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Tracer concentration profiles measured in central London as part of the REPARTEE campaign

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Abstract

There have been relatively few tracer experiments carried out that have looked at vertical plume spread in urban areas. In this paper we present results from cyclic perfluorocarbon tracer experiments carried out in 2006 and 2007 in central London centred on the BT Tower as part of the REPARTEE (Regent's Park and Tower Environmental Experiment) campaign. The height of the tower gives a unique opportunity to study dispersion over a large vertical gradient. These gradients are then compared with classical Gaussian profiles of the relevant stability classes over a range of distances as well as interpretation of data with reference to both anemometry and LIDAR measurements made. Data are then compared with an operational model and contrasted with data taken in central London as part of the DAPPLE campaign looking at dosage compared with non-dimensionalised distance from source. Such analysis illustrates the feasibility of the use of these empirical correlations over these prescribed distances in central London.

1 Introduction

There have many been many atmospheric tracer experiments carried out in urban areas (Hanna et al., 2003; Venkatam et al., 2004) which have focused on the horizontal spread and/or the along wind spread of the plume. There have been relatively few investigations into the vertical plume spread, in the main because of the feasibility of making measurements away from the surface. The tracer experiments undertaken here complement the experiments undertaken during the CityFlux campaign in central Manchester, UK, which also focused on vertical tracer gradients in urban areas (Petersson et al., 2009).

In urban areas the URGENT (URban Regeneration and the ENvironmenT) campaign undertaken in Birmingham, UK, 1999–2000, was probably the first tracer experiment conducted to publish results concerning vertical concentration profiles in an urban area.

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Here a uniform vertical profile was found in a 20 m deep street canyon around one kilometre away from the source (Cooke et al., 2000). The results were compared with the ADMS3 model developed by CERC and there was good agreement (Britter, 2002). Similar results were found during the BUBBLE (Basel UrBan Boundary-Layer Experiment) tracer experiments in Basel, Switzerland. Here a uniform vertical profile was found in a 17 m deep street canyon, 700 m away from the source. In these experiments, three receptors were utilised: one at ground level, one at 10 m and one at a roof level of 17 m (Rotach et al., 2004).

The most extensive set of tracer experiments regarding vertical dispersion was undertaken in Oklahoma City during the Joint Urban 2003 campaign. An instrumented crane system was developed and receptors were placed approximately every 5 m from about 10 m to up to 75 m (7 receptors in total). The sampling crane was placed approximately 1000 m away from the SF_6 release site (Flaherty et al., 2007). A total of 32 releases were made both during daytime and night-time. For the daytime experiments conducted in July, the results indicate that the plume was relatively well mixed where the lowest concentration measured in the vertical profile was typically within 50% of the maximum concentration. However, maximum concentration was measured more often in the lower half of the profile. The daytime and night-time results revealed only a slight difference, though a less-uniform profile was seen during night-time indicating that convective mixing is important for dispersion (Flaherty et al., 2007). During the Joint Urban 2003 campaign, one experiment was also carried out where the source-receptor distance was only 500 m. Here, a distinct vertical concentration profile was revealed where the 75 m receptor measured one quarter to one half of the maximum concentration that tended to be nearer the ground than when source receptor distance was 1000 m (Flaherty et al., 2007). This highlights the dependence of distance on the vertical concentration profiles on distances downstream. Five experiments investigating vertical dispersion were also undertaken in the early-to-mid twentieth century. Here, more exotic tracers such as smoke at Porton Down, UK, 1923–24, (Pasquill, 1974), sulphur dioxide (Prairie Grass, 1956; Nieuwstadt and van Ulden, 1978) and

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zinc cadmium sulphide (Green Glow, 1962; Barad et al., 1962) were used. The data set most extensively used for evaluating vertical concentration profiles have been the Prairie Grass dataset. One complication with this dataset though is the use of sulphur dioxide as a tracer which is known to undergo dry and wet deposition. The deposition needs to be taken into account when analysing these data (Britter et al., 2003).

This paper presents data from tracer experiments completed during two campaigns in 2006 and 2007 of the REPARTEE (REgent's PARk and Tower Environmental Experiment) project in central London, UK. Horizontal distances ranged between 500 and 1000 m, but the highest receptor was at 190 m, allowing better determination of the dependence of the concentration profile on height. Accompanying Doppler lidar measurements elucidated the turbulent structure of the boundary layer.

2 Experimental

2.1 Site description (building morphology)

The BT Tower (lat. 51:31:17 N lon. 0:08:21 W) is located in Fitzrovia in central London (see Fig. 1). The main structure is 177 m tall with a further section of aerial bringing the height up to 189 m. It has had grade 2 listed building status since 2003. The experimental area consists of densely packed mixed residential and commercial buildings with 4–5 storeys. Buildings within 250 m of the nearby DAPPLE project site (Wood et al., 2009a) have a mean height of 21 m and range up to approximately 50 m.

2.2 Tracers (technique, layout, source-receptor distances)

2.2.1 Technique

The compounds used here as tracers are inert, non-toxic and are a specific type of perfluorocarbon called a perfluoroalkylcycloalkane which are based around a saturated carbon ring which is fully fluorinated. Typical atmospheric background concentrations

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for the most commonly used perfluorocarbons in tracer experiments are in the low ppqv range (Simmonds et al., 2002; Kim et al., 2002; Watson et al., 2007) and the current growth rate is, if any growth rate at all, less than 1 ppqv per year (Watson et al., 2007). These compounds have been used previously in dispersion experiments ranging from long range studies (Draxler et al., 1991; Straume et al., 1998) down to city and neighbourhood scales (Arnold et al., 2004; Martin et al., 2008; Shallcross et al., 2009; Wood et al., 2009).

2.2.2 Release

Cyclic perfluoroalkanes were obtained as pure liquids (F2 chemicals Ltd., Lancashire, UK) and gravimetric dilutions of Perfluoromethylcyclopentane (PMCP) and Perfluoromethylcyclohexane (PMCH) were prepared (Linde Gases Ltd., UK). Release gases were prepared at appropriate gaseous concentrations (PMCP 4%, PMCH 1.5%, and PDMCH 0.25%) in air with certification accuracy of ±2%. The release apparatus consisted of a stainless steel 15 l silica lined canister (Restek Ltd., Bellefonte, PA, USA). A specialist software programme, READ30, which is supplied by the manufacturer, monitors the output from the pressure transmitter. Temperature dependencies and non-linearity of the sensors are mathematically compensated for after the release (given the known air temperature). The gas flow rate was controlled by the use of a Flostat Flow Controller (Type MNBS12) (Roxspur Measurement and Control Ltd., Hampshire, UK).

2.2.3 Sampling

Samples were taken at each receptor position using an air-sampling pump (SKC Ltd., Dorset, UK) sampling at a flow rate of about 0.9 l min^{-1} and taking air from ~1.5 m above ground level. Samples were collected in 10 l Tedlar bags (SKC Ltd., Dorset, UK). The release/sampling start time was synchronised for all release and receptor sites by the use of radio-controlled clocks. Physical isolation of the release and sampling teams was ensured at all times before, during and after the experiment, in order to avoid contamination of the collected air samples.

2.2.4 Analysis

The analytical instrumentation consists of gas chromatograph (Model 6890, Hewlett Packard Ltd., USA) attached to a mass selective detector (Model 5973, Hewlett Packard Ltd., USA). For determining cyclic pefluorocarbon concentrations, the mass spectrometer is operated in negative ion chemical ionisation (NICI) as well as selected ion-monitoring (SIM) mode. The technique is highly selective and sensitive, due to very efficient formation of stable molecular anions. For pre-concentration of the samples, an adsorption desorption system (ADS) was used. Varying volumes of calibration standard were trapped onto a cryogenically-cooled micro-trap filled with a carbon-based adsorbent. The trap is maintained at a temperature of $-50\pm3^{\circ}$C during sampling. The adsorbent used was 10 mg Carboxen 569, 40–50 Mesh (Supelco, Bellefonte, USA). Several litres of air may be trapped on to the adsorbent filled micro-trap without exceeding the theoretical breakthrough volumes (BTV). The trap is cleaned under an auxiliary flow of helium at a temperature of 255°C and was replicated four times. The trap is quantitatively desorbed at 255°C. Negligible band broadening occurs due to the small internal diameter of the micro-trap along with the rapid thermal desorption (3–4 s duration). Samples were calibrated using a dilution of a gravimetrically prepared standard purchased from Linde Gases Ltd., UK.

2.3 Experimental layout and source-receptor distances

2.3.1 REPARTEE 1–26 October 2006

An arc of six receptors, with 3 at the BT Tower site (ground level, 160.3 m a.g.l. and 190 m a.g.l.), and 3 other receptors along the arc, were put in positions detailed in table 1). The release of PMCP was made at the intersection of North Row and Balderton Street. The buildings surrounding the release positions are mostly 4–5 storeys high.

The release position is about 1300 m upwind of BT Tower. North Row is a one-way street: traffic flows towards the east along North Row. No access from Balderton Street onto Oxford Street is possible. Almost no traffic was observed on North Row or Balderton Street during the entire release period. Tracer was released for 59 min between 13:50 and 14:49 p.m. at a height of 0.36 m at an average release rate of $3.348\pm0.076\times10^{-6}\,\mathrm{kg\,s^{-1}}$. Six samples were taken at each sampling position according to the following scheme, allowing for 1 min in between each sample in order to have time for personnel to change bags to the sampling pump (1: 13:50–13:59, 2: 14:00–14:09, 3: 14:10–14:19, 4: 14:20–14:29, 5: 14:30–14:39, 6: 14:40–14:49). Table 1 gives the distances from source to the receptor along with the bearing from ° N of the source with respect to the receptor.

2.3.2 REPARTEE 2–7 November 2007

Six dosage experiments (35 min sampling compared with 15 min releases) were undertaken from two release positions with samples taken at 11 receptor sites. The timings of the experiments are shown in Table 2. The layout of these, along with the relevant source- receptor distances, is shown in Fig. 1. Receptors 3–5 refer to ground level, 160.3 and 190 m at the tower, respectively. There are also some basic anemometry measurements made at each release position which includes wind speed and direction.

2.4 Meteorological measurements

Meteorological measurements on top of the BT Tower were taken from a lattice mast on the top of the BT Tower (51.521469° N, 0.138881° W) using a Gill ultrasonic anemometer (R3-100 with symmetric head) sampling at 20 Hz attached to the lattice mast. The sampling height was 190 m a.g.l. A secondary meteorological reference was mounted on the roof of the Westminster City Council Library (51.5210° N, 0.1605° W, the roof and anemometer head heights were 15.5 and 18.4 m, respectively, see Barlow et al.,

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2009). Measurements made at each source release location during the 2007 experiments were made using 2-D sonic anemometers (Windsonic, Gill Instruments) operating at 1 Hz frequency. Wind measurements were taken at both release sites 1.5 m a.g.l.

2.5 LIDAR Measurements

Doppler LIDAR (LIght Detection And Ranging) measurements were taken during the 2007 REPARTEE 2 campaign. The instrument was a Halo Photonics 1.5 μm scanning Doppler lidar sited in the car park of the University of Westminster on Marylebone Road. The instrument ran continuously from 24 October to 14 November 2007 including the 7 November when the tracer experiments were carried out. Due to the proximity and height of the neighbouring buildings, the lidar was restricted to making only vertical stare measurements i.e. directly upwards, measuring the vertical velocity component of turbulent mixing and aerosol backscatter to a height resolution of 30 m at a sampling rate of 0.25 Hz. One of the main advantages of using a high resolution remote sensing instrument such as a lidar was to provide turbulent profiles of the boundary layer alongside the tracer experiments, and to determine boundary layer depth.

3 Results and discussion

3.1 Concentration-time profiles and general comments

3.1.1 REPARTEE 1

The results from the two REPARTEE campaigns can be used to evaluate the spread of a plume in all directions: vertically, laterally and along-wind. Figure 2 shows the variation with time of the 9-min time-resolved concentrations at five of the receptor positions for REPARTEE 1. Values are plotted in the form of C/Q values where C is the concentration in kgm^{-3} at 20°C and Q is the release rate in kgs^{-1}.

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Figure 2 illustrates that there is a finite amount of tracer at all samplers within the first sample, even at top of BT Tower. This suggests rapid transport and vertical diffusion. Averaged half hour wind speeds taken by an automated Väisälä weather station on top of the BT tower indicate an initial wind speed of 12.3 m/s – this would indicate approximately 110 s for horizontal transport at BT Tower height at that speed. With a ratio of rooftop windspeed to BT windspeed of 0.25, (Barlow et al., 2009) then we may expect a transport time of 440 s for a tracer to be advected to the BT Tower at near-rooftop heights.

With respect to vertical concentrations there is a consistent drop off with height (190 m approx. 1/5 to 1/3 of concentration at ground). Given the ratio of height to fetch (190/1300~0.15) is similar to the experiment reported by Flaherty et al. (2007) (75/500~0.15), where they observed 1/2 to 1/4 drop-off, the results reported here are very similar. This may be explained by the fact that beyond a range of ~500m, the plume is largely above the urban canopy, therefore more universal behaviour is anticipated (granted there may be stability differences between the two experiments), whereas for short range (near field <~500 m) the local street network (and thus local morphology) has more of a control on plume dispersion (Wood et al., 2009).

Comparison of receptors 8, 9, 10 on Arc 1 show that plume was centred on the BT Tower for experiments 3, 4 and 5. The relative concentrations suggest that the plume centreline was south of the BT Tower for experiments 1 and 2, giving highest concentrations at receptor 8. This pattern is confirmed by receptors 1, 2, 3, 6, 7 – with higher concentrations at southern-most receptor 7 for earlier experiments – although the pattern is not so clear. Concentrations have more similar magnitudes on Arc 2; suggesting more mixing has taken place in the additional 200 m distance downstream of Arc 1, leading to less difference laterally across the plume.

Receptors on the BT Tower (3, 4, 5) show consistently that the ground level receptor is higher than the others, although the gradient in concentration differs between runs. The concentration gradient for Release Y is much steeper than for Release X, due to the closer distance to the BT Tower. C/Q values at the base of the Tower (receptor 3) for release Y are 6 times larger than for release X, whereas C/Q values for receptors 4 and 5 at greater heights are quite similar, being within a factor of 2. This indicates that the plume concentrations within the urban canopy drop off more rapidly with distance downstream than in the air above. The results also show that significant amounts of tracer have reached a height of 190 m within 500 m of the source.

3.2 Vertical distribution

The dataset most extensively used for evaluating vertical concentration profiles has been the Prairie Grass dataset. One complication with these data though is the use of sulphur dioxide (noted previously) and that its deposition needs to be taken into account when analysing these data (Britter et al., 2003). The results from the early-to-mid twentieth century experiments were later analysed in the main by comparing the results with Eq. (1), which is a generalisation of the Gaussian plume model. The main aim has been to determine the shape exponents:

$$\left(\frac{\chi_Z}{\chi_0}\right) = \exp(-bz^s) \quad (1)$$

χ is the concentration at an elevated (z) position and at ground level (0) and b is a constant. A value of s=1 implies an exponential vertical profile and s=2 for a Gaussian vertical profile.

It was concluded (Eliot, 1961) that s<2 (and closer to 1) for both the Green Glow and the Prairie Grass experiments, respectively. Nieuwstadt and van Ulden concluded, based on the Prairie Grass experiments, that s ranges from 1 in unstable conditions, 1.3 in neutral conditions and 2 in stable conditions (Nieuwstadt and van Ulden, 1978). In other words, they concluded that a Gaussian profile is only a suitable description during stable conditions. It should be noted that these values of s were determined for rural areas over relatively flat terrain, but in areas with higher surface roughness, s typically will be higher (as shown later).

Based on a theoretical approach, Calder concluded that the shape exponent s is dependent on the exponent (α) in the best fitting power law describing the relationship between height and wind speed according to Eq. (2) (Calder, 1949):

$$s = 1 + 2\alpha \quad (2)$$

This relationship was later questioned and Eq. (3) was then proposed (Pasquill, 1983).

$$s = 1 + \alpha \quad (3)$$

The important conclusion, that s depends on α, still holds though. The power law exponent (α) can be determined by Eq. (4):

$$U_Z = U_R \left(\frac{Z}{Z_R} \right)^{\alpha} \quad (4)$$

Where U is the wind speed and Z is the height of the measurement and R a reference measurement. Based on the dependency of the power law exponent with altitude, Irwin demonstrates that α increases (and therefore also the shape exponent) with increasing surface roughness and atmospheric stability (Irwin, 1979). Hunt and Weber (1979) conclude that s should decrease with source-receptor distance. At shorter source-receptor distances, the plume will be dispersed closer to the ground in the surface layer where the value of α is higher compared with a plume that fills up more of the boundary layer (Hunt and Weber, 1979). However, only the effect of atmospheric stability (based on the results from the Prairie Grass experiments) had been verified by experimental results before the present study. The vertical concentration profiles have been compared with the Gaussian plume equation and the results are shown in Fig. 4 for the vertical concentration profiles obtained at three different source-receptor distances used across both campaigns. A clear dependency of the shape of the vertical profiles is found with distance where the shape exponent decreases with distance. From these experiments, it was noted that for source-receptor distances around 1000 m the shape exponent s is close to 2 (Gaussian profile), for distances shorter than 1000 m s is greater than 2

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and for distances longer than 1000 m less than 2 (a shape in between Gaussian and exponential).

Surface roughness is estimated to be comparable between the 2006 and 2007 campaigns as the wind direction was similar and the urban canopy is reasonably homogeneous. The campaigns were conducted at the same time of the year (26 October 2006 compared with 7 November 2007) and all of the experiments took place during overcast conditions with moderate to strong winds (mean windspeed 12.0 and 7.6 $m s^{-1}$, respectively for 2006 and 2007). Hence, comparable stability is assumed, classes C (slight incoming solar radiation, moderate windspeed) and D (overcast) according to Pasquill's stability classes. It should be noted that the estimated s values reported here cannot be used to draw generalized conclusions since the shape of the vertical concentration is also dependent on atmospheric stability and surface roughness; although for source-receptor distances 460 and 980 m the experiments were simultaneous using different tracers, therefore stability and roughness affect the profiles identically. Comparable results can therefore only be expected to occur in cities with a similar magnitude of surface roughness as London and during similar atmospheric stability. These results would suggest that the shape of the vertical concentration profiles are closer to Gaussian in urban areas than in rural areas (compared with the results found for the Prairie Grass experiments) as a result of the increase in surface roughness.

3.3 Lateral distribution

Lateral concentration distributions for all six experiments during the REPARTEE 2 campaign have also been obtained: Fig. 5. results are displayed based on source X for the arc furthest away from the sources, i.e. for receptors 1, 2, 3, 6 and 7. The origin for the lateral distance has been located at has been located at the receptor measuring the highest concentration. A positive distance implies going southwards along the arc and a negative distance going northwards. Qualitatively, a Gaussian distribution in the lateral direction seems a reasonable approximation. The width of the plume for an individual experiment is comparable with the width of the Gaussian profile. The asymmetry of the profiles is caused by the limit in the number of receptors, since the receptor measuring the highest concentration is not perfectly on the plume centreline. The approximation of a lateral Gaussian profile was also found to be valid during the BUBBLE experiments with source receptor distances of 700 and 1000 m (Rotach et al., 2004).

3.4 Meteorological results

3.4.1 Reference anemometry measurements

Shown in Table 3 are the anemometry measurements made during the experiments carried out in 2007. An extensive study of the relationship between the meteorology of the two reference anemometry sites has been undertaken, studying the relationship between wind speeds measured at the BT Tower and the top of WCC (Barlow et al., 2009). There is a high degree of correlation between the measurements with the ratio of the mean values of BT Tower/WCC wind speeds being in the region of 4.1:1 over the whole year (although a slope of 5.7 is obtained when a linear regression is performed through 30-min means). The values measured during the 2007 experiment are slightly higher than the average but well within the range of measurements made and can be judged to be atypical conditions.

3.4.2 In-street meteorological measurements

In-street sonic anemometry measurements were performed at both release positions and the results for these are shown in Table 4. Direction measurements show a reasonable agreement with BT Tower for position X while there is clear offset between BT Tower direction and release position Y. Given the release position of Y along a major thoroughfare it is possible that there is a degree of street channelling due to traffic flow occurring here.

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3.4.3 LIDAR data

Shown in Fig. 6 are the LIDAR measurements categorised into the individual experimental periods for the 7 November, 2007. The various variables measured by the LIDAR are shown here during the experiments to illustrate quantitative differences between consecutive tracer experiments.

The boundary-layer top measured finds the limit to which the LIDAR measures backscatter, which again we assume is equivalent to aerosol. The 7 November was a relatively cloudless day and these will show the top of the "entire" boundary layer i.e. somewhere in the entrainment zone between the cleaner troposphere and the more polluted boundary layer below. For experiments 1 and 2 there is a very similar boundary layer, convective layer and turbulent mixing layer heights.

The convective mixing layer height is calculated using a threshold on the value of the vertical velocity variance. The variance gives us a measure of the intensity of the vertical turbulence occurring, which is dominated by convection during the day. As the sunlight dissipates, the convective layer falls in the late afternoon although there is a slight offset between the turbulent mixing layer and the convective mixing height indicating some shear mixing. This starts to occur during the 3rd experiment with the turbulent mixing layer dropping to about 500 m. This general pattern would be deemed to be representative of meteorological conditions at this time of year. Given a similar wind direction between experiments we may expect maximum concentrations to increase during the course of the day as the convective layer and the turbulent mixing layer lowers. The limited number of experiments here and the slight variations between reference wind directions during experiments means it is hard to attribute concentrations to changes in boundary conditions although it contextualises the data in terms of meteorological conditions.

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3.5 Model evaluation

The dosage, D, is defined as the time-integrated concentration, C, over an exposure period, T: the exposure period in this case is the sampling period and this has been selected to be sufficient for the whole emitted tracer-cloud to clear the experimental area, in which case D is independent of T. The dosage of gas accumulated over the sampling time, D (in kgm^{-3}s), is made dimensionless by choosing appropriate velocity scales using the wind speed, U_H (in ms^{-1}), since we focus on the neighbourhood scale, we expect the urban geometry to control the dispersion. It is then appropriate to choose the mean wind speed at mean roof level, U_H, for a scale of wind speed and for these data we use the WCC wind speed.

This gives the natural dimensionless dosage as

$$D^* = \frac{DU_H H^2}{M}. \quad (5)$$

These data are then plotted against normalized (to building height, H) distance from the source.

$$\frac{DUH_b^2}{q} = K\frac{H_b^2}{x^2} \quad (6)$$

The constant K in the model is likely to depend on urban morphology parameters and is also dependent on what wind speed is being used in the model. Here, the chosen wind speed for the BT Tower experiments is the one obtained from measurements on top of Westminster City Council building in central London, UK, where the DAPPLE area is located. Data here are presented in conjunction with data taken from central London measured during the DAPPLE campaign of 2007 campaign for reference (Wood et al., 2009a). The DAPPLE field site is in Westminster, central London, centred on the intersection of Marylebone Road and Gloucester Place, NW1. This involved multiple source dosage experiments from multi-position sources over a number of different wind flow regimes. The correlation is shown in Fig. 7.

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The simple correlation model does reproduce the upper bound of the concentrations at distances up to 1 km as found here if an appropriate value of K is chosen. A value of K of 10 encompass almost all cases encountered here whereas a K of 20 may be used to encompass even the more specific cases when the tracer is channelled in a street canyon. Over the REPARTEE distance we would expect the effect of street channelling to be minimised resulting in data falling below the lower bound and this is indeed the case.

4 Conclusions

Novel experimental results were obtained from central London dispersion experiments as part of the REPARTEE campaign. Vertical tracer profiles up to 190 m using the BT Tower were obtained over horizontal distances of up to 1 km were elucidated using the controlled release of cyclic perfluoroalkanes. Comparison of these vertical profiles would indicate that the general shape of the vertical concentration profiles are closer to Gaussian in urban areas than in rural areas (compared with the results found for the Prairie Grass experiments) as a result of the increase in surface roughness. A Gaussian distribution was found to be a good approximation for data obtained and the widths obtained are approximated well by a Gaussian profile.

Experimental data were then pooled with experimental data obtained as part of the DAPPLE campaign. Both these campaigns were based in central London and together looked at distances of <100 m up to 1 km. The variability of the non-dimensional dosage is plotted against the non-dimensionalised straight-line distance from the source and this illustrates that the empirical upper bound derived from the DAPPLE dataset ($K=10$) can be extended out to longer range. This decay of downstream concentration is consistent with an inverse square relationship and the extension of the relationship is useful in terms of emergency response planning. The street channelling effect observed at shorter distances which resulted in exceeding in a $K=10$ fit was not observed over the longer distances measured here.

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Table 1. Geographical data for the sampling positions for the 2006 experiment (26 October).

Position	1	2	3	4	5	6
Position or intersection of	Great Portland St and Langham St	Cleveland St and Clipstone Mews	BT Tower, ground level	BT Tower, T35	BT Tower, T45	Cleveland St and Foley St
GPS coordinates	51.5189 N 0.1422 W	51.5225 N 0.1411 W	51.5214 N 0.1391 W	51.5214 N 0.1391 W	51.5214 N 0.1391 W	51.5202 N 0.1384 W
Approximate distance from release position (m)	920	1240	1270	1280	1280	1230
Angle from release postion (° from N)	229	218	226	226	226	231
Distance above ground (m)	0	0	0	160	190	0

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Table 2. Release and sampling times for the six experiments conducted during the REPARTEE 2 campaign (all times LT).

Experiment	Release time	Sampling time
A	13:00:00–13:15:00	13:00:00–13:35:00
B	13:45:00–14:00:00	13:45:00–14:20:00
C	14:30:00–14:45:00	14:30:00–15:05:00
D	15:15:00–15:30:00	15:15:00–15:50:00
E	16:00:00–16:15:00	16:00:00–16:35:00
F	16:45:00–17:00:00	16:45:00–17:20:00

Table 3. Meteorological measurements made during REPARTEE 2 (calculations of wind speed and direction were calculated from a sonic anemometer using double-rotation streamwise analysis) Wood et al. (2009b).

Exp. no.	BT Tower (190 m)				WCC Library (18.4 m)			
	Wind[a] dir (°)	St dev. (°)	Wind speed (m/s)	stdev	Wind dir (°)	St dev. (°)	Wind speed (m/s)	St dev. (°)
1	280	10	8.0	5.0	272	60	1.7	2.7
2	285	9	8.9	5.1	302	61	1.6	2.7
3	279	9	8.8	4.2	264	51	1.7	2.5
4	272	8	8.1	2.8	260	47	1.8	2.4
5	276	9	7.3	2.2	261	47	1.4	1.5
6	287	8	7.0	2.5	288	55	1.3	1.5

[a] Wind directions are bearings from North.

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Table 4. In-street meteorological measurements made during REPARTEE 2.
Position *X*: in the intersection of Nottingham Place and Nottingham Street. Nottingham Street
Position *Y*: on Portland Place between Devonshire Street and Weymouth Street.

Experiment		1	2	3	4	5	6
Average wind direction (angle from North)	*X* (°)	292	279	292	288	286	294
	RSD	20	21	29	21	19	15
	Y (°)	20	22	16	1	22	27
	RSD	10	10	9	19	16	9
Average wind speed (ms^{-1})	*X* (m/s)	1.00	1.14	0.84	1.01	0.81	0.95
	RSD	53	55	55	63	61	49
	Y (m/s)	1.18	1.18	1.30	0.65	0.78	0.99
	RSD	48	44	45	61	58	46

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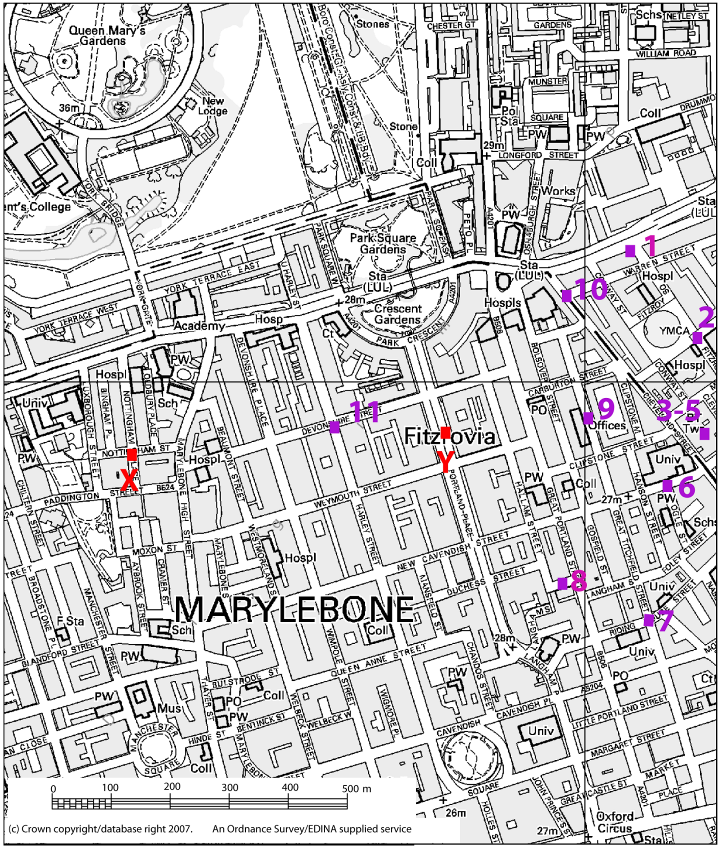

Fig. 1. Experimental setup for the 2007 experiment.
Source locations: X, Y.
Receptor locations: 1 to 10.
Note: receptors 3 to 5 located at heights 0, 160 and 190 m on BT Tower.

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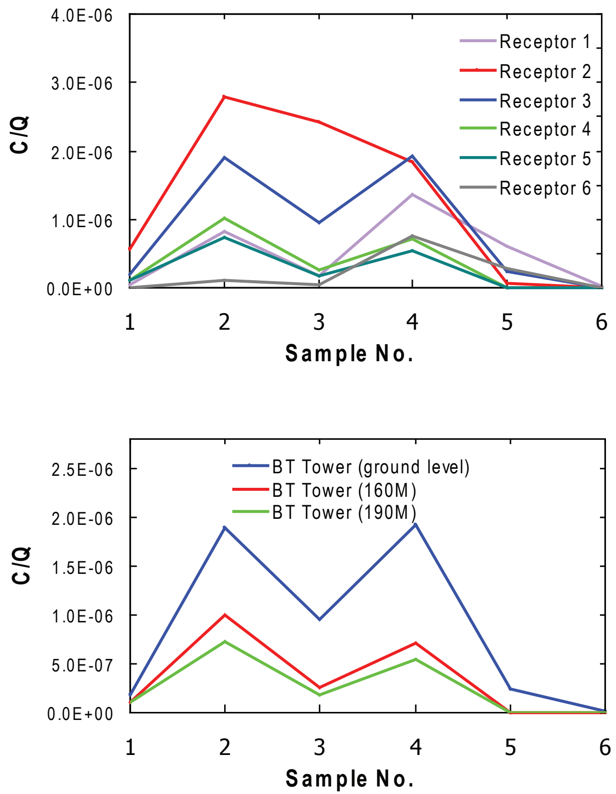

Fig. 2. Time series of concentration – for REPARTEE 1 (26 October 2006)
Sampling intervals 1: 13:50–13:59, 2: 14:00–14:09, 3: 14:10–14:19, 4: 14:20–14:29, 5: 14:30–14:39, 6: 14:40–14:49
Release interval: 13:50 and 14:49,
Release height: 0.36 m,
Release rate: $3.348\pm0.076\times10^{-6}$ kg s^{-1} (all times LT).

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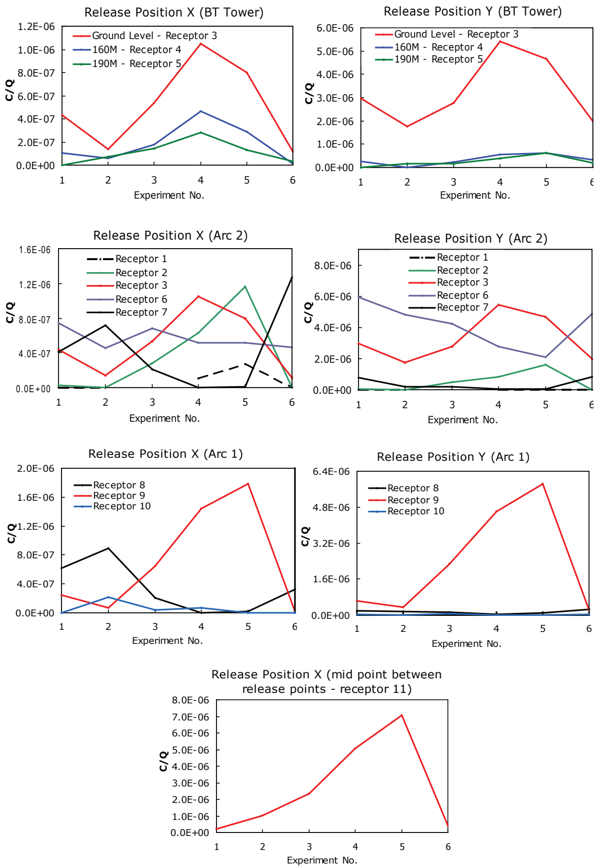

Fig. 3. Time-series of concentration for REPARTEE 2 (7 November 2007). Six experiments carried out: Release interval: 15 min,
Sampling interval: 35 min, Starting concurrently at 13:00 with each experimental period lasting 45 min.

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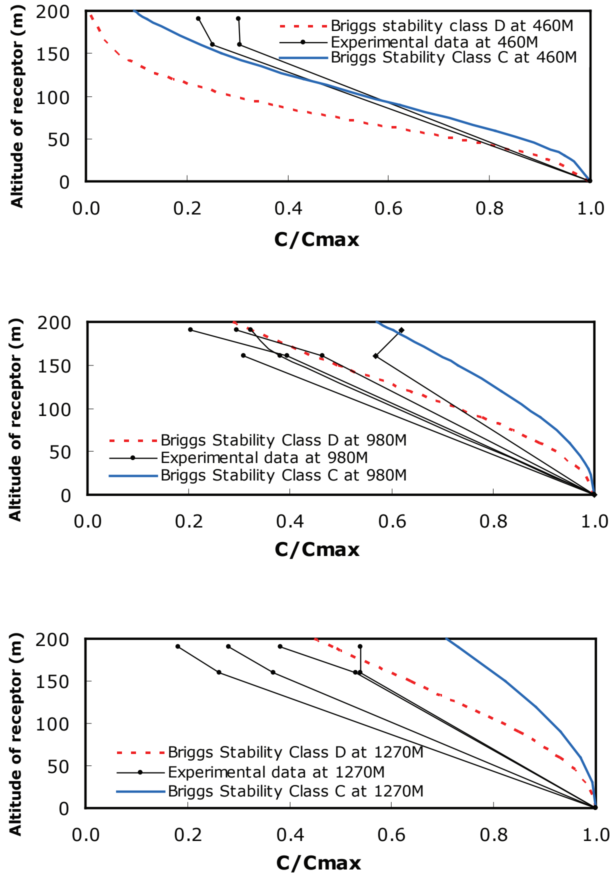

Fig. 4. Vertical gradient profiles for different source-receptor distances: 460, 980 m (2007 data); 1270 m (2006 data).

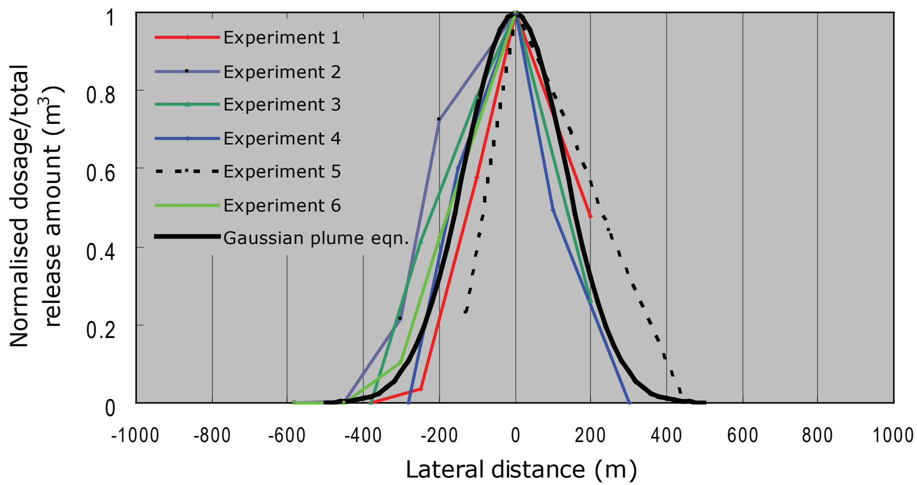

Fig. 5. Lateral concentration profiles during REPARTEE 2.

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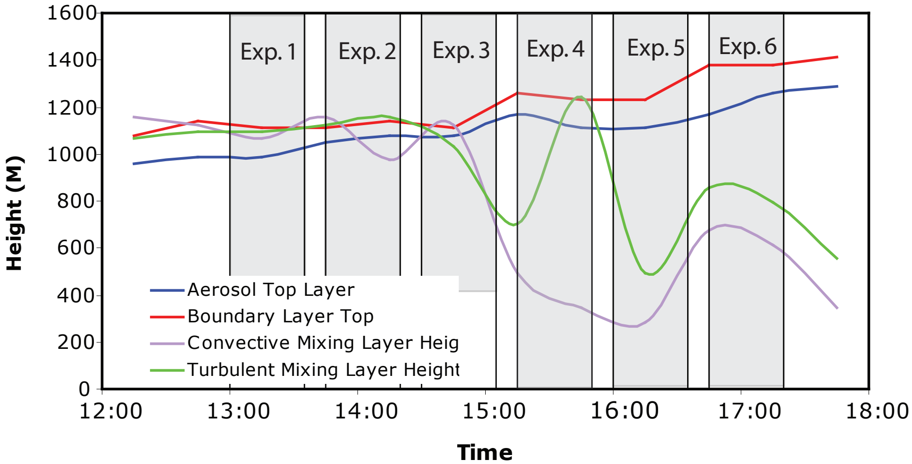

Fig. 6. LIDAR measurements during REPARTEE 2 (all times LT).

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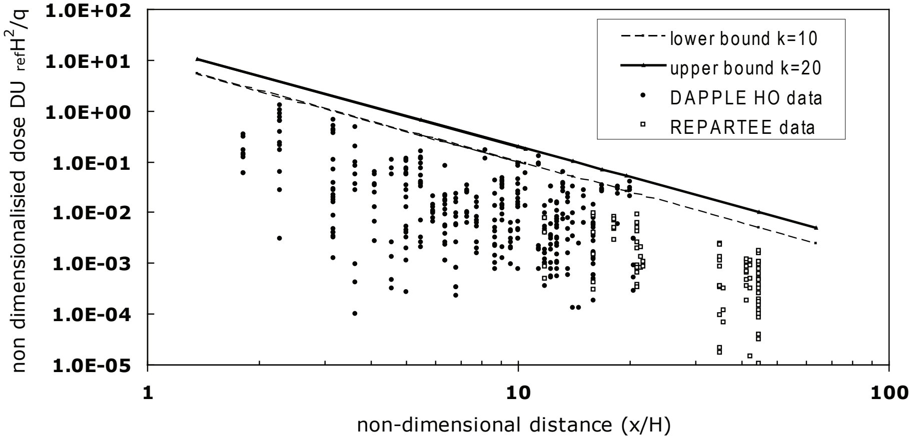

Fig. 7. Evaluation of simple correlation model based on experimental data from both REPARTEE and DAPPLE HO campaigns centred in London.

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