Referencing of street-level flows measured during the DAPPLE 2004 campaign

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1. Introduction

Street-level mean flow and turbulence govern the dispersion of gases away from their sources in urban areas. A suitable reference measurement in the driving flow above the urban canopy is needed to both understand and model complex street-level flow for pollutant dispersion or emergency response purposes. In vegetation canopies, a reference at mean canopy height is often used, but it is unclear whether this is suitable for urban canopies. This paper presents an evaluation of the quality of reference measurements at both roof-top (height \( = \ H \)) and at height \( z = 9H \) \( = 190 \) m, and their ability to explain mean and turbulent variations of street-level flow. Fast response wind data were measured at street canyon and reference sites during the six-week long DAPPLE project field campaign in spring 2004, in central London, UK, and an averaging time of 10 min was used to distinguish recirculation-type mean flow patterns from turbulence. Flow distortion at each reference site was assessed by considering turbulence intensity and streamline deflection. Then each reference was used as the dependent variable in the model of Dobre et al. (2005) which decomposes street-level flow into channelling and recirculation components. The high reference explained more of the variability of the mean flow. Coupling of turbulent kinetic energy was also stronger between street-level and the high reference flow rather than the roof-top. This coupling was weaker when overnight flow was stratified, and turbulence was suppressed at the high reference site. However, such events were rare (<1% of data) over the six-week long period. The potential usefulness of a centralised, high reference site in London was thus demonstrated with application to emergency response and air quality modelling.

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scale of the obstruction (Smalley et al., 2008), which is usually larger than the average tree.

Given difficulties in interpreting a rooftop reference, it is preferable to use one in the inertial sublayer where possible. However, during the Joint Urban campaign in Oklahoma City, Klein and Clark (2007) found that turbulence statistics deep within a heterogeneous street canyon depended on stability when scaled using winds at 250 m, but showed weaker dependence when a reference at 80 m was used (equivalent to roof height but measured 2.5 km upstream). Given that the flow had adjusted to the higher roughness of the Oklahoma Central Business District, significant correlation of street-level turbulence statistics with the given reference measurements is questionable. However, the Oklahoma results are consistent with the BUBBLE campaign (Christen, 2005) where only in the "above roof layer" did flow profiles show stability dependence when local scaling was used. Therefore, whilst higher level or upstream reference data are "cleaner", being free of local obstructions, false conclusions can be drawn about processes governing street-level turbulence when stability significantly changes the structure of the atmosphere between reference level and canopy level. Hence, coupling of the flow between street and reference site should be explicitly tested.

In addition, for operational applications such as pollution dispersion modelling or emergency response to hazardous releases, the highly localised reference measurements used during field studies would not be available. Sensitivity studies in Benson et al. (2008) indicated that reference wind direction was the most important input parameter influencing in-street mean flow and turbulence features in a Reynolds-averaged CFD study of a complex street canyon in York, UK. It is therefore of significant interest to evaluate whether "city-scale" reference measurements (e.g. centralised telecommunications tower) accurately represent above-roof flow at the "street" or "neighbourhood" scale.

This paper presents street-level flow measured in central London during the 2004 campaign of the DAPPLE project (Dispersion of Air Pollution and its Penetration into the Local Environment; Arnold et al., 2004) and its relationship to both roof level and higher level reference measurements. The aim of the work is to investigate the influence of local flow obstructions and stability on the suitability of reference measurement locations. Firstly, both reference level measurements are evaluated in terms of local obstructions distorting the flow. Secondly, each reference is used to explain the mean flow structure at street-level, thereby expanding the simple model proposed in Dobre et al. (2005). Finally, the coupling between street-level turbulence and the outer flow is quantified.

2. Experimental description

Measurements were taken during the second DAPPLE project field campaign in the spring of 2004 between 20th April and 12th June. An overview of DAPPLE and available datasets is given at www.dapple.org.uk, and in Arnold et al. (2004). The DAPPLE field site was located in Westminster, London, at the intersection of Marylebone Road with Gloucester Place (lat. 51:31:16N lon. 0:08:21W). Marylebone Road is approximately 38 m wide and orientated WSW-ENE. Gloucester Place is 20 m wide and intersects Marylebone Road perpendicularly (see Fig. 1). Buildings near the intersection are: Westminster City Council House on the SW corner which is 15 m in height with a central clock tower of diameter 5 m which stands 34 m above roof level; Marathon House on the NW corner, 11 m high with a tower-block section which stands 42 m above roof level, of plan dimensions 15 × 33 m; on the NE corner buildings are approximately 30 m high; and Bickenhall Mansions on the SE corner is 23 m high. Within 250 m of the intersection, the tallest building is 53 m, the average building height H = 21 m, and there are no uninterrupted street canyons greater than 150 m in length, i.e. L/H < 7.

Velocity and sonic temperature data were acquired by eleven three-axis, Gill Instruments (R3-50 or R3-100) ultrasonic anemometers (or "sonics"), giving wind-speed measurements with accuracy < 1%, and direction accuracy < ±1°. Four sonics were deployed at the intersection, in pairs at 4 m and 7 m in height, on two lamp-posts in the central reservation of Marylebone Road (Sites 1 and 2, Fig. 1). Two sonics were mounted on lamp-posts 40 m east of the intersection, one at Site 3 on the north side and one at Site 4 on the south side of Marylebone Road, respectively 4.1 and 4.3 m above the ground and ~3 m and 15 m from the nearest building wall. Sonics mounted on lamp-posts were located ca. 2.7 lamp-post diameters away from them horizontally, therefore some flow distortion due to the lamp-post wake affected results when the sonics were downstream. These sonics were sampled at 5 Hz via radio communications between 16th May and 22nd May. Two more sonics were placed on short masts on the pavement at Sites 11 and 12 (respectively 0.5 m and ~5 m distance from walls), with measurement height 1.5 m. These were only deployed for several hours during daytime on certain days to support studies of pollutant exposure in the breathing zone (Kaur et al., 2005). All sonic data were subject to quality control procedures, in particular spike removal.

Roof-top reference conditions were monitored on the Westminster City Council (WCC) building using two sonics at Site 10. The reference labelled WCC in Fig. 1 was on the WCC roof-top in an identical location to that used in the first DAPPLE campaign of 2003 (Dobre et al., 2005). The reference labelled LIB was situated nearby on the WCC Library roof-top, chosen for its potentially better exposure. Both measurements were made at a height of 2 m above the roof-top, i.e. 17 m above the ground. An additional sonic was installed on top of the BT Tower (labelled BT), approximately 1.6 km away to the east (lat. 51:31:17N lon.0:08:21W). This is the tallest building within several kilometres of the site, with good exposure to winds in all directions. The anemometer was clamped to an open lattice scaffolding tower of 18 m height, situated on top of the main
building structure, resulting in a measurement height of 190 m, or \(z \sim 9\, H\).

Throughout this paper a right-hand Cartesian co-ordinate system is used, as shown in Fig. 1. The \(u\) and \(v\) velocity components are aligned along Marylebone Road and Gloucester Place respectively, and the street network is oriented 20° anti-clockwise of north. Positive \(u\) is a wind from WSW to ENE and positive \(v\) is a wind from SSE to NNW. The horizontal wind vector direction is denoted by \(\theta = \tan^{-1}(v/u)\) where \(\theta = 0^\circ\) indicates WSW flow. Data have been averaged over 10 min which Dobre et al. (2005) determined to be long enough to capture the mean street canyon recirculation whilst allowing longer timescale shifts in wind direction to be observed. Despite being a relatively short averaging time for upper level reference data (at \(z = 190\) m) that may result in greater uncertainties in second order moments, the aim of this section was to relate street-level flow to the outer flow and therefore the averaging time was determined by street-level processes.

3. Conditions at reference sites

This section presents the climatology of winds, and assesses each reference site in terms of their deviation away from being “perfect”, i.e. no flow distortion or local wake production of turbulence. Then, the roof-top references are compared with the upper level reference to establish how representative they are of the outer flow.

3.1. Assessing the influence of local disturbances on reference site measurements

Fig. 2 shows the relative frequency distribution of the upper level BT Tower reference wind direction, \(\theta_{BT}\), and sector-averaged wind-speed, \(U_{BT}\) for the campaign, based on 10 min averages. Winds were predominately from the northerly sector, (i.e. \(-135^\circ < \theta < -45^\circ\)) and moderate wind-speeds were recorded with a mean of 4.5 m s\(^{-1}\). High pressure systems pre-dominated during the campaign, which brought northerly sector flow and moderate wind-speeds, with a mean wind-speed at the LIB roof-top reference site of 1.25 m s\(^{-1}\). This contrasts with the first DAPPLE campaign (29th April–22nd May 2003) when south-westerlies dominated and the mean wind-speed at the WCC roof-top reference site was \(\sim 2.3\) m s\(^{-1}\).

To indicate local flow distortion at the BT and LIB reference sites, following Smalley et al. (2008), sector-averaged values of vertical streamline deflection (i.e. \(\tan^{-1}(w/(u^2 + v^2)^{0.5})\)) are shown in Fig. 3. Mean values over sectors of 15° were calculated and error bars show the 10th and 90th percentiles. In Fig. 3a, it can be seen that streamline deflection is upward (positive) for all directions for the BT reference, suggesting flow distortion due to the Tower itself. The vertical deflection angles near \(0^\circ\) show large variability: this direction coincides with lower wind-speeds (see Fig. 2b) and thus local convective influence may be present. Nevertheless, the deflection is relatively small and the mean difference between horizontal wind-speed and wind vector magnitude is estimated to be 5%. Fig. 3b shows that deflections for the LIB roof-top reference generally small. However, there is a more consistent updraught at \(\theta_{LIB} \sim 90^\circ\). As the sonic was located \(\sim 3\) m from the edge of the roof and surrounding buildings are lower, it is likely that there was upward displacement of flow near the edge of the building.

Fig. 4 shows the local turbulence intensity \(T\) calculated for both BT and LIB reference sites, defined as \(T = \sigma_U / U\) where \(\sigma_U = \sqrt{(\bar{u}^2 + \bar{v}^2 + \bar{w}^2)/3}\). For the BT reference, the mean value is 0.15 over all directions and variability is low – there is an outlier value at \(\theta_{BT} = -15^\circ\), but overall there is no evidence of significant generation of turbulence due to local obstructions. Based on this, and the small amount of streamline deflection, the BT reference site is here taken to be representative of the outer flow. The homogeneity of flow statistics with wind direction, together with the Tower’s considerable height above the urban canopy, might suggest that it is within the inertial sublayer, but this will be tested explicitly in a subsequent publication. For the LIB roof-top reference, turbulence intensity is much higher as it lies within the roughness sublayer; however particularly large values can be seen in broad peaks centred on \(-45^\circ\) and \(-165^\circ\). Flow from \(-45^\circ\) places the sonic in the wake of the Marathon House tower-block described in Section 2. The wake length is here estimated to be 10 times obstacle width, giving approximately 240 m. This approximation is consistent with the wind-tunnel study of the DAPPLE site by Carpentieri et al. (in press). As the tower-block is \(\sim 75\) m upstream, wake turbulence is likely to be acting. For \(-165^\circ\), the sonic is \(\sim 50\) m downstream of the tower on top of the WCC building, and therefore probably in a wake region of length \(\sim 50\) m. Roof-top reference LIB is therefore expected to be a less reliable indicator of the driving flow for wind directions centred on \(-45^\circ\) and \(-165^\circ\).

Although wake turbulence generated by roof-top obstacles may well be transported down into the street and have a genuine influence on street-level flow, a reference measurement which is overly influenced by one nearby obstacle is undesirable.

3.2. Relating roof-top reference sites to upper level reference site

Both roof-top references are now related to the upper level reference to assess how well correlated they are with the outer flow. Fig. 5 shows the relationship between 10 min averages of wind direction measured at the BT Tower and both roof-top reference sites for the campaign. For LIB there is a reasonably linear correlation: despite the suspected influence of local tall buildings, the flow does not appear to be consistently deflected. This is in contrast to WCC, for which clear “rectification” (i.e. \(\theta_{WCC} \sim \text{constant for } 0 < \theta_{BT} < 100^\circ\)) occurs, and building wakes may have caused the broad spread of \(\theta_{WCC}\) for \(\theta_{BT} \sim -60^\circ\) and \(-100^\circ\). This reference was used in the first DAPPLE campaign, when predominant wind directions lay between \(-45 < \theta_{WCC} < 60^\circ\). Fortunately, for most of this range, Fig. 5b shows that \(\theta_{WCC} \approx \theta_{BT}\) and thus the reference was a reasonable one to use. The large peak in the frequency of wind direction \(\theta_{WCC} \sim 45^\circ\) observed by Dobre et al.
(2005) may have been partly due to local channelling on the roof-top, as observed here. The main conclusions of Dobre et al. (2005) still hold and their model is further tested in Section 4.1. It can be seen that the LIB roof-top reference is a more reliable indicator of outer flow direction.

Fig. 6 shows the ratio of reference wind-speeds $U_{LIB}/U_{BT}$ as a function of $U_{BT}$, with a 100 point moving average overlaid. This ratio is a function of stability and for $U_{BT} < 2.25 \text{ m s}^{-1}$ (the 10th percentile wind-speed) there is a large spread in the ratio due to buoyant- or wake-produced turbulence. For higher wind-speeds, $U_{LIB}/U_{BT}$ tends to a near-neutral value of 0.23, which is determined by the upstream roughness (weighted in favour of the directions for which the highest wind-speeds occurred, i.e. $\theta_{BT} \approx 45, -45$ and $-110^\circ$ as shown in Fig. 2b).

4. The relationship between reference wind conditions and in-street wind flow dynamics

Having evaluated both roof-top and upper level references, the coupling between street-level and outer flow will now be investigated.

4.1. First order statistics: mean flow

The model of Dobre et al. (2005) for mean flow within a street canyon driven by reference level winds is modified here to allow for the asymmetry in up- and downdraught strength, as observed by e.g. Brown et al. (2000). The reference wind vector is decomposed into two components: one parallel to the street ($u_{||}$) and the second perpendicular to the street ($u_{\perp}$). Positive $u_{||}$ is a wind from WSW to ENE and positive $u_{\perp}$ is a wind from SSE to NNW. Components of the wind vector measured in the street ($u = (u_{||}, u_{\perp}, u_z)$) are here assumed to be related by linear relationships to components of the reference wind vector ($u_f = (u_{||f}, u_{\perp f}, u_{zf})$)

$$u_{||} = u_{||f} \hat{u}_{||}(x_t/W, x_z/H, H/W)$$

$$u_{\perp} = u_{\perp f} \hat{u}_{\perp}(x_t/W, x_z/H, H/W, \text{sgn}(u_{\perp f}))$$

$$u_z = u_{zf} \hat{u}_z(x_t/W, x_z/H, H/W, \text{sgn}(u_{\perp f}))$$

(1)

where the hatted variables are dimensionless functions of dimensionless variables denoting street aspect ratio ($H/W$) and position in the canyon ($x_t/W, x_z/H$), where $x_t/W = 0$ lies mid-way between the walls. The across-street and vertical velocity components are associated with the recirculating component of the flow: note that the dimensionless functions $\hat{u}_{\perp}$ and $\hat{u}_z$ are functions of incident wind direction, indicated by $\text{sgn}(u_{\perp f})$, to reflect asymmetry of the recirculation strength across the street.

The in-street wind direction, $\theta$, is given by

$$\tan \theta = \frac{u_{\perp}}{u_{||}} = \frac{u_{\perp f} \hat{u}_{\perp}(x_t/W, x_z/H, H/W, \text{sgn}(u_{\perp f}))}{u_{|| f} \hat{u}_{||}(x_t/W, x_z/H, H/W)} = \frac{\hat{u}_{\perp}}{\hat{u}_{||}} \tan \theta_f$$

(2)

As all street canyon sites (3, 4, 11, 12) lie on Marylebone Road, then $\theta$ is defined according to the Cartesian co-ordinate system with $u_{\perp} = v$ and $u_{||} = u$. Calculating in-street wind direction is a two-step process: a) linear regression between in-street and reference wind components to obtain hatted variables (equation (1)), and b) calculate wind direction using hatted variables in
Fig. 5. Reference wind direction comparison: a) \( \theta_{\text{LBP}} \) against \( \theta_{\text{WCC}} \), b) \( \theta_{\text{WCC}} \) against \( \theta_{\text{BT}} \).

The methodology used here is to identify which reference gives a model prediction with best fit to the data-points. Scatter is due to deviations of the flow away from “perfect” street canyon flow, or uncertainty in flow statistics. For low wind periods the 10 min averaging time may even be shorter than the advection time between the street and the BT Tower: in addition, the influence of local buoyancy and traffic may cause additional scatter. Qualitatively, for positive angles (southerly flow sector) the best agreement is given using the BT reference (Fig. 7c). For negative angles the fit is less good in each case with a wide spread of \( \theta_3 \) for \(-135 < \theta_3 < -100^\circ\), which corresponds to the site being in the weaker, updraught side of the recirculation. For near-perpendicular flows, large scatter in mean flow direction is expected as the along-street component may be switching direction due to “rectification” at timescales smaller than the averaging time (Dobre et al., 2005). For WCC and LIB roof-top references, the clustering of points for \( \theta_3 \sim -120^\circ \) is consistent with the “rectification” effect discussed for Fig. 5b, due to local obstructions. Despite its great height with respect to the street, the BT Tower reference appears to be most representative of the outer flow which drives the street scale mean flow.

Fig. 8 shows the model applied to data from Sites 3, 4 and 11 to test how closely the flow at each site resembles idealised street canyon flow. The top row shows measured and calculated direction \( \theta \) for each site as a function of reference wind direction \( \theta_{\text{BT}} \), the middle row shows the linear regression between parallel flow components \( u_\parallel \) and \( u_{\text{BT}} \), and the bottom row shows measured and calculated recirculation strength \( u_C = (u_x^2 + u_y^2)^{0.5} \) against perpendicular component \( u_{\perp} \). In general, the model predictions agree well with the data: the asymmetry in recirculation for Site 3 (Fig. 8g) is well captured, and contrasts with Site 4 (Fig. 8h) which is on the opposite side of the street. As Site 4 is much further from the wall than Site 3 (15 m, \( |x_3/H| \sim 0.1 \)) cf. 3 m, \( |x_4/H| \sim 0.4 \), it is much closer to the recirculation centre and this may explain the smaller asymmetry in recirculation strength with wind direction. Despite the low height of Site 11 (\( x_1/H \sim 0.07 \)), there is a remarkably good fit in direction for \(-45 < \theta_3 < 45^\circ \) (Fig. 8c). The large spread of data for \( \theta_{\text{BT}} \sim -120^\circ \) is probably due to a fence which was upstream for this flow direction. Despite the influence of passing traffic, pedestrians and street furniture, typical street canyon flow is recognisable. However, for Site 12, at \( x_2/H \sim 0.07 \) but on the north side of Marylebone Road, the model fit was poor (not shown), indicating that any street canyon type flow was being disrupted by local flow patterns. For practical reasons the site was located only 0.5 m from a wall and the in-street wind direction indicated channelling parallel to the wall for most reference wind directions.

4.2. Second order statistics: turbulent kinetic energy

The previous section demonstrated the coupling between mean flow dynamics within the street and the mean outer flow at the reference height. This section now considers coupling between in-street turbulent mixing and both the mean and turbulent components of the outer flow. Site 3 was chosen for this analysis as it has the largest number of data-points (>4000) over the full range of wind directions.

Turbulent kinetic energy (TKE), represented by \( \overline{\tau} \), was chosen to represent turbulent mixing, and is given by \( \overline{\tau} = \left( \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right)/2 \). Note that due to the 10 min averaging period, larger scale contributions to TKE will not be included, particularly for upper level measurements, leading to underestimation. Following Smalley et al. (2008), data were selected for which there was little influence from local obstructions. Fig. 9 shows the sector-averaged turbulence intensity calculated for Site 3 (\( T_3 \)) as a function of \( \theta_{\text{BT}} \). Large values can be observed for easterly sector flow, i.e. \( \theta_3 = 180^\circ \pm 90^\circ \), where the sonic is in the lamp-post wake. For the range \(-45^\circ < \theta_3 < -75^\circ \), turbulence intensity at Site 3, and the BT reference site (see Fig. 4), is low and approximately constant, and there...
is an even spread of data-points across the bins (mean number per bin ± standard deviation: 203 ± 33). Constant turbulence intensity is here assumed to indicate that both measurements are not being influenced by additional wake turbulence, thus only the range \(-45° < \theta_r < +75°\) is used.

Firstly, the relationship between in-street TKE and the outer mean flow is investigated by calculating the correlation coefficient between TKE and a) the mean wind-speed \(\langle U_r \rangle = 0.66\) b) the parallel component \(\langle U_{r|t} \rangle = 0.30\); and c) the perpendicular component, \(\langle U_{r|s} \rangle = 0.68\). These results show that variability in in-street TKE at Site 3 is best explained by the perpendicular component of the mean flow. As seen in the previous section, there is a strong relationship between this component and the recirculation within the street. In contrast, TKE is less well correlated with the parallel component. Therefore it can be deduced that most turbulent mixing at this site is driven by the recirculation. The range of winds considered encompasses the range where flow is parallel to the street, (“channelling flow”) taken by some authors (e.g. Rotach, 1995) to be \(0 ± 30°\). The present result suggests that the recirculation is a strong feature of the flow even for channelling flow.

Secondly, the relationship between in-street TKE and reference height TKE was investigated. Following the Smalley et al. (2008) methodology, two further constraints were applied to the data to ensure that the underlying dependence of TKE on mean wind-speed was removed: a) the reference wind-speed was constant to within \(0.1\ m\ s^{-1}\), and b) there was negligible correlation between reference wind-speed and TKE at both the in-street site and reference site, i.e. \(\langle TKE \rangle_{r|t} = 0\) \(\langle TKE \rangle_{r|s} = 0\).

For constraint a) data were ranked in intervals of \(\Delta U_r = 0.1\ m\ s^{-1}\), and those intervals with more than 29 data-points were analysed, which is approximately twice the number used in Smalley et al. (2008). (NB: \(U_r = 2.5\ m\ s^{-1}\) was included with only 24 to span the range of wind-speeds). According to constraint b), data intervals were rejected if correlations \(\langle TKE \rangle_{r|t}\) and \(\langle TKE \rangle_{r|s}\) were significant, chosen when \(R^2 > 0.03\), after Smalley et al. (2008). Then the regression \(\bar{TKE} = A\bar{U}_r + B\) was computed and Table 1 shows the results, indicating a statistically significant linear relationship at at least the 2% level. These results concur with the Smalley et al. (2008) result, that the TKE within the street is directly correlated with TKE in the flow above roof. Note that the \(U_r\) values lie evenly spread between the 10th (2.25 m s\(^{-1}\)), 25th (3.40 m s\(^{-1}\)), 50th (4.84 m s\(^{-1}\)) and 75th percentile (6.51 m s\(^{-1}\)). The analysis was also completed for higher values of the wind-speed (7.2, 7.8, 8.5 m s\(^{-1}\)), even though the number of samples was 17, 15 and 15 respectively.

Interestingly, the offset value, \(B\), is reasonably constant across all wind-speed ranges tested (mean \(B = 0.34\), standard deviation 0.09 m\(^2\) s\(^{-2}\)). As this is in-street TKE when the TKE of the external flow is extrapolated to zero, one interpretation is that the offset quantifies TKE production due to processes other than shear production. Traffic is likely to dominate for this site, being heavy at most times of day (ca. 3000 vehicles per hour during the day, Tomlin et al., submitted for publication). Smalley et al. (2008) did not observe such large, consistent offsets. Their measurement heights were at \(z = 5 m \pm 0.5 \), whereas Site 3 is at \(z = 4.1 m \pm 0.2 \). It is possible that Site 3 experiences stronger influence from traffic-produced turbulence due to its height and being next to a bus lane with regular double-decker buses of height ca. 6 m.

5. Stability effects

Bulk thermal structure of the layer between the roof-top reference and the BT Tower was determined by calculating the ratio between virtual potential temperature \(\theta_T\) (approximated using the sonic temperature \(T_S\)) at each reference site, i.e. \(\theta_{VT}/\theta_{LIB-}\)
A ratio greater than 1 implies that the atmosphere is statically stable. This was found to happen on 1% of occasions (out of 5361 coincident 10 min averaged data-points). Such events happened overnight on eight nights out of the total of 42 on which data were recorded. General features associated with each event were

- Increase in the ratio of wind-speeds, $U_{BT}/U_{LIB}$ (clearly driven on half of the occasions by an increase in $U_{BT}$)
- Normalised TKE at the BT reference dropped to near zero values whilst the LIB rooftop TKE was maintained and
- Standard deviation of sonic temperature at the BT reference, $s_{TsBT}$, became higher than at the LIB rooftop, $s_{TsLIB}$.

All these observations suggest that the BT Tower was in a stable layer aloft, where the local temperature gradient was large, and on occasion a nocturnal jet was probably occurring.

Fig. 10a and b shows one of the stronger examples of a stable layer on 2nd May 2004, and a weaker event on 3rd May. Fig. 10a shows a time series of $T$ and $s_{Ts}$ for both BT and LIB reference sites. Before 2nd May, $T_{LIB}$ is clearly higher than $T_{BT}$, in contrast to the 2nd and 3rd May. $\sigma_{TsBT}$ became higher than at the LIB rooftop, $\sigma_{TsLIB}$. All these observations suggest that the BT Tower was in a stable layer aloft, where the local temperature gradient was large, and on occasion a nocturnal jet was probably occurring.

Table 1

<table>
<thead>
<tr>
<th>$U_r$ range (m s$^{-1}$)</th>
<th>Number of samples</th>
<th>$A$</th>
<th>$B$</th>
<th>$R^2$</th>
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<td>0.19</td>
</tr>
</tbody>
</table>

Lower interval wind-speed.
The correlation between 01:50 and 07:20 on 2nd May, indicating suppression of measurements) was above the critical threshold $R_b$ top reference. The bulk Richardson number (based on BT and LIB to near zero at the BT reference but is maintained at the LIB roof-top reference site measurements, and was rarely decoupled overnight decoupling events appear to be rare in London, suggesting better coupling to the upper level reference. Given that such overnight decoupling events appear to be rare in London, overall the BT reference is suitable for scaling street-level turbulent flow.

6. Conclusions

This paper presented data from the second DAPPLE campaign in late spring 2004, an evaluation of reference measurements and analysis of coupling between street-level and outer flow. Several conclusions can be drawn from the results:

1) The paper presented a methodology for assessment of reference sites. For the conditions studied, the upper level BT reference at $z \sim 9$ H was more suitable for scaling street-level flow as it was free of local obstructions which affected the roof-top reference site measurements, and was rarely decoupled due to stable conditions. The LIB roof-top reference showed some correlation to street-level flow but was more useful in explaining mean flow variability rather than turbulent kinetic energy variability. The results support the use of a central reference site in London in order to inform air quality or emergency response management studies. The BT Tower could potentially be a suitable long-term reference to support studies at street scale – efforts to enable this are currently underway.

2) The decomposition model of Dobre et al. (2005) was applied to flow recorded within a relatively regular street canyon with $H/H_W \sim 0.5$, in order to determine which reference level wind velocity was more appropriate. Whilst the application of the model to more complex flows is less successful (Klein et al., 2007), here it explained a reasonable amount of the flow structure at several sites, even at low heights potentially influenced by traffic-produced turbulence. The model makes an assumption that the linear relationship between parallel components in the street and that above is invariant with wind direction. Although Soulat et al. (2008) suggested theoretically that this should not be the case, given the spread of data for the current sites, the results show it is a reasonable first order assumption. It is concluded that the model shows that the recirculation is a strong feature which dominates mean flow structure for this particular street.

3) Street-level turbulent kinetic energy was best correlated with the perpendicular component of the reference flow at Site 3. This shows the importance of the recirculation in mixing air at street-level. Noted also was the wide spread in street-level wind direction for near perpendicular reference flow, particularly when the street-level measurement was in a down-draught. This indicates two things: a) flow rectification means that the parallel component of street-level flow does not disappear for mean perpendicular flows, as in idealised simulations, and b) this unsteady process (even at the scale of 10 min) leads to large amounts of turbulent mixing.

4) Stable conditions occurred occasionally overnight, and street-level flow was less well coupled to the upper level reference as a result. However, the present results showed that such events occurred < 1% of the time over 6 weeks in late spring in London, which is in agreement with earlier work in central London by Spanton and Williams (1988) who analysed sodar reflectivities and determined that ground based inversions occurred <1% of the time over an 18 month period. The present result is to be contrasted with Klein and Clark (2007)’s analysis of data from the Joint Urban campaign in July 2003 in Oklahoma City, where a stable layer was often observed overnight, with a nocturnal jet. This implies that it cannot be generalised as to whether stable conditions are uncommon over urban areas at night, as they are a strong function of thermal advection due to regional scale flow processes (e.g. Great Plains low level jet, katabatic winds, sea breezes) in addition to the impact of local urban cover type on the surface energy balance. A year-long dataset of turbulence statistics for both LIB roof-top and BT reference sites is currently being analysed to establish a better climatology of such events for London.

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