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Observations of wind speed profiles over Greater London, UK, using a Doppler lidar ☆

Daniel R. Drew *, Janet F. Barlow, Siân E. Lane

Department of Meteorology, University of Reading, UK

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ABSTRACT

To calculate the potential wind loading on a tall building in an urban area, an accurate representation of the wind speed profile is required. However, due to a lack of observations, wind engineers typically estimate the characteristics of the urban boundary layer by translating the measurements from a nearby reference rural site. This study presents wind speed profile data obtained from a Doppler lidar in central London, UK, during an 8 month observation period. Used in conjunction with wind speed data measured at a nearby airport, the data have been used to assess the accuracy of the predictions made by the wind engineering tools currently available.

When applied to multiple changes in surface roughness identified from morphological parameters, the non-equilibrium wind speed profile model developed by Deaves (1981) provides a good representation of the urban wind speed profile. For heights below 500 m, the predicted wind speed remains within the 95% confidence interval of the measured data. However, when the surface roughness is estimated using land use as a proxy, the model tends to overestimate the wind speed, particularly for very high wind speed periods. These results highlight the importance of a detailed assessment of the nature of the surface when estimating the wind speed above an urban surface.

1. Introduction

To design tall buildings in urban areas, wind engineers need to calculate the maximum potential wind loading on the structure. This requires an accurate representation of the characteristics of the urban boundary layer (UBL) in strong wind conditions. Several theoretical and empirical models to describe the vertical distribution of mean wind speed have been proposed, the predictions of which are dependent on the characterisation of the underlying surface. However, at present, due to the lack of both observed wind speeds and surface roughness data, there has been limited validation of the models in urban areas.

For a horizontally homogeneous surface, a number of equilibrium wind speed profile models are available; power law, log law and Deaves and Harris model (Davenport, 1960; Simiu and Scanlan, 1996; Deaves and Harris, 1978). However, in urban areas there may be several changes in the nature of the surface within a few kilometres of the site. A number of studies have developed theoretical models which consider the effects of surface heterogeneity. Panofsky and Dutton (1984) and Elliott (1958) considered the growth of a new inner boundary layer at a step change in surface roughness. Deaves (1981) used this concept to extend the applicability of the Deaves and Harris model to heterogeneous terrain. This was subsequently adapted into the UK wind loading code and the ESDU data items (ESDU, 2006; British Standard, 1995).

A number of studies have investigated the characteristics of the boundary layer in various urban areas. Rotach et al. (2005) and Li et al. (2010) investigated the urban wind speed profile over Basel and Beijing respectively using data obtained at various elevations on meteorological masts. However, these observations are confined to heights relatively close to the surface. To detail the wind characteristics for higher altitudes, ground-based remote sensing techniques, such as Doppler Sodar, have been deployed in a number of urban areas. Emeis (2004) investigated the characteristics of the boundary layer up to a height of 210 m agl over Hannover. While, Barlow et al. (2008) observed the wind speed profile up to a height of 110 m above Salford, UK. In addition, Tamura et al. (2001) used observations from a number of Doppler Sodars located at various sites across Tokyo to consider the impact of variations in terrain roughness of the upstream fetch on wind speed profiles. Due to the increased terrain roughness of the upstream fetch, the mean wind speeds at low altitudes measured at a city centre location were lower than those observed at both a coastal and suburban location.

As part of the ACTUAL project (Advanced Climate Technology: Urban Atmospheric Laboratory, 2011) a pulsed Doppler lidar has been installed at a site on Marylebone Road, Greater London, to

* Tel.: +44 11 837 86 010.
E-mail address: d.r.drew@reading.ac.uk (D.R. Drew).

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obtain the characteristics of the urban boundary layer. This study presents the wind speed profiles observed during high wind speed periods for a range of wind directions. The objectives of this paper are twofold: (1) to compare the observed wind speed profiles with the predictions of both the equilibrium and non-equilibrium models and (2) to investigate whether a detailed assessment of the urban surface improves the accuracy of the models.

2. Wind speed profile models

For sites with a long fetch over a homogeneous terrain, the boundary layer can be considered to be in equilibrium with the underlying surface. (i.e the wind speed profile does not change as the fetch of upwind uniform terrain increases). Rao et al. (1974) showed that an equilibrium profile is established for a fetch of the order of 100 times the boundary layer height. In practice there are very few sites, where a sufficiently long upwind fetch of uniform terrain occurs for an equilibrium boundary layer to exist. A number of both equilibrium and non-equilibrium wind speed profile models are available, and are reviewed here.

2.1. Power law

The power-law model is an empirical formula for the mean velocity profile, which is based on finding the magnitude of the exponent, α, which provides the best fit of wind speed observations between two heights:

$$U(z_1) = U(z_2)\left(\frac{z_1}{z_2}\right)^{\propto} \tag{1}$$

where $U(z_1)$ and $U(z_2)$ are the wind mean wind speeds at a height of z_1 and z_2 respectively.

Eq. (1) is based on the assumption that the magnitude of the exponent is a constant between the two heights and is only dependent on the roughness of the underlying terrain. In reality however, α varies with wind speed, stability and the height range of the fit. In addition, the power law does not meet the lower or upper boundary conditions. Consequently the model fits best over the range of moderate heights $30 < z < 300$ m Cook (1997).

2.2. Log law

Asymptotic similarity considerations for a neutral boundary layer show that by matching the law of the wall with the velocity defect law in the region where both laws apply (known as the inertial sublayer), the wind speed profile is given by

$$U(z) = \frac{u_*}{k}\ln\left(\frac{z}{z_0}\right) \tag{2}$$

where u_* is the surface friction velocity, k is von Karman's constant and z_0 is the surface roughness length. For regions with densely packed surface obstacles, such as vegetation and buildings, the mean flow does not penetrate to the surface; therefore the wind profile is displaced vertically:

$$U(z) = \frac{u_*}{k}\ln\frac{(z-d)}{z_0} \tag{3}$$

where d is the zero plane displacement. Despite being applied to the whole boundary layer, the log wind profile is only valid in the inertial sublayer (ISL). The ISL typically extends from a height of 4–6 times the mean building height to approximately 10% of the boundary layer depth (Ricciardelli and Polimeno, 2006). Tieleman (2008) and Li et al. (2010) showed that the log law does not provide a good representation of the wind speed profile above heights of approximately 200 m.

2.3. Deaves and Harris model

The Deaves and Harris model (DH) meets both the upper and lower boundary conditions and is therefore applicable to the entire boundary layer, not just the surface layer (Deaves and Harris, 1978). The DH wind speed profile is given by

$$U(z) = \frac{u_*}{k}\left[ln\left(\frac{z}{z_0}\right) + 5.75\left(\frac{z}{h}\right) - 1.88\left(\frac{z}{h}\right)^2 - 1.33\left(\frac{z}{h}\right)^3 + 0.25\left(\frac{z}{h}\right)^4\right] \tag{4}$$

where h is the height of the neutral boundary layer

$$h = \frac{u_*}{Bf} \tag{5}$$

where f is the Coriolis parameter and B is an empirical constant estimated to have a magnitude of 6 from observed wind profiles (Tieleman, 2008).

2.4. Roughness change models

Several theoretical methods have been developed to deal with the effects of a heterogeneous surface (Elliott, 1958; Panofsky and Dutton, 1984; Deaves, 1981). When flow encounters a change in surface roughness, a new inner layer develops (known as an internal boundary layer), which propagates upwards through the upstream layer as the downstream distance increases. Such growth was observed using Doppler Sodars in Tokyo (Tamura et al., 2001). Elliott (1958) showed that the depth of the IBL, δ, can be derived from

$$\delta(x) = 0.28z_{02}\left[\frac{x}{z_{02}}\right]^{0.8} \tag{6}$$

where x is the distance from the roughness change boundary and z_{02} is the roughness length of the downstream surface. Above δ, the wind speed is independent of x and equal to the value given by the equilibrium profile (at the same height) just upwind of the roughness change.

Mertens (2003) and Heath et al. (2007) assumed that within the IBL, there is an equilibrium log law wind profile, governed by the nature of the new surface. By equating the upstream and downstream wind speed at δ, the wind speed, U at a height of z above the downstream surface can be expressed as

$$U(z) = \frac{\left(\ln\left[\frac{\delta-d_1}{z_{01}}\right]\ln\left[\frac{z-d_2}{z_{02}}\right]\right)}{\left(\ln\left[\frac{z_A-d_1}{z_{01}}\right]\ln\left[\frac{\delta-d_2}{z_{02}}\right]\right)}U_A(z_A) \tag{7}$$

where z_{01} and z_{02} are the roughness lengths and d_1 and d_2 are the displacement heights of the upwind and downwind surfaces respectively and U_A is a reference upwind rural wind speed U_A, (measured at a height z_A).

Deaves (1981) developed a method to deal with the non-equilibrium effects based on a solution of the full elliptic form of the Navier–Stokes equations, which is obtained using a simple eddy-viscosity closure assumption. This solution is consistent with the Deaves and Harris equilibrium wind speed profile (Eq. (4)) when $x \to \infty$. Deaves (1981) applied the method to a wide range of surface roughness changes and collapsed the results onto a series of curves. These curves were fitted with simple equations which are used in the ESDU 82026 to directly estimate the boundary layer velocity profile for a distance x from a roughness change.

Both the equilibrium internal boundary layer method (Eq. (7)) and the Deaves (1981) model enable the wind speed profile downstream of a step change in roughness to be estimated from a wind speed measured at a single height above the upwind surface. However, several changes in roughness typically occur upwind of an urban site. By assuming the growth of a new internal layer at each step change, both techniques can be applied for multiple changes in roughness length. This study considers the accuracy of these models by comparing the urban wind speed profile derived using reference wind data collected at London Heathrow with observations from the Doppler lidar at the central London site. The analysis has also been performed using two methods for estimating the surface roughness length: (1) using land use as a proxy (2) values based on the urban morphology.

3. Measurement and instrumentation

Two instrument sites used in this study are located within central London, UK (Fig. 1). A Doppler lidar has been installed on the roof of the Westminster City Council building (at a height of 21 m) on Marylebone Road in west-central London (51.5213°N, 0.1606°W). In addition, a sonic anemometer is mounted on an open lattice tower on top of the BT Tower (51.5215°N, 0.1389°W) with its head at height 190.3 m (Barlow et al., 2009). The distance between the two sites is approximately 1.6 km. The data analysed in this study were collected from 22nd May 2011 to 6th January 2012.

Fig. 1. Instrument sites in central London. ©2011 Google-Imagery ©DigitalGlobe, GeoEye, Getmapping plc, Infoterra Ltd. and Bluesky, the GeoInformation Group.

3.1. Sonic anemometer observations

The BT tower is the tallest building within several kilometres of its surroundings and consequently has good exposure to winds in all directions. Wood et al. (2010) used a flux source-area model to show that the measurements at 190.3 m during neutral conditions were affected by the surface 1–10 km upwind of the tower (pertaining to the 10 and 90% probability contours). Within this distance the land use is typically residential and commercial with the exception of two large parks; Regent's Park (1.66 km^2) approximately 0.64 km north-west and Hyde Park (2.53 km^2) approximately 1.7 km south-west. Wood et al. (2010) calculated the mean building height in this region as 8.8 ± 3.3 m and the zero-plane displacement as 4.3 ± 1.9 m. The instruments at the top of the BT tower are therefore approximately 22 times the mean building height.

The three wind components (u, v, and w) and temperature, T, were measured by the sonic anemometer (R3-50, Gill Instruments Ltd., 0.01 ms^{-1} resolution and accuracy) at 20 Hz. Barlow et al. (2011) performed wind tunnel simulations of the flow around the BT tower and the lattice tower on which the anemometer is located. It was observed that both the tower and the lattice slightly distorted the flow and therefore small correction factors were derived (approximately 2% of the mean wind speed). The anemometer has since been moved to a higher position, it is therefore expected that any error is smaller. Lane et al. (2012) showed a slight increase in the turbulence intensity for northerly flow, consistent with flow being distorted by the lattice tower.

3.2. Doppler lidar observations

The lidar is a Halo Photonics Streamline pulsed Doppler lidar, which uses light of sufficiently low wavelength to be eye safe. A Doppler Beam Swinging (DBS) method has been used to obtain wind speed profile data. This scan type was preferred to the Velocity Azimuth Display (VAD) approach as it has a shorter scan time and is therefore more capable of capturing the unsteady flow experienced in an urban area (Pearson et al., 2009). Each scan cycle is completed in approximately 21 s, but due to limitations of the lidar software, the interval between scans is limited to a minimum of 120 s. Data are averaged into 80 30 m gates along the lidar beam, however the first three are not usable as at short distances only part of the return signal is detected (Wandinger, 2005). A full description of the DBS method and lidar quality control is provided in Lane et al. (2012).

3.3. London Heathrow

London Heathrow weather station (51.4787°N, 0.44904°W) is located on the outskirts of Greater London at a distance of approximately 20 km south west (260°) from the WCC building. Hourly wind speed and direction data measured at the site have been obtained for the whole observation period. It is noted that there are a number of buildings close to London Heathrow, however the Met Office state that the data are collected at standard exposure. This is defined as being over level, open terrain at a height of 10 m above the ground, where open terrain is defined as an area where the distance between the anemometer and any obstruction is at least 10 times the height of the obstruction.

3.4. Surface parameters

To estimate the wind speed profile at a given location using the models outlined in Section 2, the magnitude of a number of parameters describing the surface of the upstream terrain is required. In the absence of observations, a common approach of estimating the roughness length, displacement height and power law exponent over a relatively large area is to use land use as a proxy (Rooney, 2001; Barlow et al., 2008; Boehme and Wallace, 2008). Table 1 details the terrain dependent parameters for extreme winds in the UK, taken from Cook (1997). However, the problem for those interested in urban areas is that land use categories are usually very broad (as they have to cover all types of land use) (Britter and Hanna, 2003). For example, Choi (2009) showed that there are typically only two urban categories (urban and suburban) in the various wind loading codes and for each of the categories there can be a large variation in the magnitude of z_0 and d (Wieringa, 1993).

Alternatively, the magnitude of z_0 and d can be estimated using a morphological approach. Macdonald et al. (1998) showed that the relationship between the surface parameters and the size and spacing of the buildings can be expressed as

$$\frac{z_0}{h} = \left(1-\frac{d}{h}\right)\exp\left\{-\left[0.5\beta\frac{C_D}{\kappa^2}\left(1-\frac{d}{h}\right)\lambda_F\right]^{-0.5}\right\} \tag{8}$$

$$\frac{d}{h} = 1 + A^{-\lambda_P}(\lambda_P - 1) \tag{9}$$

Table 1
Value of the terrain-dependent parameters for the UK (Cook, 1997).

Description	Typical rural	Suburban	City
Roughness length, z_0 (m)	0.03	0.3	0.8
ABL height (m)	2550	3000	3250
Exponent α	0.16	0.24	0.32

where C_D is the drag coefficient of a single obstacle, A is a tuning parameter controlling the curvature of the d/h graph, β is a parameter which modifies the drag coefficient to a value more appropriate to the particular configuration of obstacles, λ_P is the ratio of the total plan area of the buildings to the total plan area of the surface and λ_F is the frontal area ratio in the direction facing the wind to the total plan area.

Morphological data for Greater London were available from the Virtual London dataset; a digital model of more than 3.5 million buildings licensed to the Centre for Advanced Spatial Analysis (CASA) at University College London (Evans, 2009). From this data, Padhra (2010) derived the plan and frontal area density ratio for westerly wind direction for the whole of Greater London (1650 km^2) at a resolution of 1 km^2. It is not however possible to determine the magnitude of β and A for each individual gridbox. It is therefore assumed that within each gridbox there is a staggered array of obstacles aligned along the wind direction. For such an arrangement, Macdonald et al. (1998) derived values of β=1 and A=4.43. Using Eqs. (8) and (9), the magnitude of the surface parameters has been estimated. Fig. 2 shows the displacement height is estimated to be greater in central London where the buildings are taller and more densely packed. It peaks at a value of 19.5 m (approximately 0.8 h) at a distance of 5 km east of the gridbox which contains the WCC building and gradually decreases to a value of close to zero at the rural boundary. A secondary peak is shown approximately 5 km south east of the central peak; this corresponds to the location of a number of tall, densely packed buildings (London's CBD).

Fig. 3 shows the estimated roughness length across Greater London for westerly flow. An initial increase in roughness length between the rural edge and central London reaches a peak (at a value of 1.8 m) at a distance of 5 km upstream of the displacement height peak. Further downstream, the roughness length gradually decreases towards the rural boundary. Again however, there is a secondary peak (z_0=2.0 m) in the CBD region of London. In the city centre (the area within 5 km of the BT) the mean roughness length is approximately 1.1 m, while in the suburbs, (the area between 5 km and 10 km from the BT tower) it is approximately 0.6 m. Both of these values are therefore significantly higher than the corresponding values given in Table 1.

4. Results and discussion

4.1. Mean wind speed profile

The data obtained by the lidar has been analysed to derive the mean wind speed profile for the whole observation period, shown in Fig. 4. For heights of up to 1000 m the measured data fits well with a logarithmic wind profile. Above 1000 m, there is a large increase in wind speed and therefore a deviation away from a log law profile. For the lidar gate which contains the BT tower (170–200 m), a mean wind speed of 8.1 ms^{-1} was derived. In comparison, the mean wind speed observed by the sonic anemometer on the BT tower was only 7.7 ms^{-1}. Lane et al. (2013) showed that despite the large spatial distance between the two instruments

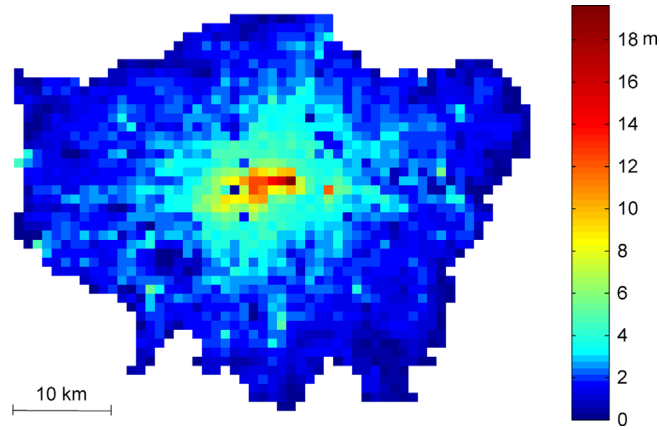

Fig. 2. Displacement height (m) of Greater London derived from urban morphology database on a 1 km^2 resolution.

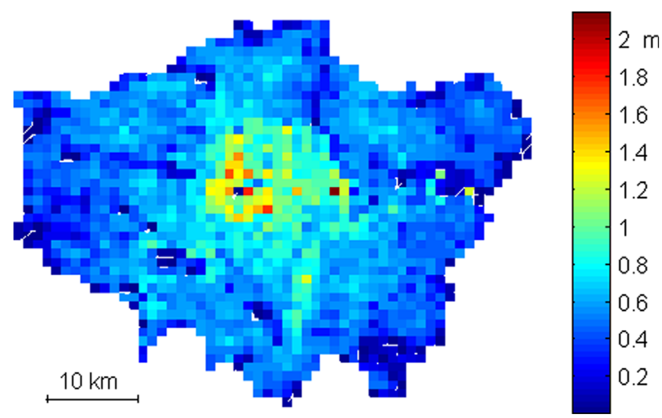

Fig. 3. Roughness length (m) derived from urban morphology on a 1 km^2 resolution for westerly flow.

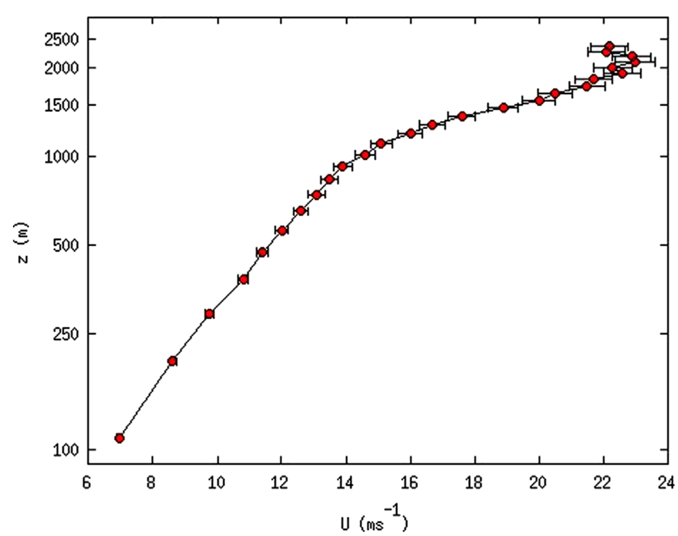

Fig. 4. The mean wind speed profile averaged over the whole observation period (4578 h). Confidence intervals (95%) of the mean are shown.

and the low sampling frequency pf the lidar, there is good agreement between the datasets. However, the lidar wind speed is generally higher by between 0 and 0.5 ms^{-1}.

While the mean wind speed profile exhibits a logarithmic profile up to a height of approximately 1000 m, Fig. 5 shows that

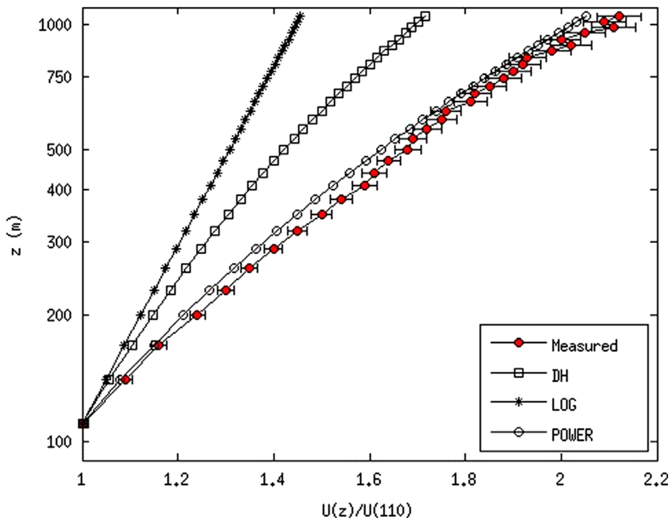

Fig. 5. Comparison between the measured wind speed profile and the profiles predicted by the equilibrium models based on the parameters stipulated in Cook (1997). The wind speeds have been normalised using the wind speed measured in the lowest gate ($z = 110$ m).

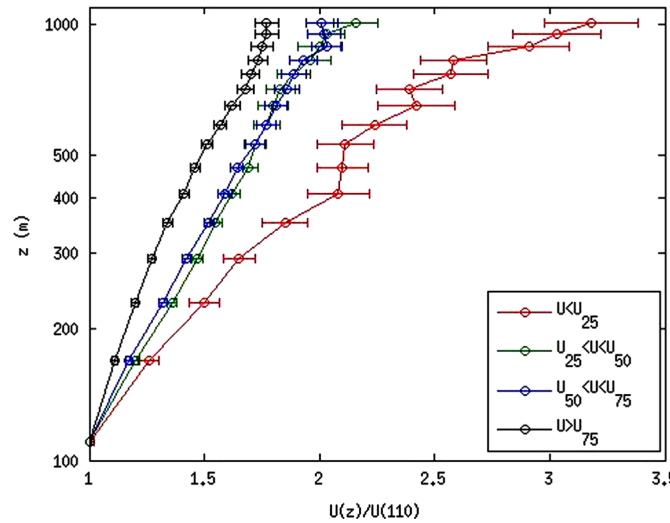

Fig. 6. The mean wind speed profile averaged over the whole observation period filtered by the wind speed observed in the lowest lidar gate. Confidence intervals (95%) of the mean are shown.

based on the surface parameter values stipulated in Table 1, the power law shows best fit to the shape of the measured wind profile. In comparison, both the Deaves and Harris model and the logarithmic profile underestimate the wind shear observed above 110 m. The underestimate of the wind speed suggests that the surface parameters given in Table 1 are too low for the central London location. For example, if α is increased to a value of 0.34, the power law profile remains within the 95% confidence interval of the measured data for all heights up to 1000 m.

The mean wind speed profile presented in Figs. 4 and 5 has been derived by averaging all of the hourly wind speed profiles obtained from the lidar and therefore includes a full range of wind speeds and stability conditions. However, when considering the potential wind loading on a structure, there is a focus on high wind speed periods. The hourly wind speed profiles have therefore been filtered into quartiles based on the wind speed observed in the lowest gate ($U_{25} = 4.7$ ms^{-1}, $U_{50} = 6.75$ ms^{-1}, and $U_{75} = 8.87$ ms^{-1}). Data measured by the sonic anemometer on the BT Tower shows that as the wind speed increases, the conditions are more likely to be neutral. For each hour, a local stability parameter was calculated as $\varsigma = z - d/L$ where the locally-scaled Obukhov length was calculated as

$$L = \frac{-u_*^3 T}{\kappa g(\overline{w'T'})} \tag{10}$$

and $g = 9.8$ ms^{-2} is acceleration due to gravity. For the highest wind speed quartile, the conditions were neutral ($-0.1 < \varsigma < 0.1$) for approximately 30% of the time, in comparison to 6%, 12% and 20% for the lowest, second and third wind speed quartiles respectively.

Fig. 6 shows the mean wind speed profiles derived for each wind speed quartile. The profile obtained from low wind speed periods (lowest quartile) shows the largest deviation from a logarithmic relationship. It also shows a relatively large spread in wind speeds for each height. The profiles for the second and third quartiles are very similar, with a lower wind shear than the low wind speed data. This is to be expected as the logarithmic profile is strictly only valid for neutral stability. For the upper quartile wind speeds, the profile shows a logarithmic relationship up to a height of approximately 500 m with very little spread in the wind speed at each height. Further analysis shows that the Deaves and Harris equilibrium model (with the parameters stipulated in Table 1) provides a good fit to the profile, remaining within the 95% confidence interval of the measured data up to a height of 400 m.

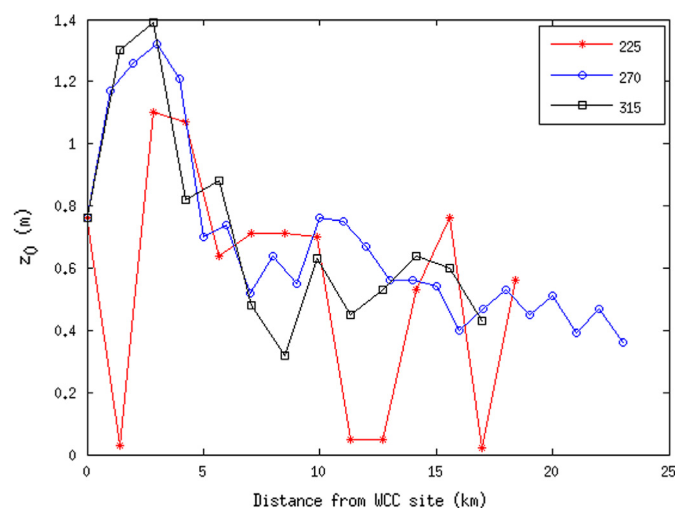

Fig. 7. The magnitude of the roughness length derived from an urban morphology database for three wind directions from the WCC building to the rural boundary.

4.2. Surface heterogeneity

The wind profile data obtained for the upper wind speed quartile have been subfiltered by wind direction (based on observations at London Heathrow). For 80% of the time a wind direction of 225°, 270° or 315° was observed. For each direction the nature of the surface over the fetch has been investigated. Based on the urban morphology data, the magnitude of the roughness length tends to remain relatively constant in the city centre (1.2–1.4 m), before decreasing to a relatively constant value in the suburban region (0.4–0.6 m). However, this relationship is complicated by the presence of a number of large parks relatively close to the city centre, for example the south westerly wind direction is now considered.

For the gridbox which contains the WCC building a roughness length of 0.76 m was estimated. In a south-westerly direction (225°), the magnitude of z_0 decreases to a value of approximately 0.03 m at a distance of approximately 1.5 km upstream, this corresponds to Hyde Park which is characterised as flat, open

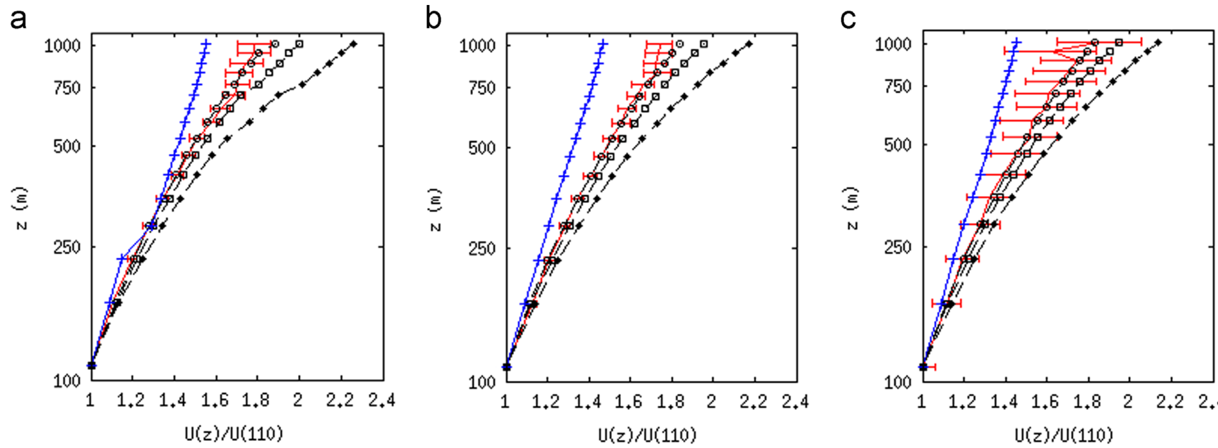

Fig. 8. The measured mean wind speed profile for high wind speed periods ($U > U_{75}$) for (a) South westerly (b) westerly and (c) north westerly winds. The results have been compared to the predictions of the IBL (Blue) and ESDU (Black: V_{10} stars, V_{15} squares, and V_{20} circles) predicted profiles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

grassland. Immediately upstream of Hyde Park, z_0 increases as the nature of the surface returns to high density buildings, this continues until a distance of 11–13 km where there is again a large reduction in z_0, which is associated with Richmond Park. ESDU 82026 states that for gradual changes in roughness length (when the ratio of the larger value of z_0 to the smaller value is less than approximately 3), it is assumed that there is not a step change in roughness and a mean z_0 value is taken. Consequently, for flow from the south-west (225°), 8 step changes in roughness length were identified. For westerly (270°) and north-westerly (315°) directions, the surface is less heterogeneous and consequently only 3 and 4 step changes in roughness respectively were identified.

4.3. Directional wind speed profiles

Fig. 8 shows the measured mean wind speed profiles for the three wind directions. Despite the variations in the nature of surface, a similar profile is shown for all directions. The wind speed profiles estimated by applying the IBL model (Eq. (7)) for the multiple roughness length changes and using the method outlined in the ESDU 82026 are also shown. As the ESDU profiles are dependent on the magnitude of the reference rural wind speed, a range of values have been considered (V_{ref} = 10, 15 and 20 ms^{-1}). In contrast, the IBL model is independent of the friction velocity for each surface, consequently the derived $U(z)/U(110)$ profile is constant for all reference wind speeds.

For the south-westerly direction and a reference wind speed of 10 ms^{-1}, the ESDU wind profile between 110 and 290 m is the result of an inner layer which develops for the change in roughness at a distance of 5.5 km, see Fig. 7 ($z_{0upstream}$ = 0.69 m, $z_{0downstream}$ = 1.09 m). Any step changes closer to the WCC building are not observed in the profile as they have not developed to a height of 110 m, therefore the impact of Hyde Park is not observed in the profile. Between 290 and 560 m, the wind profile is governed by the inner layer which develops as a result of the roughness change at a distance of 11 km (associated with Richmond Park). At greater heights, the profile is governed by inner layers which develop at roughness changes which occur at a distance further upstream. As the reference wind speed increases, the height of each inner layer increases and consequently large differences are shown between each of the model wind speed profiles. For the westerly and north-westerly directions, the ESDU model profiles are less complex due to the reduced number of step changes in roughness.

For each wind direction, the mean wind speed profile (observed for upper quartile wind speeds) has been compared with the results of the two models. For the south westerly direction, the ESDU models (with V_{ref} = 15 and 20 ms^{-1}) provide a good representation of the measured wind speed profile, remaining within the 95% confidence interval up to a height of 750 m. As the reference wind speed decreases, the ESDU model data show a larger deviation from the measured profile. The IBL model is not as accurate; however it is within the 95% confidence interval of the measured data between the heights of 260 m and 440 m. A similar result is shown for the westerly and north-westerly directions, with the ESDU (V_{ref} = 15 and 20 ms^{-1}) profiles providing a good fit to the measured data.

4.4. Assessing the non-equilibrium model using reference data from London Heathrow

The analysis performed thus far has considered the accuracy of the various wind speed profile models assuming a known wind speed at a reference height (z = 110 m), and therefore has been limited to an assessment of the shape of the profiles. However, a reference wind speed in an urban area is rarely available, consequently a wind engineer generally obtains an estimate of the urban wind speed profile by translating the measurements from the nearest weather station.

In this section, the ESDU and IBL models have been used to estimate the urban wind speed profile based on wind speed observations at London Heathrow. For each hour for which the wind direction was between 250° and 270°, the wind speed measured at Heathrow has been translated to an estimate of the wind speed at a series of heights above the WCC building. The analysis has been performed using two methods for representing the nature of the surface between the sites: (1) using the parameters derived from the urban morphology database and (2) by applying the values given in ESDU (2006) based on land use categories. Fig. 9 shows that by using the urban morphology database, 5 step changes in roughness length were identified. In comparison, assessing the land use over the fetch yields only 3 categories (urban, suburban and parkland) and therefore 3 step changes in roughness length.

During the observation period, the wind direction was between 250° and 270° for 1052 h. The data were then organised into quartiles based on the wind speed observed at Heathrow. Fig. 10 shows the estimated mean wind speed profile for each quartile compared with the measured data. For all 4 wind speed quartiles, the wind speed profiles predicted by the ESDU model with the surface parameter data obtained from the urban morphology database show a good fit with the measured data. The results are within the 95% confidence interval for all heights up to 450 m. Above this height, the model tends to overestimate the wind speed. The predictions of the ESDU model with the surface parameters determined using land use as a proxy are not as accurate, particularly for the high wind speed quartile.

The wind speed profiles derived using the equilibrium internal boundary layer model do not show as a good a fit to the measured data. Using the surface parameters data obtained from the urban morphology database, the model underestimates the wind speed at all heights. However, the predictions of the model provide a better fit when the surface parameters are derived from land use.

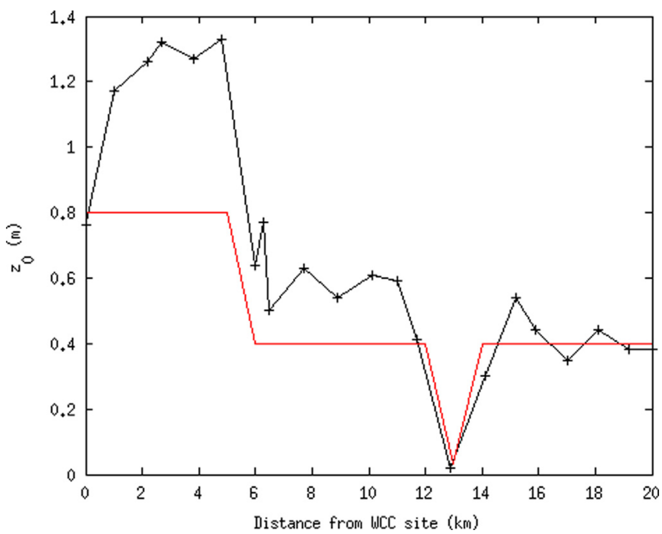

Fig. 9. The magnitude of the roughness length for the surface between the WCC building and London Heathrow, estimated using an urban morphology database (Black) and land use as a proxy (Red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Conclusions

The purpose of this paper was to investigate the wind speed profile over an urban area in high wind speed conditions. As part of the ACTUAL project (Advanced Climate Technology: Urban Atmospheric Laboratory, 2011) a pulsed Doppler lidar has been deployed in Doppler Beam Swinging mode in central London with the aim of determining the urban wind speed profile. This paper has presented results obtained over an 8 month period (May 2011–Jan 2012). The mean wind speed profile for the whole observation period has been shown to fit well with a logarithmic relationship below 1000 m. Above this height, there is a rapid increase in wind speed and therefore a large deviation from the log profile.

The length of the observation period has allowed the investigation of the wind speed profile for a range of wind directions and speeds. For low wind speed periods, conditions are rarely neutral (only 6% of the time) and consequently, the wind speed profile shows a large deviation from a log law relationship. In contrast, for high wind speed periods, neutral conditions occur for 30% of the time and consequently there is less variability in the mean wind speed profile.

For approximately 80% of the observation period, the wind direction was either south westerly, westerly or north westerly. For each direction the nature of the underlying surface has been characterised using an urban morphology database. In general, the magnitude of the roughness length tends to remain reasonably

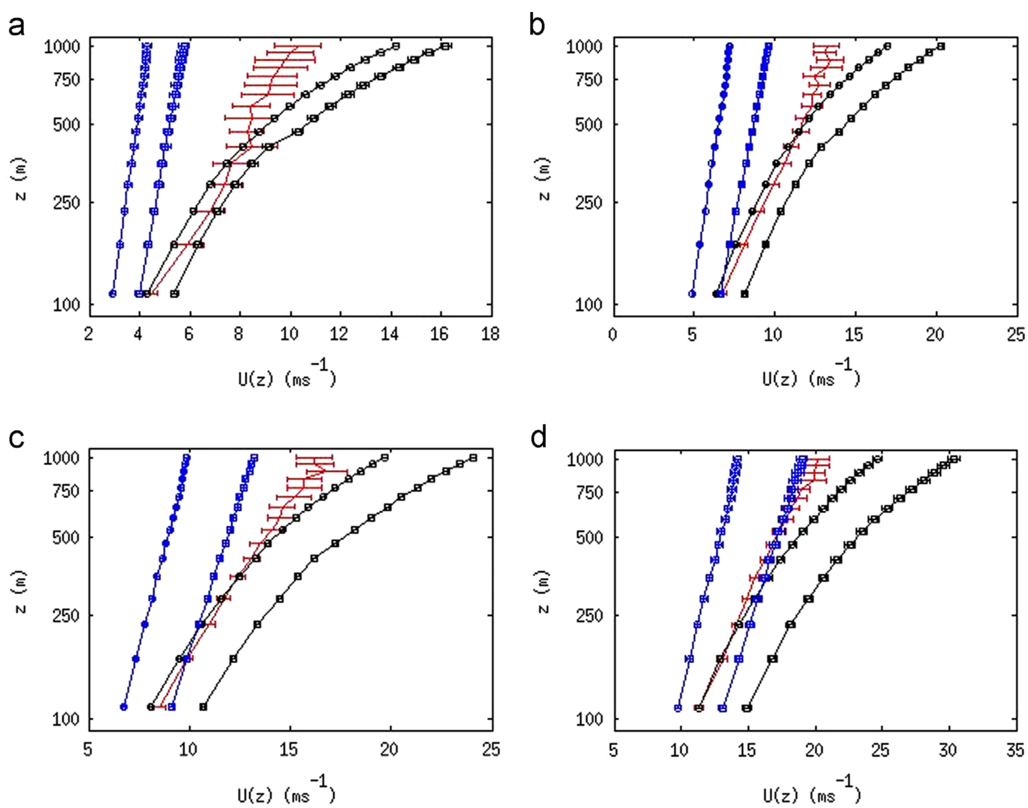

Fig. 10. The measured mean wind speed profile at the WCC building for wind direction 250–270° (red) compared with the predictions of the ESDU models (Black) and IBL model (Blue) for a range of wind speed conditions (a) $U < U_{25}$, (b) $U_{25} > U > U_{50}$, (c) $U_{50} > U > U_{75}$, and (d) $U > U_{75}$. For each model, the wind speed profile has been estimated using the roughness length given in Cook (1997) (circles) and values derived from urban morphology (squares). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

constant in the suburbs before increasing close to the city centre. However, there is a number of large parkland areas scattered throughout the city therefore the fetch for each direction is heterogeneous. Despite this, a similar wind speed profile is observed for the three wind directions.

The second aim of this paper was to investigate the accuracy of the models used by wind engineers to estimate the urban wind speed profile. The analysis has shown that when used in conjunction with surface parameters derived from an urban morphology database, the non-equilibrium model outlined in the ESDU 82026 provides a good representation of the urban wind speed profile. For heights below 500 m, the predicted wind speed profile shows a good fit with the measured data, remaining within the 95% confidence interval. Above 500 m, the model tends to overestimate the wind speed. This relationship is shown for a range of wind speed conditions. In contrast, the equilibrium internal boundary layer model tends to underestimate the urban wind speed at all heights.

The models were also applied using surface parameter data derived using land use as a proxy. However, for this approach the predictions of the ESDU model are not as accurate; it tends to overestimate the wind speed, particularly for very high wind speed periods. In contrast, the predictions of the equilibrium IBL method are improved by using the simple land use derived surface parameters. These results highlight the importance of a detailed assessment of the nature of the urban surface when using the ESDU 82026.

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