_F \sim 0.2$ within 250m	Cup and vane U(ref), z = 0.8H 2x sonics across intersection, z=0.3H, 2x sonics in adjoining street canyons.		Tracer experiments, pollution and personal exposure measurements
Klein and Clark (2007)	Oklahoma City, US (Joint Urban 2003)	City centre, complex street canyon H ~65m, range 4 to 127m, $L_Y/H \sim 2.4$, $H/W \sim 2.6$	2x masts with 5 sonics each, $0.02 < z/H < 0.24$ 1x sonic on rooftop, z =1.2H Sodar U(ref) z = 3.8H		Tracer experiments, lateral flow measurements, tethered balloon